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In 2016 he moved to Snam, Europe's largest natural gas utility. Snam has led the experimentation of hydrogen blending in existing gas pipelines and launched a biomethane and gas mobility business. An American and Italian citizen, Marco also serves as non-executive director of S&P Global and as President of Gas Naturally, a European gas industry association. He is a visiting fellow at the University of Oxford and a member of the General Council of the Giorgio Cini Foundation in Venice. He holds a degree in Philosophy and Economics from the London School of Economics, and has worked for Goldman Sachs in London.
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Illustration by Neva Chieregato

> "The aim of this book is to highlight just how important hydrogen can be for our planet. We're not looking at an easy job but the effort is worth it."
>
> Marco Alverà

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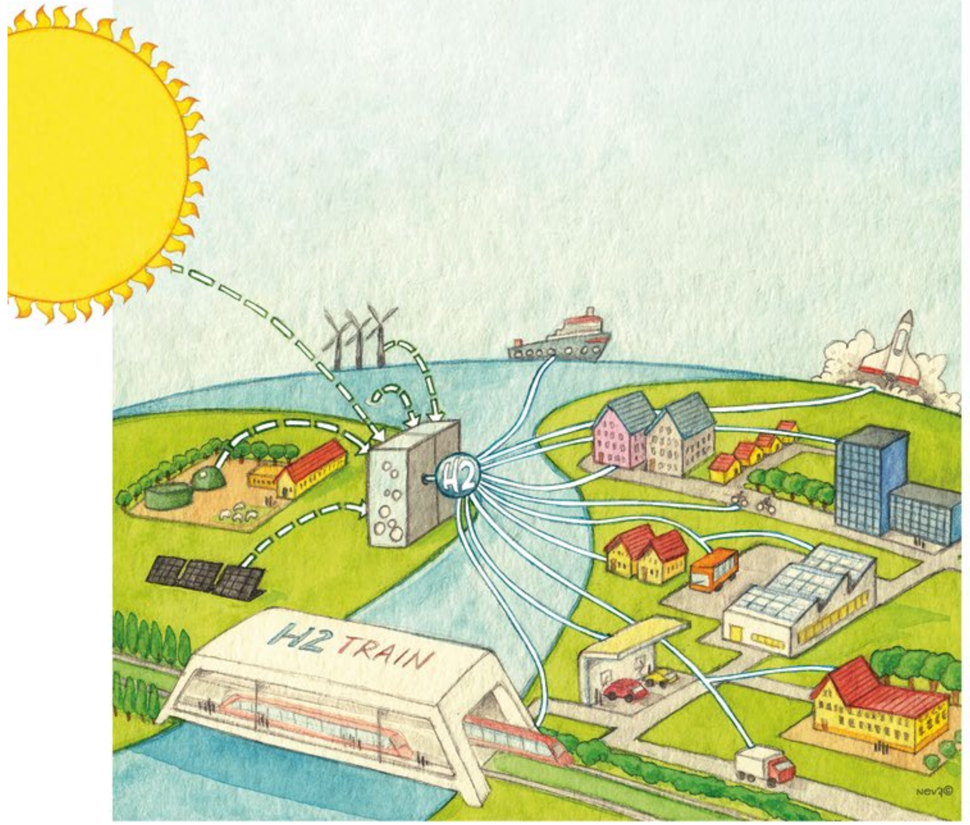
Healing the climate with hydrogen



MONDADORI

It is 2050, and the world is set to feel the first refreshing drafts of global cooling. Temperatures have stabilised. Rainforests and reefs survive.
We can trade, prosper and travel while respecting the equilibrium of our planet. When we take a long-haul flight or turn up the heating, we are using clean energy. Ships, buses and trucks no longer belch CO_2 and fumes, but pure water.
The pipes into our homes carry gas made from waste or renewables. We are harnessing the power of the sun and the wind – transformed into hydrogen.

Climate change and air pollution are defining issues for our generation.
Current policies to tackle them are not working. CO_2 emissions are still rising. If they go unchecked, we could face 4 degrees of global warming by 2100. Even 3 degrees could have a very severe impact on our planet.
To prevent this, we need deep decarbonisation across the world, and an approach that transcends the boundaries of nations and energy sectors, and at the same time supporting employment, economic activity and better living standards.
Hydrogen could make that possible. It is a way of turning the power of the sun and the wind into something that behaves like oil and gas – efficient and easy to transport, store, distribute and use – but is also infinite and clean. It can use existing infrastructure. It can help bring renewables into those stubborn sectors like industry, heating and heavy transport, where electricity is hard to use. Above all, it can bring more green energy to a growing population, supporting prosperous, productive and secure lives.

GENERATION | H

To Lipsi and Greta,
who are made of starstuff

Marco Alverà

GENERATION H

Healing the climate with hydrogen

Preface by **Dr Fatih Birol**

Contributions by **Dr Gabrielle Walker,**
Lord Turner, Baroness Worthington,
Luigi Crema, McKinsey & Company

MONDADORI

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Preface

by Dr Fatih Birol, Executive Director of the International Energy Agency

Seizing the hydrogen moment

Has hydrogen's time finally come? It offers valuable ways to help bring down carbon emissions from the global energy system and boost efforts to combat climate change – but it faces major hurdles in order to reach the necessary scale.

There have been numerous false starts for hydrogen in the past. General Motors built its first vehicle powered by hydrogen in 1966. But rather than transforming the automobile industry, the GM Electrovan ended up in a museum. More than 50 years later, we're still waiting for hydrogen to live up to its promise.

Today, hydrogen is enjoying unprecedented momentum and could finally be on a path towards fulfilling its longstanding potential as a clean energy solution. The impressive successes of solar and wind power, as well as batteries and electric vehicles, have shown that strong policy support and technology innovation can combine with entrepreneurial drive to build global clean energy industries. With the global energy sector in upheaval, hydrogen is drawing greater interest from a diverse group of governments and companies.

I hope this book will help inform international efforts to enable hydrogen to play an important role in clean energy transitions.

At the moment, the world is not on track to reach international climate goals that aim to reduce carbon emissions quickly and significantly enough to prevent a dangerous increase in global temperatures. Last year, the world's energy-related CO_2 emissions rose by 1.7% to a historic high of 33 gigatonnes.

To turn things around, renewable energy sources like wind and solar will have to account for a much bigger share of global supply, and fast. But they have obstacles to overcome, including the fact that the amount of electricity they produce can vary depending on the weather or the time of day or year. That raises concerns about the flexibility of countries' power systems as renewables' share increases.

Hydrogen is one of the leading options for storing energy from renewable energy sources and has the potential to become the least costly way of storing electricity over days, weeks or even months.

And storage is just one of the key energy challenges that hydrogen can help address. It can also fuel trucks and ships and serve as a key raw material for refineries, chemical plants and steel mills. All of those areas are ones where it is proving difficult to meaningfully reduce emissions.

Today, the predominant way of producing hydrogen is from fossil fuels. The amount generated from coal and natural gas this year for industrial uses would be enough, in theory, to run approximately half the cars on the road worldwide. But current hydrogen production releases about the same amount of carbon emissions as the economies of the United Kingdom and Indonesia combined.

This can be reduced if industries currently producing hydrogen capture and store their carbon emissions – or if the supply comes from hydrogen generated from renewable power sources. That is a significant challenge requiring major efforts from governments and businesses around the world. But it's also a great opportunity to start establishing a global clean hydrogen industry for the future.

Hydrogen also has a cost problem. Producing it from renewable electricity is currently two to three times more expensive than producing it from natural gas. That said, solar and wind costs have plunged in recent years – and as they keep dropping, clean hydrogen will become more affordable.

At the same time, electrolysis, the technology that uses electricity to turn water into hydrogen, needs to be developed on a far greater scale to bring down costs. So do fuel cells and refueling equipment for hydrogen-powered vehicles in order to make the use of hydrogen affordable.

The development of hydrogen infrastructure also presents a challenge. In the transport sector, for example, hydrogen prices for consumers wanting to drive fuel-cell vehicles are highly dependent on how many refueling stations there are, how often they are used and how much hydrogen is delivered per day. Tackling this is likely to require planning and coordination that brings together national and local governments, industry and investors.

What's more, regulations are currently limiting the development of a global clean hydrogen industry. Government and businesses must work together to ensure existing regulations are not an unnecessary barrier to investment while ensuring that key objectives such as safety are being met. Trade will benefit from common international standards for safely transporting and storing large volumes of hydrogen.

Governments will be crucial in determining whether hydrogen succeeds or fails. Most of the more than 200 clean hydrogen projects under way worldwide still rely heavily on direct government funding. But smart policies could encourage the private sector to secure long-term supplies of clean hydrogen and give investors the incentives to back the best businesses.

The IEA outlined its recommendations for scaling up clean hydrogen in the study published in June at the request of Japan's presidency of the G20 this year. Those recommendations include establishing a role for hydrogen in countries' long-term energy strategies, stimulating commercial demand for clean hydrogen, providing support for the private sector by reducing the risks of early investments in emerging hydrogen projects and putting public funds into research and development.

Existing infrastructure – such as the millions of kilometres of natural gas pipelines around the world – offers one of the clearest opportunities to scale up hydrogen. Introducing clean hydrogen to replace just 5% of the volume of countries' natural gas supplies would significantly boost global demand for hydrogen and drive down costs.

The transport sector is also very important. Pursuing targets to use hydrogen to powering high-mileage cars, trucks and buses to carry passengers and goods along popular routes can make fuel-cell vehicles more competitive.

We also need to kickstart international hydrogen trade with the first shipping routes. Hydrogen and hydrogen-based fuels can potentially transport energy from renewables over long distances – from regions with abundant solar and wind resources, such as Australia or Latin America, to energy-hungry cities thousands of kilometres away.

There have been recent encouraging signs. Citing the IEA report, G20 energy and environment ministers agreed at their June meeting in Karuizawa, Japan, to step up international efforts to foster the development of hydrogen.

China, as the world's second largest economy and biggest automobile market, will be one of the key players for hydrogen's development and has made it clear that it sees hydrogen fuel-cell vehicles as part of the future of its transport sector.

Following on from our *Future of Hydrogen* report in June, the IEA will continue to further expand our hydrogen expertise in order to monitor progress and provide guidance on technologies, policies and market design. We will continue to work closely with governments and other stakeholders.

The world should seize today's golden opportunity to take advantage of hydrogen's vast potential and make it a key part of our sustainable energy future.

Foreword

The seeds for this book were sown at an unlikely gathering in Norway 12 years ago.

I was working at an oil and gas company, heading upstream operations in the Americas, UK, Russia and Norway, and had accepted an invitation to spend time at a friend's house in a remote village on a fjord called Bjelland.

So I took a plane to Stavanger, and then a very small helicopter, which landed in the middle of a sheep field. In retrospect that had quite a carbon footprint, but it led me to a light-bulb moment. On a hike up a mountain with Dr Gabrielle Walker, the climate scientist and author[1], we talked for hours about climate change, its impact and what needs to be done.

Gabrielle talked me through the science, and she knows her stuff, but she landed the winning punch with a sort of Pascal's wager[2] of energy. She told me that I didn't have to be a climate change believer to start doing something about it. If there was even a chance that the advocates were right, the risks involved in global warming were simply too big to take. That rang true. I returned from that hike determined to engage with the problem. As my engagement grew, so did my concern.

I was concerned that our efforts were focused on having more wind and solar energy in the electricity mix, when electricity only accounts for 20% of global energy. There didn't seem to be any realistic plan to decarbonise the rest of the system.

I was concerned that, while Europe must demonstrate leadership on climate change, with direct responsibility for a tenth of the globe's emissions, it cannot win the war alone. We need a global effort, and one that brings economic opportunities for all the world's citizens while minimising overall costs and sharing them fairly.

And I was concerned that the energy system's different sectors found it so difficult to coordinate a response. As I discovered through my 20-year working life – moving from electricity to gas supply, to oil production, commodity trading and then energy infrastructure – the players in the system are not fully aware of what the others do. Energy sources (coal, oil, gas, nuclear, renewables and hydro) and segments (extraction, trading, electricity production, energy transport and storage, distribution, sales) have distinct and often divergent business objectives, operate in markets that have limited overlap, and use different language and metrics[3].

This confusion hinders policy-makers too, making it difficult to overcome inertia in government and business.

That's a list of worries. Combined with my growing understanding of the potential of climate change to bring damage to our lives, it left me downbeat on our ability to find actionable solutions to avert the crisis.

But lately some positive things have been happening.

People have been mobilising, making concrete changes to their lifestyles. They are using their wallets, their investments and the ballot box to get companies and governments to do better on climate change. Witness the global climate strike on 20 September 2019, the rise of ethical funds, green finance and companies with zero-carbon objectives, and the green turn taken by the European Parliament in recent elections[4], which is leading to a ratchet on European climate targets.

Meanwhile, the technological horizon is broadening. We are no longer just talking about greening power and increasing electrification, but also about decarbonising industry, transport and seasonal heating using biomethane, carbon capture and storage (CCS), and hydrogen made from renewable energy.

Clean hydrogen can be a game changer. It has the potential to be an effective, affordable and global solution alongside renewable electricity and other low-carbon and renewable fuels. It can be a vital source of energy for a growing population while containing climate change. It can also reduce air pollution, which is estimated to kill millions of people a year, and is a huge cost to society in terms of healthcare.

And it can act as a great connector for the fragmented energy system. I have never liked the strategy of picking one technology and opposing all other available routes. In particular, CCS has long been distrusted by some, who see it as taking resources away from renewables. However, its role in the production of low-carbon hydrogen may help persuade naysayers that CCS can contribute to the energy transition.

One of the biggest hurdles has been cost, but that is changing, with the reduction in the cost of renewable power improving prospects for cheap green hydrogen. This should encourage us to work through all the other challenges in hydrogen's path, so that we can leverage its full potential.

Snam, the energy infrastructure company I work at now, can play a key role. We are studying the potential to transport hydrogen in a blend with natural gas, so we can provide the physical network to connect producers and markets. We also aim to provide a network for ideas, policies and technological dissemination. If the world needs to develop green gases, where better than a gas infrastructure company to get things moving?

That's why we decided to convene a global hydrogen conference in Rome, and write a paper pulling together the different strands of our work. And over the summer, as I was writing this paper with my team and sharing ideas with leading thinkers on the topic – including Fatih Birol, Lord Turner, Baroness Worthington, Luigi Crema and Gabrielle Walker – our ambition grew and we decided to turn it into an instant book.

The aim of this book is to highlight just how important hydrogen can be for the future of our planet, and to spur policymakers, businesses and consumers to start working to realise its potential.

We hope you like it.

Marco Alverà

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[1] *Gabrielle Walker has written several books on climate change and energy, including* The Hot Topic.

[2] *The philosopher Blaise Pascal argued that believing in God was a bet worth taking, because the potential cost of getting it wrong was to miss out on a few luxuries, while the cost of not believing and being wrong was eternal damnation.*

[3] *In this book, we also give values in megawatt hours (MWh), our Esperanto of energy.*

[4] *Green parties (Group of the Greens/European Free Alliance) obtained 74 seats in the 2019 European elections, going from 7% to 10% of the parliament and becoming the fourth political force.*

Executive summary

Clean hydrogen is the missing link that can help the world decarbonise, particularly in hard-to-reach sectors.

Fast facts

- Climate change is a global issue. It doesn't matter where CO_2 is emitted, just the overall quantity. And it is a stock, rather than a flow, issue. What really matters is not how much CO_2 we will emit in a given year, but the total amount accumulated over time. Pollution is a separate issue, mainly local and urban, caused by other gases and fine particles.
- Our efforts on climate change are not good enough. We are on track for a level of global warming which will have very serious consequences.
- Renewable electricity alone does not provide a pathway to reach net zero emissions. We will also need low-carbon and renewable gases, including biomethane made from waste, biosyngas, low-carbon gas with carbon capture and storage, and hydrogen.
- You can make clean hydrogen from solar and wind power. It is a way to bring renewable energy to homes, cars, trucks and factories. Clean hydrogen can also be produced by capturing the carbon from natural gas and other fossil fuels.

- As well as fighting climate change, hydrogen reduces air pollution because it burns so cleanly.
- Hydrogen can be transported efficiently over long distances and stored indefinitely. That could allow us to tap into the vast solar reserves of deserts, which receive enough energy in 4 hours of sunlight to supply the world's energy needs for a year.
- Long-distance transport can level out energy prices to aid economic development, and link national and local efforts into a global solution.
- The hydrogen market today is already worth $100bn per year and could reach $2.5tn in 2050[5].

The world is trying to cut carbon emissions using the tool of green electricity. This has merits, but alone it will not be enough to prevent extreme climate change. It does not fully decarbonise industry, shipping and aviation. It puts a prohibitively high cost on winter heating. It leads to a fragmented response, within the energy sector and across geographies, with individual nations each trying to find their own way to reduce emissions.

Adding clean hydrogen to our palette of options can help solve these problems.

Synthesized from renewable electricity, and transported and stored through gas infrastructure, green hydrogen can act as a connector between the gas and electricity worlds.

Hydrogen has the potential to help renewables to grow further, penetrating the hard-to-abate sectors. It can power industry. It can be used to make energy-dense green fuel for planes and trucks, improving air quality, and combining the cleanliness and efficiency of electric motors with the convenience of fuels. And it can store renewable energy to cover seasonal slumps, which could enable it to deliver peak winter heating at lower cost than other decarbonisation options.

Hydrogen also has the potential to link countries together in a global decarbonisation effort. Areas with abundant solar and wind resources or cheap natural gas and carbon storage capacity – particularly in the Middle East, North Africa and Russia – could generate competitive hydrogen. And existing hydrocarbon infrastructure provides a head start for the development of a hydrogen economy as it could potentially be used to transport, store, blend and distribute hydrogen at scale.

Getting green hydrogen off the ground will require a lot of work. Considerable obstacles in the realm of safety, public perception, adapting or providing infrastructure and appliances need to be overcome. Reaching the huge scale implied by climate objectives would also inevitably imply a whole host of operational challenges, including the availablity of space, water, materials and the logistics of operation and maintenance.

But there is good news on cost, which has in the past been one of the main hurdles holding hydrogen back. The cost of renewable power has fallen dramatically, and will continue to do so. And because the electrolyser industry is in its infancy, the cost of converting green power to hydrogen should fall fast as demand rises.

Our analysis shows that below about $2/kg ($50/MWh), hydrogen should reach a tipping point where it will be competitive in large markets without subsidies. This could be achieved through the manufacturing economies of scale from adding 50GW[6] of electrolyser capacity between now and 2030.

A policy that could deliver this extra demand is one that mandates the blending of a limited proportion of hydrogen in the natural gas network. More tests are needed on the tolerance to hydrogen blends across the transport, storage and distribution networks and some equipment will need to be adapted. But Snam's initial experiments are promising, implying that blending could be a route to create hydrogen demand without expensive investments in infrastructure or appliances.

For an idea of the numbers involved, growing the percentage of hydrogen to natural gas transport pipelines in Europe and Japan to 7% by 2030 would more than deliver the required electrolyser capacity. The fully ramped up system would cost 0.02% of GDP per annum.

A larger "coalition of the willing" would reduce the percentage of hydrogen in the blend required to reach the tipping point, as well as further cutting the cost per person. There are several other areas in which clean hydrogen is being earmarked as an ideal decarbonisation lever, including heavy transport (shipping and road haulage), that would accelerate the process.

Lowering the cost of green hydrogen would facilitate the further spread of this clean resource in other sectors and other geographies. This approach would provide a just transition and minimise overall costs. Early developers of the technology would have a competitive advantage when hydrogen takes off.

To realise its full potential, hydrogen must convince policymakers and consumers that it is safe and reliable. The Hindenburg continues to cast a dark shadow. This means enshrining a commitment to safety and demonstrating a track record of safe use, along with credible, evidence-based information campaigns.

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[5] *http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf*

[6] *Calculated using BNEF cost curves for the LCOE of renewable power and a 12% learning curve for electrolysers.*

1. The challenge

Our efforts to avert climate crisis are not good enough. An effective solution needs to provide a strategy for deep and fast decarbonisation, be truly global and enable growth and economic development.

Climate change is the existential challenge of our generation. Scientists have been warning of dangerous global warming for decades, and in recent years politicians and the public have begun to grasp the seriousness and urgency of the problem.

Average global temperatures have risen by almost 1 °C over the past century. This deceptively small number masks a host of growing hazards. For a start, that one-degree average includes the oceans, which are slow to warm. On land, meanwhile, average temperatures are already 1.5 degrees higher[7]. This makes extreme heat waves much more common, as Europe has seen in 2003, 2006, 2007, 2010, 2015, 2018, 2019…

According to a study[8] published in July 2019, the climate of London in 2050 may resemble that of Barcelona today, and about a fifth of cities globally, including Jakarta, Singapore, Yangon and Kuala Lumpur will experience climatic conditions currently not seen in any major cities in the world.

In the Arctic, temperatures are rising much faster, melting sea ice and thawing permafrost. As it thaws, permafrost releases powerful greenhouse gas, which could take us over a climate cliff – leading to irreversible and catastrophic warming.

Rainfall patterns are changing, often making dry areas drier and wet areas wetter. Worsening droughts in Asia and Africa lead to famine, mass migration and conflict. Warmer air can hold more moisture, so extreme rainstorms are more frequent and more intense, increasing the risk of floods. Warmer seas provide more potential energy for storms, and there is evidence that the most powerful hurricanes are getting fiercer. Dorian's devastation in the Bahamas this September could be a taste of things to come.

The extra carbon dioxide is acidifying oceans. This is eating away at coral reefs, and it could mean that plankton and molluscs are unable to form shells, threatening ocean food chains.

Sea levels are rising as ice caps pour more and more fresh water into the oceans, and because water expands as it warms. In my home town of Venice, tidal floods are becoming far more frequent, threatening the fabric of this unique city, already corroding the columns of St Mark's Basilica. But of course the global problem is much greater, with rising risk of floods from Bangladesh to Manhattan. Hundreds of millions of people living close to sea level could be displaced[9]. Worse, ice sheets in Greenland and the West Antarctic are thought to be unstable. If warming goes too far, they could melt and raise the oceans by several metres.

Crucially, today's global warming is extremely rapid compared with climate shifts of the past, which gives nature and civilisation little time to adapt.

Burning issue

This convulsion is clearly linked to human actions. Burning fossil fuels for power, heating, transport and industry; cutting down forests for cattle farming; cement manufacture and other industrial processes – all of these generate CO_2 and other greenhouse gases that trap solar heat.

Burning coal and oil also causes air pollution, including nitrogen oxides and fine particles, which is estimated to kill millions of people per year and is a powerful driver for policy action[10].

To date we have emitted more than 2200 billion tonnes of CO_2 equivalent (including the effects of other gases). To keep global warming below the 2-degree threshold, and thus give us a chance of avoiding the worst consequences of climate change, we can't afford more than another 700 billion tonnes or so[11].

This does not give us long to solve the problem. Today we emit about 42 billion tonnes a year[12] (around 33 billion tonnes are energy related) so our remaining budget is less than 17 years at current consumption.

Of course the hope is that emission levels will soon start to decline, buying us more time. Which is why giving long-term targets such as "net zero by 2050" is worthwhile, but shouldn't be an excuse for not acting now. For our carbon budget to 2050, closing a coal plant today is worth 30 times as much as closing it in 2049.

If we don't stay within budget, we will have to take a lot of CO_2 out of the air instead. Planting trees and burying charcoal can help to do this but on a limited scale, so we will probably need to master carbon capture and storage (CCS). Trials have shown that concentrated streams of CO_2 from factories and power plants can be captured, and one day we may capture CO_2 directly from the air and store it underground. That will be expensive, and will require stable geological reservoirs, meaning that we shouldn't regard CCS as a free pass to emit carbon today; instead it could be a tool to help us meet the budget.

So we don't know exactly how many years we have before we should no longer emit CO_2, but Europe's vision is to get to or near net zero by 2050, and the world should follow suit not long after[13].

Population growth increases the scale of this challenge. By 2050, there will be around 9.7 billion of us, up from 7.7 billion today. And then there is the question of what should be considered a fair transition. Developing countries can reasonably argue that they should have more time to reduce emissions, as they didn't cause the problem and they have a right to reach the living standards of developed countries. That would create a powerful headwind. Today US citizens consume on average 12 megawatt hours (MWh) of energy a year; Chinese citizens 4.5 MWh and Indian citizens 1.1 MWh, while in Africa it is less than 0.5 MWh. The energy Americans use to cool their homes is equal to Mexico's total energy use. If everyone consumed as much energy as Americans do, global emissions would rise by 400%.

Progress

> ***"The struggle to rein in global carbon emissions and keep the planet from melting down has the feel of Kafka's fiction. The goal has been clear for thirty years, and despite earnest efforts we've made essentially no progress toward reaching it."***
>
> **Jonathan Franzen, *The New Yorker*, 8 Sept 2019**

We have made a great effort to rise to this challenge. At the Paris agreement of 2015, most of the world's nations signed up to the goal of limiting warming to well below 2 degrees. Meanwhile, the technology to generate renewable electricity has improved more quickly than anyone expected. The ambitious targets set by Europe drove the industrialization and mass production of solar and wind technology. As a result, the cost of solar capacity fell by 75% from 2010 to 2018.

But this positive narrative does not tell the whole story. Emissions started to rise again in 2017, and reached the highest ever level in 2018. Some European countries – Italy is a virtuous exception – are set to blow through their CO_2 targets also due to higher-than-expected coal consumption. If we carry on as we are, we may face catastrophic global warming.

I think that we are struggling to gain traction because our current pathway doesn't address the energy system as a whole, is difficult to scale up without incurring high costs, and tries to solve a global problem with a collection of local solutions.

Too narrow

Renewable electricity has been almost the sole focus of policy initiatives. This has two implications for the carbon budget.

First, the narrow focus on solar and wind has meant that we have taken our eye off the ball in other areas, especially coal, where the industry has performed something of a perception miracle. When I engage policymakers in Europe on measures to phase out coal with the help of natural gas, I am often told that we are already past coal.

Yet coal is still very much with us. It still accounts for 21% of European power generation, As a result of coal's tenacity, the carbon intensity of power generation in Germany only decreased by 4% from 2012 to 2016, despite €85 billion of investments in renewables.

Even more worryingly, coal accounts for as much as 67% of power generation in China and 74% in India where coal capacity is still growing and existing plants are only 11 years old.

Second, the idea that you could clean up power and then electrify everything was always somewhere between lazy and wishful thinking, not least because green power is hard to use far away from where it is generated (whether through time or space) and gives us no clear path to decarbonising steelmaking, chemicals, air travel, freight and winter heating (see chapter *3. How hydrogen helps*).

Indeed, the International Renewable Energy Agency suggests[14] that electricity will reach 49% of global energy consumption by 2050, and that the energy transition will require significant investments across the board; $110 trillion to 2050, of which 18%

in oil and gas (including CCS), 35% in energy efficiency, 23% in infrastructure and 24% in renewables[15].

One reason we focused on green power and missed out other parts of the energy system is a lack of collaboration between molecules and electricity. This is largely because different companies only see their bit of the energy system, with limited areas of overlap. For instance, the electricity sector knows a lot about gas used to generate power, but less about gas use in heating, industry and transport.

This isn't helped by the alphabet soup of energy units. Other industries have consistent units. IT uses bits (Mb, Gb, Tb); telecoms use bits per second; car companies use horsepower. That helps if you are trying to choose a computer, a phone company or a car.

If you need energy, it isn't quite so simple. Electricity companies think in megawatt hours (MWh); oil producers deal in barrels of oil equivalent (boe); gas companies see the world in cubic meters (cm), or cubic feet, or million British thermal units (MMBTU). Mining companies measure tons of coal equivalent (TCE). Climate scientists chart gigatonnes of CO_2 equivalent emissions ($GtCO_2e$)[16]. And do you want to measure capacity, or hourly, daily or yearly flows? Would you like to find out how much that might cost in dollars, euros or yuan?

This means that thinking about a full-system pathway for climate change, and which technologies might be able to do what, is a bit like trying to choose a t-shirt on the internet when you can see the pictures but can't quite work out what size each shirt is, how many per pack and what they cost.

Energy (MWh)	Oil (boe)	Natural Gas (cm)	Natural Gas (MMBTU)	Coal (TCE)	Hydrogen (kg)
1	0.61	94.79	3.41	0.12	25

Table 1. Energy unit conversion

	Oil	Natural Gas	Coal	Grey Hydrogen	Green Hydrogen	Blue Hydrogen
Energy equivalent costs ($/MWh)	43	27	11	50	125	60

Table 2. Energy prices in Europe in 2018 (Brent, TTF, ARA)

The segments of the energy system also have different business objectives, with the power industry keen on support for renewables, but less keen for their coal-fired assets to become redundant. There is also opposition to anything involving natural gas, including the development of CCS, on the basis that it would lock in fossil fuels and hamper the growth of green electricity. Mothballed power plants are the Betamax and CDs of the energy industry – a reminder that stranded assets haven't in the past stopped new technologies from driving the market forward.

Expensive

Second, the current path is difficult to reconcile with population growth, energy access and economic development.

True, the cost of green power has fallen massively. In many cases it is cheaper than grid electricity, as measured by levelised cost of electricity (LCOE). But this does not take into account the investments in transport and storage needed to use renewables properly (see page 27). These costs rise along with the percentage of intermittent power in the mix. And in some applications, for instance winter heating and transport, full electrification is more expensive than other decarbonisation options.

So far, strategies for decarbonisation have focused on individual sectors. We haven't really looked at resource optimization across sectors and geographies. To help us pick the lower-hanging fruit first we need a proper CO_2 abatement cost curve, showing $/$CO_2$ avoided.

As well as being more expensive than it looks, green electricity alone provides no way to decarbonise energy intensive industry and air travel, and doesn't sit well with heavy road and maritime transport.

That has led to consumption decline becoming part of the decarbonisation advocacy of some, fusing climate concerns with those over income inequality and excessive consumption.

Activists call for people to embrace a simpler way of life, to consume less. The Swedes have invented the word flygskam (flight-shame) for a movement to encourage people to take fewer planes and be proud of taking trains (tagskyrt – train-brag) instead. This works particularly well in Sweden, where trains run on electricity and electricity is very green. Globally, 25% of train travel is still diesel-fuelled.

While this simpler-life narrative may resonate with some people in wealthier nations, it takes no account of those who seek a better standard of living for themselves, their families and their community.

Looking at the interests of our planet and our species overall, any solution would be better than no solution, because the overall costs of climate change are so high. In fact, the costs will fall disproportionately on those who live in the hottest – usually the poorest – areas of the world, and on those yet to be born.

But try telling that to people in the developing world, who have done little to cause the problem and who are now increasing their energy consumption as living standards climb. They won't take kindly to a global agreement that increases their energy costs, erodes their competitive advantage and limits their growth potential.

Comparing electricity costs

The costs of energy sources are usually compared through levelised cost of energy (LCOE), the average cost of a unit of output, assuming a given load factor. This is calculated by adding up all the costs at plant level and dividing them by the amount of electricity that the plant will produce throughout its useful life, discounting at an appropriate rate to allow for the time distribution of costs incurred and production obtained.

However, LCOE may lead to misleading conclusions when used to compare intermittent renewables with programmable generation.

It wrongly assumes that the power from different technologies receives the same price. In reality, solar and wind power tend to be most productive when and where the market value of electricity is very low. By contrast, programmable technologies such as fossil fuel generation, bioenergy and hydroelectric power can be switched on or turned up when the market value is higher.

And LCOE does not take into account the interactions between a power plant and the rest of the electrical system. The intermittency of solar and wind means that the rest of the system must adapt, by operating at partial load, switching off, or rapidly increasing or reducing load. This generates extra cost and also extra emissions, as the machines don't work at their most efficient setting. If existing flexible resources are not sufficient, new and costly storage capacity is needed.

Finally, the best sites for sun and wind are often far from the centres of consumption, which implies the need for new power lines.

To overcome these limitations, the International Energy Agency introduced VALCOE – Value-adjusted Levelized Cost of Electricity, which takes into consideration energy, capacity and flexibility.

Or try to convince those in Europe that already feel left behind and who see the factory that employs them close because it has to pay higher costs for clean energy and is competed out of existence. As the French *gilets jaunes* have shown, an increase in fuel costs of only 10% can spark rebellion, and it is hard to maintain policy rigour in the face of popular discontent. Recent reports suggest that regional politicians in China may be thinking about scaling back their climate efforts because of declining GDP growth. With energy poverty on the rise and energy costs a big political issue in many countries, any solution that isn't perceived as fair, and which negatively impacts a country's competitive position, has a poor chance of surviving.

The relationship between energy costs and jobs will become increasingly close with the rise of automation and artificial intelligence, which substitute labour costs with energy costs. Cheap labour will no longer provide a competitive edge on the global playing field. Instead, cheap energy will. Over-reliance on green electricity means nations making their own transition pathway, which could impose vastly different energy costs on different regions, resulting in disparate economic performances. That may make it difficult for the solution to stick.

A world divided

Finally, we have struggled to ensure the global approach that is necessary to solve a global problem.

The international consensus that made Paris possible was the product of a remarkable convergence between the US and China, born of President Obama's desire to cement his legacy and President Xi's ambition to reassert China's international credentials. With the world's two biggest emitters committed to working together, other countries had no excuse not to pitch in, and the two huge economies had plenty of carrots and sticks to apply to any laggards.

This united front has now broken down. US support for Paris has waned, and the relationship between China and the US has become more tense. I went to the COP 24 held in Katowice (Poland, December 2018), and was surprised at how low morale was in the negotiating teams. The US and China had sent delegations

but were not playing ball. Hydrocarbon-producing countries were dragging their feet. And the discussions had deteriorated into crossed vetos and horse trading; without strong political commitment, and sticks and carrots, it was difficult to make any sort of progress.

Upcoming COPs will have a tough job to restore the global consensus. The Chilean president Sebastián Piñera has launched the upcoming summit stressing the sense of urgency that must pervade the climate change challenge, and work is already starting to prepare for the Anglo-Italian effort that will be the COP26.

Even the Paris Agreements were arguably more important as a global statement of intent than a precise pathway for a climate change solution. The commitments of the countries which signed up (called Nationally Defined Contributions or NDCs) are not enforceable, nor do they add up to the reduction required to limit warming to well below 2 degrees.

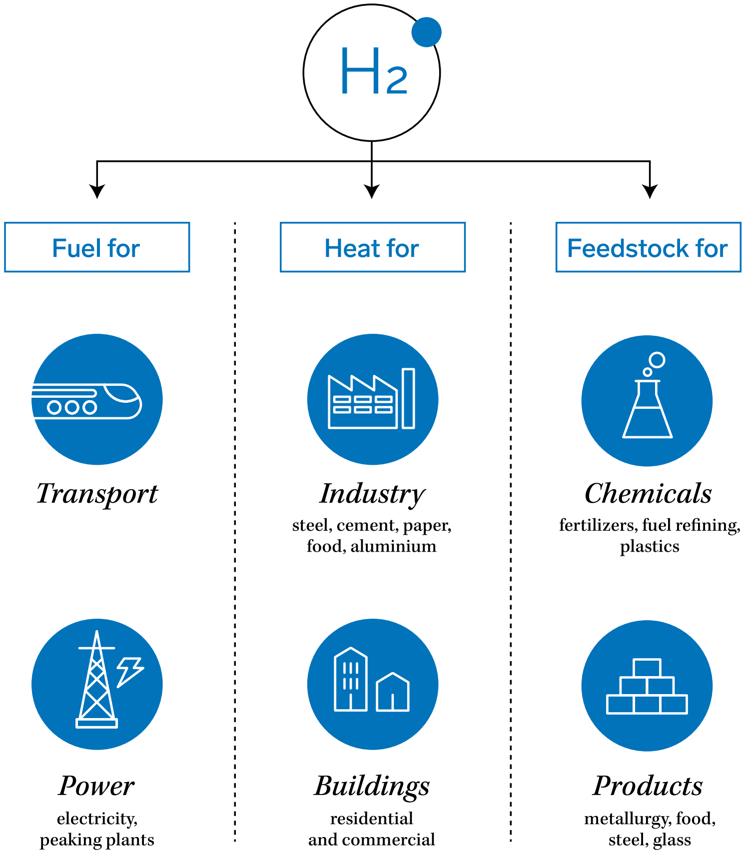
Indeed, scenarios such as the IEA New Policies (a bottom-up view that considers all the initiatives countries have said they will pursue) show that with NDCs we can expect a gradual evolution in the global energy system, rather than the radical improvement we need. From now to 2040, global energy demand is expected to increase by 27%, with the share of renewables rising from 4 to 10% and natural gas going from 22% to 25%, while oil falls from 32% today to 28%. The real shocker from my perspective is that this scenario still has a lot of coal in the mix in 2040: it accounts for 22% of the energy mix, from 27% today[17]. Such a scenario would imply about 3 °C of global warming in 2100[18].

And Paris doesn't quite add up to global strategy, but rather a collection of national strategies. That is largely due to the fact that electricity is difficult to transport, so decarbonising through electricity means solving lots of national or local problems separately.

That creates two issues.:

- First, the most virtuous regions can lose out. In order to incentivise renewables, Europe has added €60bn of

The many uses of hydrogen



source: BloombergNEF

annual subsidies[19] to already high energy costs – an expensive initiative on a $/$CO_2$ basis. This has been a drag on economic performance, as some companies struggle to compete on the global playing field and either close down or move operations (and emissions) to other countries.

- Second, if everyone has to be largely self-sufficient you lose efficiency. The emphasis on national plans has led to Germany putting down solar panels in the Black Forest, where they will produce for around 1000 hours per year, while sunnier North African countries could yield almost double that.

Self-sufficiency could also create political problems. For instance, Europe's 2050 climate objectives imply a long-term reduction in natural gas imports from Russia and North Africa, which might pose challenges in these regions.

Three key features

The issues that have held us back give clues to what we should be trying to do. Our pathway should be:

Definitive. So far we have approached climate change in an "every little helps" way. Now that time is short, we need a plan for how to actually meet the carbon budget.

Affordable. To get durable support, we need a solution that doesn't cost too much, and that preserves or even creates employment – especially for the poorest nations and parts of society.

Global. It is no use if Europe reaches zero in 2050 while emissions from developing nations keep climbing. The whole world must be involved. To enable this we must find a way to trade clean energy, creating a global market.

The missing link

Green hydrogen can help meet all of these needs. It straddles the world of molecules and electrons, weaving together different strands of the energy system. It can distribute power between regions and seasons, serving as a buffer to increase energy-system resilience. Because hydrogen can be used to export green energy from regions with ample wind and sun, or from natural gas producers with CCS, it could level out clean energy prices and so lead to a fairer global economy. Hydrogen can unshackle industry from its carbon burden, enabling economic growth and encouraging countries to sign up to a climate solution. And with clean hydrogen the basis for zero-carbon, guilt-free air travel, tourism can flourish too. Hydrogen also improves air quality because it burns so cleanly.

Hydrogen shouldn't be considered a technology, but a technology enabler. Like an internet of energy, hydrogen can connect all the sectors of the economy and society to trigger competition and innovation across sectors and geographies and make energy more affordable, available and abundant for a growing global population.

That's not to say that hydrogen will make the energy transition easy. Climate objectives involve an overhaul of the global energy system that will require unprecedented mobilization of resources – and a huge scale-up of all available options, with all the operational, commercial, financial and policy challenges that this entails.

Hydrogen will not be immune to these challenges – and because it is downstream of renewable energy, and requires specific midstream, distribution and consumption solutions, its development will be dependent on what happens elsewhere in the value chain.

But if hydrogen isn't a silver bullet, it can certainly make the transition easier. And that is an objective worth pursuing.

The basics

"Hydrogen is an odorless, colorless gas which, given enough time, produces people."

Edward R. Harrison – *Cosmology: The Science of the Universe*

Created in the forge of the early Universe, hydrogen is the prime ingredient in the Sun and countless other stars, as well as in our bodies. It is a powerful way to convert, store and use energy. It can be generated using potentially limitless inputs; it can act as a fuel, an energy vector and a chemical feedstock; and it emits no CO_2 when it is used.

Make it

You can use electricity to split water into hydrogen and oxygen, a process called electrolysis. You may remember making a simple electrolyser at school with a battery, a beaker of water, pencils and alligator clips, and watching the oxygen and hydrogen bubbles form.

If the power source is surplus renewables, this is called green hydrogen. Or you can extract hydrogen from natural gas and other fossil fuels, using steam reformers. That creates carbon dioxide as a by-product (the result is known as grey hydrogen), so carbon capture and storage would be needed to make this a climate-friendly option, producing what's known as blue hydrogen.

Two newer production methods are methane cracking, which leaves solid carbon as a residue, and extracting hydrogen from oil fields by injecting oxygen (see *Contributions from thought leaders*, Luigi Crema, Fondazione Bruno Kessler, on page 110). There are more than 40 ways of making hydrogen.

Move it

Hydrogen can be sent through pipelines, or carried in tanks as a compressed gas or a liquid. Existing gas networks can carry natural gas blended with some hydrogen.

Store it

Unlike electricity, hydrogen is cheap and easy to store. Salt caverns could hold huge quantities at very low cost.

Use it

Hydrogen can be burned to drive a turbine. It can be piped into people's homes for hydrogen boilers, cookers and cooling devices. It can be converted into electricity using a fuel cell, to power a car or truck. In all these cases, the only waste product is pure water.

Hydrogen is used in oil refining and steel making, and is the feedstock for many chemical products – including ammonia, which is used to make fertilizers; and methanol, a basis for plastics, resins and paints.

For more detail see *Appendix 2. How hydrogen works*

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[7] https://www.ipcc.ch/report/srccl/

[8] PLOS ONE https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0217592

[9] https://www.ipcc.ch/report/ar5/wg2/

[10] This appears to be the case in China's coal-to-gas switch policies, for example. In 2017, particulate pollution in Beijing declined by 54% largely as a result of the reduction in coal-boiler use. According to a methodology developed by the University of Chicago, these gains would add 2.4 years to the life expectancy of all residents in the area if they persisted (Global Gas Report, Snam IGU and BCG, 2018).

[11] https://www.theguardian.com/environment/datablog/2017/jan/19/carbon-countdown-clock-how-much-of-the-worlds-carbon-budget-have-we-spent

[12] https://www.ipcc.ch/sr15/

[13] https://www.nytimes.com/paidpost/shell/net-zero-emissions-by-2070.html

[14] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf

[15] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf

[16] To facilitate comparison and communication between different sectors of the energy system, all figures in this book are also given in MW and MWh.

[17] In this NDC-consistent scenario, the size of the relative starting positions implies that a percentage point switch from coal and oil to gas in power generation and transport has the same CO_2 benefit as increasing current renewables by 10%.

[18] Similar results are given by the BP Evolving Transition scenario, where energy demand is expected to rise by 32%, with the share of renewables in the mix going to 15%, natural gas to 25%, oil falling to 27% and coal to 20%.

[19] https://ec.europa.eu/transparency/regdoc/rep/10102/2019/EN/SWD-2019-1-F1-EN-MAIN-PART-4.PDF

Overview applications

1 Kg H_2 can

Fuel a fuel cell car to drive for 130 km[1]

Provide 2 days of heating for an average household[2]

Be used to produce 9 kg of steel[3]

1 Assuming a FCEV from the C/D passenger car segment / calculated today's efficiencies, which will further decline over time

2 Assuming an average heating demand of 10 MWh per household

3 Via the dri-eaf process where raw iron is reduced using H2 in the DRI

2. Third time lucky?

Hydrogen has been touted as an energy solution before. But with new motivation, falling costs and a growing band of supporters, this time is different.

First glimmers

> *"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable."*
>
> **Jules Verne, 1874**

Known in the 18th century as inflammable air, and first synthesised through electoysis in 1798, hydrogen has a long history as a potential fuel.

Arguably the earliest internal combustion engine, built by Isaac de Rivaz in 1804, burned hydrogen. Fuel cells were developed in the mid-19th century. In Germany and England in the 1930s, Rudolf Erren converted internal combustion engines of buses and trucks to run on hydrogen. But cheap oil and safety concerns held it back from hitting the big time.

A false dawn

The first time I seriously engaged with the prospects for Hydrogen was in 2002, when I was heading the Strategy team at an Italian utility, today one of the world's largest producers of renewable energy. I was sent to Japan for a week, to the global hydrogen congress.

There was a buzz around hydrogen at the time. These were the years of peak oil and gas. Meanwhile, global warming was starting to creep up the policy-making agenda. And of course, we are talking about the time of the dot-com boom, when technology's potential to disrupt the communications, information and retail industry was becoming clear.

These threads – geopolitics, global warming and technology – were pulled together in Jeremy Rifkin's book *The Hydrogen Economy* (2002), which argued that the old energy paradigm was on its last legs, and that hydrogen was going to be a safe, clean and locally produced alternative, a new world-wide energy web to redistribute global power.

But I came back from Kyoto feeling that hydrogen was not about to take off at all. The concept seemed too narrow, the technology complex and costly, and the interested parties few and conflicted.

Quite a lot of my conference seemed to be about using hydrogen as a way of getting nuclear energy into one's car, which didn't fill me with excitement given that Italy had already shut down its nuclear power plants following a referendum. While geopolitics might make petrol more expensive, it would still be competitive with the nuclear-to-hydrogen alternative – also given the complexities of rolling out new refueling infrastructure, changing cars and changing behaviours. And, of course, the cost of solar power was more than ten times higher than it is today, making renewable hydrogen unimaginably expensive.

Also, I wasn't quite sure who was meant to be driving the new dawn of hydrogen. Traditional energy companies, like the big oil & gas producers, had little incentive to cannibalize their own market. Governments looked unlikely to subsidize a new energy system unilaterally. Global warming was increasingly being talked about, but certainly G20 prime ministers were not yet discussing zero CO_2 policies, and the incentives to develop a whole new world just weren't there.

So on my return to Italy I put the idea of hydrogen on the back burner.

Sunrise

Now I think we need to put it front and centre. What's changed?

The hero is zero

Most importantly, the motivation to reach zero emissions is now there. Climate change has gone from being something that was talked about in the science section of newspapers to front-page news – especially in Europe, which has taken a leading role on the global stage, but also in, for instance, California and New York State.

It is hard to overstate how massive a change this has been, for the energy industry especially. In my 20 years in the energy sector I have gone from devoting maybe 2% of my time to climate change related work to something like 70% today.

Policy is following. The UK has already committed to net zero by 2050. The EU has a target for 2030 of cutting emissions by 40% (relative to 1990 levels) and an objective of 80 to 95% by 2050, both of which may well be revised up by the new, very green, European policy-making bodies. And other areas of the world are also setting ambitious objectives.

This net-zero thinking is particularly useful when it comes to hydrogen development because it forces countries not just to take incremental steps to reduce emissions, but to decide what a completely green energy system looks like and work backwards from there.

That stops us just doing more of what comes easy – decarbonising electricity generation and hoping that the technology comes through to decarbonise all the other sectors, like heating, industry and transport. That is not where we need to be pushing now, because power is broadly speaking done (we have a clear idea of how to get to zero) while for other sectors our thinking is at a much earlier stage. The focus on net zero highlights areas where green gas development would make sense, especially those hard-to-abate sectors.

Cheap and cheerful

Just as we are looking for a way to attack non-power sectors, hydrogen is looking increasingly affordable. The price of renewable electricity has come down much faster than expected. Wind and solar power have reached 20-30 dollars per MWh in many locations[20] including Portugal, Mexico, Morocco, Saudi Arabia and UAE. Solar costs could fall a further 50% in the next 10 years.

Meanwhile the system CapEx for electrolysers fell by 40 to 50% between 2014 and 2019[21]. Electrolysers should get cheaper still as volumes rise, following a similar pattern to other technologies, such as renewables. A smart combination of wind and solar in the electricity mix, with some storage, will improve the utilisation of electrolysers, further reducing the cost per MWh.

Production is only the first step of the hydrogen value chain. One reason hydrogen is cheaper than other decarbonisation solutions is that transporting, storing and using it in final consumption is significantly less expensive than the equivalent investments required to build all the infrastructure to be able to fully electrify final demand. This is even more efficient as existing natural gas infrastructure can be converted to hydrogen (see chapter *4. The power couple*).

Everybody loves hydrogen

The third reason why I think this time it is game on for hydrogen is that a lot of people want it to succeed.

The renewables industry likes hydrogen because it is a way to create a new market for renewables, increasing their penetration in the energy mix, because conversion to hydrogen allows you to power your steel mill and your winter shower with the sun.

NGOs like hydrogen for similar reasons, in that it doesn't compete with renewables but enables them, and is a good way to get to a fully decarbonised system.

The hydrocarbon industry, which has struggled to envisage a role for itself in a zero carbon world, likes hydrogen because it can be produced from traditional fuels, which gives value to reserves.

Hydrogen can also travel in existing infrastructure, which is good news for those – like Snam – who own transport and storage capacity. Because hydrogen production from methane will require CCS in order to be carbon neutral, it may also revitalize a technology that has struggled to gain traction in Europe, but which is probably necessary to meet our climate goals.

Energy intensive industries like hydrogen because it gives them a route to net-zero compliance.

Governments like hydrogen because it offers a pathway to net zero that improves air quality, uses existing infrastructure and promotes supply security; and also gives a roadmap to decarbonise industry competitively, easing the trade-off between decarbonisation and jobs. Their voters seem to like hydrogen too, if the buzz around it is anything to go by.

Even oil-producing countries may grow to like hydrogen if they have large solar or wind resources, as in the Persian Gulf, North Africa and Australia, or low fossil fuel costs and CCS potential, as in Russia.

Overall, at a time of intensifying debate on Green New Deals, and with technology costs falling rapidly, this is the ideal time to reassess the opportunities and challenges of accelerating the development of the hydrogen economy.

Hydrocarbons and the spectrum of green

Most fuels we use today are hydrocarbons – chemicals built from hydrogen and carbon. Both of these elements, when they combine with oxygen, generate energy.

But the carbon also generates carbon dioxide; the hydrogen only harmless water. So the cleaner fuels are the ones with less C and more H, generating less CO_2 for a given amount of energy.

	Carbon content	**Hydrogen content**	**$kgCO_2$ emissions per MWh produced**
Coal	**up to 90%**	**5%**	**900**
Crude oil	**84-87%**	**11-13%**	**565**
Natural gas	**75%**	**25%**	**365**
Hydrogen	**0**	**100%**	**0**

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[20] *http://www.gsb.uct.ac.za/files/EEG_GlobalAuctionsReport.pdf https://www.pv-tech.org/news/portugal-reveals-winners-of-record-breaking-solar-auction*

[21] *"Hydrogen: The Economics of Production From Renewables", BNEF August 2019.*

3. How hydrogen helps

Hydrogen's special abilities could help to achieve deep decarbonisation, especially in the stubborn sectors of industry, heating and heavy transport.

> *"Whenever I hear an idea for what we can do to keep global warming in check – whether it's over a conference table or over a cheeseburger – I always ask this question: what's your plan for steel?"*
>
> **Bill Gates, 27 August 2019**

Hydrogen is the only viable way to store renewable power over seasons, turning summer sun and autumn winds into winter power. Its high energy density means that it can pack a punch in shipping and heavy transport, where batteries are often too heavy to be practical. Green hydrogen can be used to synthesise kerosene for aeroplanes. And it can replace fossil fuels in steelmaking and other heavy industries. Without hydrogen, it is practically impossible to see how we could make manufacturing carbon neutral.

Hydrogen is not the only low-carbon gas. Biogas and biomethane can be made from agricultural or urban organic waste, through anaerobic digestion or gasification. Biosyngas is a synthetic gas made from renewable hydrogen and CO_2. Low-carbon natural gas is made by capturing the CO_2 from natural gas after it has been combusted. These clean gases share many of the same attributes as hydrogen, being cheap and easy to transport and store, and able to use existing infrastructure.

However, anything "bio" is limited by needing land for its feedstock. Cultivated land has to guarantee a secure and cheap food supply for all, and land covered by primary forests has to maintain its carbon storage capacity. Second-generation biofuels based on seaweed or other algae do not have this constraint, but could take a long time to scale up. Meanwhile, low-carbon gas with CCS currently looks more suitable for large-scale applications, rather than to decarbonise heating. Hydrogen has the additional benefit of being potentially infinite, with a huge potential to cut production costs. (For more detail see *Appendix 3. The world of green gas*)

Power: fixing intermittency and security

Reducing the carbon intensity of power generation is mainly a matter of swapping thermoelectric generation from coal and natural gas for solar and wind power: electrons for electrons. However, these renewables are intermittent. Sometimes it isn't sunny, and sometimes it isn't windy, and sometimes it is neither sunny nor windy – a state the Germans charmingly call "dunkelflaute", dark doldrums, or "cold dunkelflaute" for when power demand is also high.

So the more you rely on these energy sources, the harder it is to ensure that you don't end up short. You need to have more panels and turbines than would be required in optimal conditions, so as to ensure adequate production levels even when conditions are not perfect. You need to transport electricity from further and further away, on the basis that it is always going to be sunny/windy somewhere. And you need to store electricity, for instance through batteries or pumped storage (where you pump the water up to a higher-altitude reservoir with surplus power, and let it flow back down to generate power when required).

These are called integration costs, and they increase rapidly as the share of intermittent renewables goes up.

With hydrogen you can cut integration costs by shifting huge amounts of energy between places and times at low cost. You can burn it in power stations to lift the doldrums or meet peak winter demand.

Such dispatchable power also improves the stability and security of the power system. And that is an issue that has been under the spotlight over the summer. In July 2019, a power outage left 72,000 New Yorkers in the dark. In the UK, when a lightning strike tripped out two generators in August 2019, the network system suffered blackouts, leaving a million homes without power, crippling railway transport and affecting Ipswich hospital and Newcastle airport. The episode raised an alarm over the resilience of the energy system – especially as we move towards increased reliance on intermittent renewables. It was a drop in AC frequency that led to the blackouts, and wind farms provide less resistance to such frequency drops than traditional generators.

Security of supply is much more valuable now than even a couple of years ago. An increasing reliance on high-tech data and communications systems makes the economy more vulnerable to even short interruptions. We need to ensure that critical infrastructure is properly protected, and dispatchable energy from hydrogen could help to do that.

Hard-to-abate sectors

Broadly speaking, though, power is the easiest sector to decarbonise. It is harder to reach zero on industry, transport, heating, cooling and cooking, which account for well over 60% of our CO_2 emissions. Scaling up the use of green electricity, for example through electric vehicles and heat pumps, will help, but technical and cost reasons mean it won't get us all the way.

Industry: hot hydrogen

Cement and steel-making, which by themselves account for almost half of industrial emissions, produce CO_2 by burning fossil fuels to supply high-temperature industrial processes (700-1600 °C). As high-temperature heating is difficult and costly to electrify, hydrogen, biomass and CCS are being considered as alternatives.

The feedstock issue is even thornier. It requires innovation, like the new low-carbon clinker for cement that is being developed by Solidia, in partnership with LafargeHolcim, or using hydrogen for direct reduction to produce steel, or the use of biomass or CCS. Hydrogen infrastructure already exists where hydrogen serves as an input to industrial processes and where it is produced as a by-product, for instance in petrochemical clusters.

Hydrogen also allows gradual decarbonisation. For example, ethylene crackers do not require big process changes and shifts in safety procedures to switch to hydrogen, making the shift easier than a full overhaul towards direct electrification, which would require new machinery and often investments in transmission and distribution infrastructure.

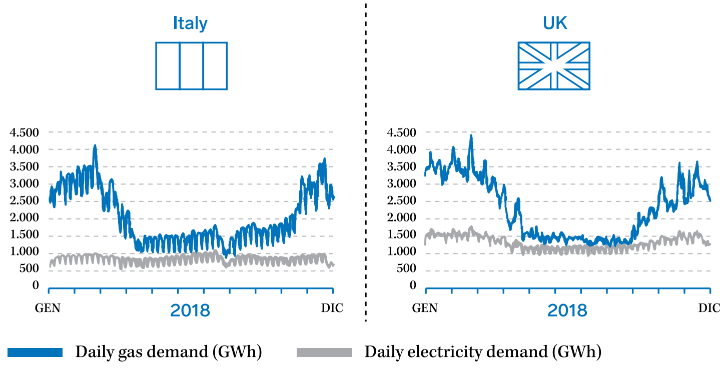
Heating: fixing seasonality

The characteristics of heating demand make it challenging, inefficient and expensive to decarbonise through electricity alone. Even in countries that are not extremely cold, such as Italy and the UK, winter peak energy demand is several times the capacity of the electricity network (see chart next page).

Natural gas networks in Europe have been designed to cope with this, and ensure supply when required. If the additional demand had to be delivered by electricity, it would require a huge upgrade of the grid.

What's more, seasonal heating demand is out of sync with one of the main renewable sources, the sun. At European latitudes, solar radiation in summer months is 2 to 5 times that in winter. Installing enough panels or turbines to meet winter demand would mean massive overproduction of renewables during the summer, and be a waste of money and land. Meanwhile, matching the seasonal load by storing electricity from the summer using batteries to do this would be ruinously expensive. Europe consumes about 2200 TWh each year for heating and cooling, and to store all that energy in batteries the investment would be around 500 trillion dollars[22]. There are not enough mountain lakes for pumped storage to take the strain; and that would be expensive anyway. The third issue with electrifying heat is that people would need to invest heavily in their homes, because heat pumps – which move heat from one place to another, and are more efficient than simply burning fuel to generate heat – require high levels of insulation and have reduced efficiency in cold climates. The interventions required are invasive, requiring heavy insulation and new piping systems in each house. The total cost of these interventions would typically be in the order of $200-300 per square metre[23].

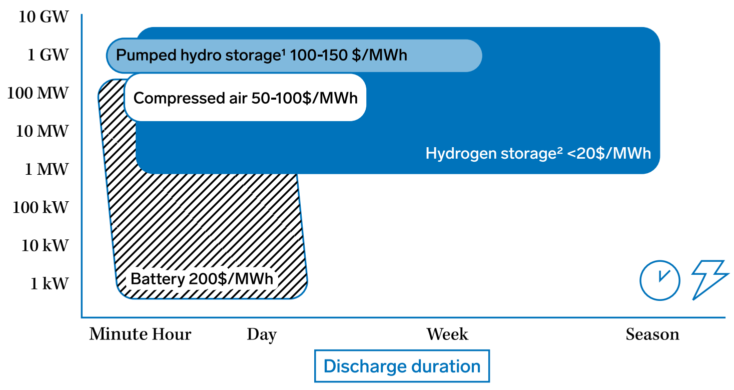
Daily energy transported by gas and electricity networks



source: Snam, ENTSO-E, National Grid, National Grid ESO

Hydrogen can be stored for months in large quantities, at relatively low cost

Comparison of energy options



1 Limited capacity (<1% of energy demand)
2 Either hydrogen or Syngas

source: IEA Energy Technology Roadmap Hydrogen and Fuel Cells, Lazard, Snam

Changes in household behaviour are notoriously difficult and slow, also because people don't like to spend money upfront even if the returns might be worth it. And this transformation in the heating stock would require mobilising financial resources on a scale that is difficult to imagine. National Grid has estimated that to decarbonise heat in the UK over 25 years from 2025 to 2050, around 20,000 homes per week would need to move to a low-carbon heat source[24]. The characteristics of heating make it an interesting niche for any form of green molecule, particularly biomethane and hydrogen. Biomethane could deliver decarbonisation of heat with no investments in infrastructure and no need to change appliances, but of course is limited in availability.

Hydrogen may provide a solution to many of electrification's challenges. Its high energy density allows much lower storage costs. You can convert electricity into hydrogen during summer, store it underground and finally use it in boilers or generators or in district heating networks in the winter.

Using pure H_2 will require retrofitting the gas grid, and installing new boilers and cookers in homes. This could be much less costly than upgrading electricity distribution and converting homes to electric heating, but it will still be an enormous undertaking. The safety and perception challenges of hydrogen would also need to be addressed. However, a research project in the UK, the H21 Leeds City Gate Project, suggests that this is feasible (see box opposite page).

Blended hydrogen with natural gas is a way of reducing the emissions of any form of gas consumption, including heating, and depending on the percentage blend may not require any investments in infrastructure or appliances. It may also provide a route to scaling up hydrogen production without significant investments in infrastructure.

Crucially, an experiment by Snam in southern Italy has shown that it is possible to blend 5% of hydrogen with natural gas in existing gas infrastructure (see box page 50). This has implications not only for heating, but also for integrating green hydrogen into the broader energy grid. And it is just the first step – we are now on track to repeat the experiment by increasing the share of hydrogen to 10%.

This doesn't mean that all heating everywhere would be delivered through green gas. The end solution will probably be a patchwork. A hybrid solution might be optimal under some conditions, with reversible heat pumps providing summer cooling and moderate winter heating, plus smaller hydrogen or biomethane boilers to kick in for the really cold snaps.

In some other cases gas and hydrogen heat pumps can be the optimal choice to supply both heating and cooling.

Leeds: the hydrogen city

Switching homes to hydrogen is a massive undertaking. Almost impossible, you'd think. Except it has already been done, in reverse.

In the 1960s and 70s, the UK undertook a nationwide gas conversion programme, from coal gas, which is 50% hydrogen, to natural gas. This involved changing 40 million appliances, reaching a peak of 2.3 million per year.

Could this be about to happen again, switching from natural gas to pure hydrogen? The good news is that in the UK the distribution infrastructure is already in place. The Iron Mains Replacement Programme, launched in 2002, has been upgrading the majority of distribution pipes to polyethylene, which are considered to be suitable for transporting 100% hydrogen.

One city may be about to lead the way. The H21 Leeds City Gate Project, a study launched by Northern Gas Networks and other partners, suggests that Leeds could be the ideal place to start. With 1.25% of the UK's population, it is a manageable size, while still big enough to show what's required to develop a hydrogen network. Leeds is also near existing hydrogen infrastructure at Teesside, and geological sites that are suitable for hydrogen storage.

The study shows that switching the network to 100% hydrogen would involve minimal disruption for domestic and commercial customers and require no large-scale modifications to property. In addition, the availability of low-cost bulk hydrogen in a gas network could revolutionise the potential for hydrogen vehicles, and support a decentralised model of combined heat and power and localised power generation using fuel cells.

The costs, according the report, would be in the region of £2 billion for infrastructure and appliance conversion, and £130 million a year for operation. Who pays for it is then the big question – as it is for the energy transition as a whole.

Hydrogen-powered pasta

"It's not like Mama used to make. Your next plate of fusilli might have an extra twist: it could be produced using hydrogen". This sentence opens a Bloomberg News story on the Snam pilot project that in April 2019 introduced a 5% hydrogen and natural gas blend into the Italian gas transmission network.

The experiment, the first of its kind in Europe, was conducted for one month in Contursi Terme, in the province of Salerno, and involved the supply of H_2NG (a blend of hydrogen and gas) to two industrial companies in the area, including the pasta maker Orogiallo. "We are the first in the world to produce hydrogen-powered pasta. Thank you Snam", wrote Orogiallo on its Facebook page.

The initiative was defined by Bloomberg News as "a shift toward greener energy sources". If all the gas transported annually by Snam were the same blend, 3.5 billion cubic metres of hydrogen (11 TWh) could be injected into the network each year, equivalent to the annual consumption of 1.5 million households. This would reduce carbon dioxide emissions by 2.5 million tons, equal to the total emissions of all cars in Rome.

Travel: free range

Mobility is where the whole hydrogen craze started. Almost any form of transport can be powered using hydrogen, by combustion of hydrogen gas or hydrogen-based fuels, or by using fuel cells, which convert hydrogen into electricity to power an electric motor. Hydrogen has much higher energy density than existing batteries, providing a similar range to vehicles powered by gasoline or diesel.

Hydrogen could yet provide healthy competition for electric cars and other light transport (see box below); but its energy density makes it especially valuable for the challenge of decarbonising heavy transport, shipping, and aviation.

Hydrogen powered buses are already gaining traction. Hydrogen buses can go more than 500 km on a full tank, versus about 200 km for electric ones. European funds and money from national and regional governments are being used to deliver almost 300 fuel cell buses and more hydrogen refueling stations to 22 European cities by 2023. China has the biggest ambitions with more than 400 buses registered at the end of 2018 for demonstration projects. In Korea, 30 buses will be running by the end of 2019, ramping up rapidly to 2000 by the end of 2022. Tokyo plans to deploy 100 hydrogen fuel cells buses during next year's Olympic Games. All of this should bring costs down, strengthen the supply chain and raise public awareness of hydrogen fuel cells.

Turning to trucks, several manufacturers (Hyundai, Scania, Toyota, Volkswagen, Daimler and PSA) are developing models. The main requirement to make trucks competitive is reducing the delivered price of hydrogen.

According to the IEA, if all the 1 billion cars, 190 million trucks and 25 million buses currently on the road globally were replaced by FCEVs, hydrogen demand would grow fourfold compared with the current global demand for pure hydrogen.

Moving onto the rails, fuel cell trains can be an alternative to electrification for short and medium distances. The world's first fuel cell passenger train entered commercial service in 2018 on a 100 km regional line in Germany, and hydrogen-powered fuel cell trains will run in the UK as early as 2022. Light rail and trams have already been developed by China and are in testing for passenger operation in the near term.

Shipping and aviation are even harder to decarbonise, requiring a very high energy content. One option is second generation biofuels, based on waste or seaweed, but hydrogen may be easier to scale up.

Ships could run on hydrogen or ammonia. As well as cutting greenhouse gas emissions, this would reduce local pollution and

Gas in the tank

Hydrogen has long been considered the automotive fuel of the future – the joke was that it would always remain so – but now hydrogen fuel cell cars are on the road and in production lines.

By the end of 2018, more than 11,000 hydrogen powered cars were on the road. This is still a tiny number compared with the 5.1 million battery electric cars and the global car stock of more than 1 billion, but there is huge potential for growth because hydrogen brings big advantages: compared with battery cars, fuel cell cars can cover long distances on a single tank, and they take only a few minutes to refuel.

Almost all hydrogen passenger cars are made by Japanese and Korean manufacturers (Toyota, Honda and Hyundai). Toyota has announced an annual production target of 30,000 fuel cell cars after 2020 from about 3000 today. Japan wants to have 200,000 fuel cell vehicles on the road within six years.

For FCEV cars to be competitive we need many more hydrogen refueling stations. According to IEA, there were 381 stations at the end of 2018, including 100 in Japan, 69 in Germany and 63 in the United States. The target for California, Japan, Korea and China together is 3200 stations by 2030.

The other priority is to bring down the cost of fuel cells and on-board hydrogen storage, so they become cost-competitive with battery electric vehicles at ranges of 400-500 km.

Many industry experts now think that with government support, technological advances and increased scale, costs will go down and demand will rise. Bosch, the world's leading automotive supplier, estimates that by 2030 20% of electric vehicles worldwide will be powered by hydrogen.

enable compliance with Sulphur Emission Control Area (SECA) requirements. However, the production cost of ammonia and hydrogen is still high relative to oil-based fuels.

Aviation could exploit hydrogen in several forms. Light aircraft could use hydrogen fuel cells. Jet engines could be redesigned to burn hydrogen, stored as a liquid. Or hydrogen and captured carbon could be combined to synthesise kerosene, fuelling conventional engines. One study concludes that by 2030, this synthetic fuel could match the price of fossil kerosene[25].

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[22] *Calculated assuming capital cost of batteries of $200/kwh.*

[23] *Snam analysis.*

[24] *http://futureofgas.uk/wp-content/uploads/2018/03/The-Future-of-Gas_Conclusion_web.pdf*

[25] *https://sites.google.com/a/sanegeest.nl/www/climate-neutral-aviation/Climate%20Neutral%20Aviation%20with%20current%20engine%20technology%20%281%29.pdf?attredirects=1&d=1*

4. The power couple

Hydrogen can connect the supply systems for gas and electricity to meet our climate challenges.

Energy companies in different sectors rarely used to talk to each other. Companies that produced and sold energy, and infrastructure companies in gas and electricity, generally identified their own needs – for new gas sources and consumers, or new power plants say – and solved them in the best way they could identify in their field of vision. It worked OK because coal, oil, gas and electricity were mostly produced and consumed separately.

However, the energy transition is changing all that. As we have seen above, we must find ways to transport and store renewables, and produce green fuels to decarbonise the sectors that cannot easily be electrified, like industry, heavy transport and peak winter heating.

The gas grid has several characteristics that can be useful for the electricity grid as it seeks to rise to these challenges:

- It is much larger. In Italy, in cold winter days, the gas grid can deliver 4-5 times the energy of the electricity grid.
- It is very flexible. While the electricity grid must balance supply and demand in real time and maintain a frequency level at equilibrium all the time, the gas grid stores an enormous amount of energy in the gas that always fills its pipes, and which allows injection and withdrawals to be decoupled.
- And it preserves energy. A lot of electrical power is lost as it is transported over long distances, and storing electricity is relatively costly, while the gas system can carry and store energy cheaply with barely any loss.

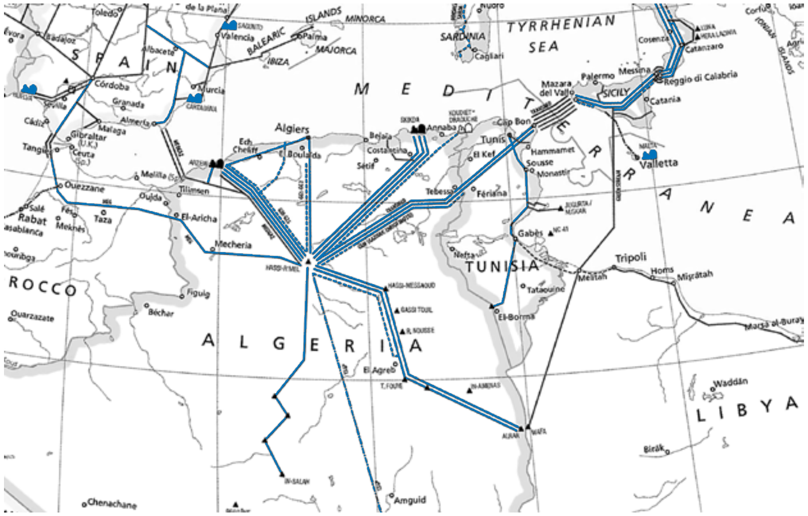
Hydrogen enables the gas and electricity grids to collaborate, as it can be produced through green electricity and also from natural gas, transported in the gas grid (in blended form, or pure with retrofits), burned for electricity, and used in hard-to-electrify sectors.

It can enable the two grids to work as an interconnected energy network, able to carry, store, transform and deliver renewable energy in different forms, continuously optimising for cost and supply security.

Internet dating

In the early stages of the energy transition, when the world is still using large amounts of fossil fuels, we can explore “virtual” power to gas. Rather than transporting renewables over long distances it makes more sense to consume them at the point of production, displace fossil fuels in that region, and export the equivalent amount of energy through the existing natural gas network.

An example of virtual power to gas is a plan that Snam has identified, which we are informally calling PPWS (put the panels where it is sunny), involving the export of renewable power from North Africa to Europe. Rather than investing in renewables on European soil, where it is often neither sunny nor windy, and burning fossil fuels in North Africa, where power plants are old and inefficient, the two regions should organize a swap. European



countries would fund installation of panels in North Africa, then share the profits. This would also support Europe's strategy to foster economic development in neighbouring countries to contain political instability and migratory pressures. This would give three layers of efficiency.

- First, solar panels in the Algerian desert would be around 80% more productive per unit of capital expenditure than panels in Germany. Land is much less expensive, and integration costs are lower.
- Second, the panels would displace natural gas that is now used for local power generation, and that could be transported to Europe with no additional infrastructure investments since there is already 30 billion cubic metres of spare capacity in existing pipelines under the Mediterranean. Contrast this with the cost of laying a power line to Europe, which was estimated as $50bn to $110bn[26] in the Desertec project. This may be why the project website now includes the power to gas (and power to liquids) option.

- Third, using the natural gas in efficient European power stations (55% efficiency and above) which are running few hours per year, instead of the old North African versions (40% efficiency) would yield 30-35% more electricity for the same gas.

Overall, the savings would be huge. Moving €10 billion of solar energy investments today from central Europe to North Africa would generate 80% more renewable power (18 TWh compared with 10 TWh) and displace 4.3 billion cubic metres of gas for export. That gas would generate 7 TWh more electricity in European power stations than it would have yielded in North Africa. The greater efficiency of the solar panels and the power stations would also cut more CO_2 per energy produced in the swap scenario (-40%) than in the "each to their own" version[27].

Of course this only makes sense while there is natural gas being used in North Africa for solar power to displace, but that is likely to be the case for a while yet.

Conscious coupling

As a first physical link between electricity and power grids, compression stations used in the gas infrastructure could become dual fuel – able to use both electricity and gas. Each compressor could be managed to optimise the use of gas and electricity in different conditions.

This would add flexibility to the system, because electric compressors provide potentially significant demand for electricity, and so could be used to balance demand across distances and over time. At times of excess renewable production one could use the electric compressors to store more gas in the pipeline, increasing the pressure. This gas could then be used when needed.

Getting hitched

Finally, the gas grid can be used to carry hydrogen, whether from excess electricity generation or from dedicated renewable or low-carbon energy sources. This approach avoids costly investments in transporting power over long distances, heavy grid integration costs, curtailment costs and investments in the electrification of final consumption. Meanwhile, investments on the gas side may be limited – or even negligible – depending on the percentage of hydrogen that is blended into the natural gas network.

Snam has made a vital first demonstration of the feasibility of blending with the Contursi experiment, blending 5% hydrogen into the pipeline network in Italy (see chapter *3. How hydrogen helps*).

The blending challenge

How much hydrogen can be blended into the gas grid depends on the different components of the system, each of which has a different threshold for hydrogen tolerance. For instance, carbon steel high pressure pipelines – commonly used for high pressure gas pipelines – should be fine to carry hydrogen at 10% (by volume) blend, and may be able to get to 100% with limited investments.

Other elements in the transmission network also look promising for high percentage blending. For instance, existing compressor stations appear to be compatible with a 5% blend, rising to 10% with limited investments. Snam's market research suggests that new compressor turbines are becoming available that could cope with blends of up to 30% – as long as the percentage is stable.

Looking at the storage system, hydrogen can be stored at any blend up to 100% if you use salt caverns, like the ones in UK, Germay and USA. The Chevron Phillips Clemens Terminal in Texas has stored hydrogen since the 1980s in a solution-mined salt cavern.

For countries like Italy, which rely on geological storage in depleted gas fields, tests are being conducted on what the effect of different blends of hydrogen will be. RING is a European project to investigate chemical and microbiological processes among rocks, water and hydrogen-blended gas at different H_2 percentage. The Austrian RAG project aims to demonstrate that depleted fields can tolerate hydrogen up to 10%.

When it comes to distributing gas, the UK has a strong advantage because it has started a project to substitute its network with plastic low-pressure pipes, which can carry any blend of hydrogen up to 100%. Countries with steel distribution pipelines can go up to 25% with no investments, and 100% with limited retrofits. And where the distribution is cast-iron, the pipelines need to be changed anyway.

Another constraint on the blending of hydrogen is end consumption. The lowest tolerance is for old compressed natural gas vehicles' tanks, which can manage 2% hydrogen only (but are rapidly being phased out). At the other end of the spectrum, industrial users of hydrogen for ammonia production and refining processes, and end users converted to hydrogen for domestic or industrial heating, power generation etc., require pure hydrogen, so would not be able to use a blend with natural gas.

Something that could give the whole network flexibility is the development of membranes – filters that separate the bigger CH_4 molecules from the smaller H_2 ones and allow to feed both the end users of natural gas and hydrogen through the same pipeline.

All of this means that the gas grid could help integrate renewables far from the point of consumption, but there is still much work to do.

Long-distance travel

In North Africa, as renewable penetration in the region rises, adding electrolysers can turn virtual power-to-gas into physical power-to-gas. Existing pipelines under the Mediterranean can potentially carry hydrogen up to 100%, but depending on the percentage we may need to adapt some plant components and revamp the compressor stations.

For an idea of the potential, on a spreadsheet, meeting all of Europe's transport, industry and heating needs with green hydrogen could be supplied with 0.8% of the Sahara's surface. Clearly, turning spreadsheets into reality is all but straightforward, and it is not only about geopolitical risk, but also about availability of water, snags or constraints in the electrolyser manufacturing process, logistics, and of course lots of sandstorms and dust. But this is potentially a huge opportunity.

In the North Sea, Dogger Bank could do the same for wind. This is an ideal place to harvest wind power, with optimal wind conditions and a shallow sea that means low construction costs. The North Sea Wind Power Hub, a consortium of transmission system operators (TSOs) consisting of TenneT, Energinet, Gasunie and Port of Rotterdam, has proposed developing artificial islands at the northeast end of Dogger Bank, and installing wind farms around them in a "hub and spoke" model.

This overcomes problems dogging offshore wind: projects close to shore get lower wind speeds and not much space; while those further offshore are costly to maintain. They also need expensive direct current (DC) cables, as alternating current (AC) haemorrhages too much power over long distances. So the plan is to build an island to collect all the electricity produced in the Dogger Bank region via AC cables. From there the power could be transformed into DC – or converted into renewable hydrogen for transport to shore. Another potential project has been identified in Germany. German transmission system operator TenneT, Gasunie Deutschland and Thyssengas are currently developing a 100 MW power-to-gas project in Lower Saxony, northwestern Germany. The project, Element One, will entail the conversion into gas of offshore wind power mostly from the North Sea. The generated green gas is expected to be channelled through existing lines from the North Sea to consumers in the Ruhr area of Germany. However, it may also be used for mobility via hydrogen filling stations and made available to industry through storage caverns. The plant is planned to be gradually connected to the network from 2022, and is an example of sector coupling involving energy, transport and industry.

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[26] *http://analysis.newenergyupdate.com/csp-today/markets/unravelling-financials-desertec*

[27] *Assuming the solar PV in North Africa displaces natural gas.*

5. The world of H

By linking together different regions, hydrogen can unite nations and play the role of pacifier.

Oil and gas have always been considered as drivers of international geopolitics. Many believe that colonialism, wars and the battle for spheres of influence have as their ultimate goal the access to these energy sources. The "energy cold war" narrative has the United States pitted against Russia and Iran, and courting Saudi Arabia and other Gulf states for energy interests. And the rise of US domestic production has opened the way to a geopolitical upheaval, bringing Saudi and Russia closer together as these historic producers now face a market flooded by shale oil and gas. Greater energy independence is also perhaps one of the reasons behind the different approach to global politics advanced by the US administration.

In traditional thinking, energy dependence gets a bad rap. No one likes to be shackled to another country for such an essential good. Energy dependence is often perceived as a game which endows producers with an undue competitive advantage, and from which consumer countries should break free. Indeed, one of the reasons why Winston Churchill nationalized the Anglo Iranian oil company (an ancestor of the modern-day BP) was to ensure control over the supply of oil, which was necessary for the British Navy to reach the same speeds as the German one. Think also of the efforts the European Union has made, so far without much success, to reduce its dependence on Russia for natural gas. Russia currently supplies 34% of EU consumption vs 21% in 2010.

Could renewable energy solve these tensions? For many, the idea that these energy sources can be locally produced, leading to energy self-sufficiency, is part of the appeal. And of course that will happen, at least in part, making the distribution of energy resources fairer.

But moving from an integrated energy system to one that is wholly local or national is not quite as good an idea as it may sound.

For a start, green electricity cannot be locally produced in the amounts required for everyone to reach net zero. In many countries, there just isn't enough space. And a collection of local or national energy systems, each with its own specific characteristics and with limited capacity for international trade, could be bad for supply security. Finally, targeting energy self-sufficiency would not free us from the critical issues related to geopolitics, but would actually risk increasing tensions.

Energy dependence has always been a double-edged sword. Those who need energy are dependent, but so are those who sell it. Algeria, Libya, Egypt, and to a lesser extent the Gulf Countries have a common problem: a demographic explosion with lots of young people who have ever-increasing demands. That puts a lot of pressure on government spending, which is largely financed by proceeds from the sale of oil and gas.

What would happen to these States if revenues from hydrocarbon production declined, rapidly, to nothing? There is a risk that this would significantly disrupt the fragile balance of the region with spill-overs in immigration and security.

This is a particularly acute concern for Europe, which has limited energy resources of its own and is almost entirely dependent on a small number of producers just across its border – North Africa, Russia and Norway. As the tensions over immigration have shown, the EU would probably have trouble managing the impact of imbalances in its neighbouring regions.

Hydrogen provides a solution to combine regional cooperation and the fight against climate change because it allows us to use cheap renewables from areas of the world that are rich in solar and wind resources, but far from consumption. IEA analysis shows that for Japan it will be cheaper to import hydrogen from the Australian desert or the Middle East than to make it domestically. Europe could import from North Africa, Norway and Russia, the same trio supplying fossil fuels today. This could balance falling imports of oil and gas to allay tensions.

The six economies of the Gulf Cooperation Council (GCC) have already launched some of the largest solar energy projects in the world. If these can be coupled with a similarly ambitious hydrogen scheme, the GCC could become a world leader in the field. The abundance of land for large solar plants, the strong industrial and intellectual capacity in the oil and gas sector and the strategic geographical location make the Gulf a natural hydrogen hub. This could offset declining oil and gas revenues. Indeed, if 20% of the UAE's land surface were used for solar plants producing green hydrogen for export, that would suffice to match its current oil and gas revenues[28].

A similar opportunity exists for other Gulf countries to future-proof their economies. Gradually switching to profitable and efficient hydrogen-based solutions at home would also allow traditional oil and gas industries to export more of their energy and to bond with cleantech companies. Jobs could be saved and multiplied through these new opportunities. Existing infrastructure is key to accelerating the development of hydrogen and as such becomes a competitive advantage for existing oil and gas exporters. Investments in existing installations can be upgraded and adapted.

Clearly, a global hydrogen market can only be developed through international cooperation involving producer and consumer countries, as well as international organisations such as OPEC, IEA and IRENA.

Much of the existing energy transport infrastructure is already transnational, and such connections do not need to be a cause of friction. As the experience of importing natural gas from Russia and North Africa has shown, these links can also provide long term mutual incentives to cooperate.

Not least, these export opportunities and this level of interdependence could encourage otherwise resistant countries to join the global effort against climate change.

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[28] *https://revolve.media/the-new-oil-green-hydrogen-from-the-arabian-gulf/*

6. The plan

A single, simple policy move by a small group of countries could be enough to spark the hydrogen revolution.

> *"The stone age did not end because the world ran out of stones, and the oil age will not end because we run out of oil"*
>
> **Attributed to Don Huberts, 1999**
> **(then head of Shell Hydrogen)**

Today green hydrogen is small fry. With somewhere between 100 and 150 MW of recently installed capacity, it amounts to only 4% of global hydrogen consumption. How can it fulfil its potential and make the leap into the energy mainstream?

It needs to overcome several hurdles, especially the challenges of safety, perception, infrastructure and cost.

Safety and perception

Hydrogen is explosive. It is flammable over an exceptionally wide range in concentrations. This makes safety one of the most important challenges that needs to be addressed. The incident at a service station in Norway in June 2019 is a timely reminder of the need to define, design and implement rigorous safety protocols.

However, 70 million tonnes of pure hydrogen is already being produced and used across the world; and of course we have been able to safely handle hazardous substances before. It has been said that hydrogen is no better or worse than any other fuel – you just have to know how to work with it. One upside is that it tends to burn away very quickly, resulting in a relatively limited threat in the event of a tank or pipeline rupture.

Security is a priority for all those dealing with hydrogen, as shown for example by the declaration signed last year by the European Union's energy ministers, or by international initiatives such as the US Hydrogen and Fuel Cells Program and the EU's Fuel Cells and Hydrogen Joint Undertaking.

Safety tests on hydrogen fuel cell vehicles have also been carried out. Toyota once ran demonstrations where it loaded its Mirai car with two full tanks of hydrogen and dropped it from 10 metres before shooting the tanks with military-grade rifles[29]. The result? A harmlessly dissipating gas, which would be picked up by on-board sensors anyway. But the volatility of hydrogen could become a concern when we think about distributing it directly into people's homes.

There is also the problem of public perception. Hydrogen is not an everyday commodity. You can't see or smell it or buy it at the supermarket. And the word is associated with "bomb" and "explosion", and the disaster that befell the German airship Hindenburg in 1937. One strength of hydrogen can also be its Achilles heel here: the fact that it can be used in different energy contexts – from fuel cells to gas networks – makes it vulnerable, in case of accidents, to a domino effect that could undermine its whole reputation.

The solution will be a track record of safe utilisation, especially through transport.

Fuel cell cars and trains can help build confidence, increase the popularity of hydrogen with laypeople and accelerate its mass use. With a hydrogen car, no behaviour change is required once the infrastructure is in place: you go to the same gas stations and fuel up in the same amount of time.

Then we need evidence-based information campaigns to inform the public about the applications and implications of hydrogen technologies. We should focus not only on climate change, air quality and energy security for coming generations, but also on the immediate benefits that hydrogen can deliver for individuals, companies and communities.

Infrastructure

One of the common criticisms of hydrogen is lack of specific infrastructure and technology for final consumers, for instance dedicated pipelines, filling stations, boilers and cars.

Clearly, this is true. And the logjam – where manufacturers don't make appliances because there is no supply infrastructure, and infrastructure companies don't build the pipes because there are no appliances – isn't easy to break.

We at Snam know something about that, through our work with compressed natural gas vehicles. For years, natural gas mobility has struggled to take off precisely because of this chicken and egg situation, despite making sense on a total cost of ownership basis (for an Italian family, owning a gas car would cost an extra €1000-2000 to buy, but save €600 on fuel costs a year). CNG vehicles also make sense for policymakers because they are a quick and easy solution to air-quality concerns and the desire to reduce the market share of diesel.

But it isn't as though the world has never built infrastructure before. On the CNG front, Snam has partnered with vehicle manufacturers including FCA and the VW group to coordinate the stations and vehicles side of the equation, which has helped get the market moving to some extent. With 250 new CNG stations (+25%) in less than 3 years, we now have over one

million natural gas vehicles on the road in Italy. This contributes to reducing CO_2 emissions, eliminating pollution and provides important savings for households. Snam also created the natural gas market in Italy, 75 years ago, where potential demand centres were identified and then pipelines were built to open up these markets.

I think the way to address the hydrogen infrastructure challenge is three-fold – and not necessarily sequential.

First we need to continue and extend our studies and trials on blending, to ensure that blends up to say 10% of the mix are compatible with existing infrastructure.

Second, we should create initial demand for green hydrogen in markets that already exist, and don't require new infrastructure and appliances. That can get the upstream costs down to a reasonable level without needing to fiddle with the market or change consumer behaviour too much.

Third, we need to work on full value-chain solutions, where demand in one area is aggregated into a cluster, and then this scale of demand is used to justify investments in infrastructure and in appliances. We see significant interest from potential long-term buyers of renewable hydrogen, who are keen to decarbonise at costs that could be comparable to other energy sources, with high supply security and low price volatility.

This is why I am a fan of the Leeds City Gate study, which makes an effort to stimulate value-chain thinking, and also of the Liverpool Manchester Hydrogen Clusters Project, which I think will be key milestones on the pathway to hydrogen development.

Cost

This is obviously an important consideration for any new technology, but in this case a hurdle that may not be as high as we thought.

Today green hydrogen from electrolysis costs about $5 per kilogram, equivalent to $125/MWh. Blue hydrogen, from fossil fuels and CCS, is much cheaper at about $2.5/kg[30] ($60/MWh); but it is constrained by CCS capacity, which is not being developed at scale in Europe yet. These are production costs. At the pump, where a small amount of hydrogen currently has to pay for a lot of infrastructure, the price of hydrogen can be as high as $10-12/kg.

At these levels, hydrogen is still a relatively expensive compared to other decarbonisation options – except new-build nuclear – and certainly more expensive than fossil fuels in most sectors.

Price landmarks are:

- At $4-5/kg, green hydrogen would only be competitive with very small-scale applications that already use hydrogen delivered in trucks.
- To reach parity with diesel in long-distance heavy transport, hydrogen would need to cost around $3/kg ($75/MW). This would potentially open a 4000 TWh market for Europe, the USA and China, but addressing it would be a relatively slow process, requiring a lot of additional infrastructure.
- Between $1.5 and 2/kg it becomes competitive with the grey hydrogen (generated from fossil fuels without carbon capture) used as feedstock for ammonia and in refineries. This would open a 70 million tonne market worth more than $100bn a year, which could be addressed relatively quickly because the market already exists.
- To compete with natural gas in heating you need to get some-where below $1/kg, at which level hydrogen would begin to be competitive with fossil fuels in many sectors around the world.

This price scale suggests that clean hydrogen development may start to speed up when it gets to $3/kg and reach a tipping point below $2/kg, where it becomes cost-competitive in an existing market.

The great news is there is lots of room to optimise costs along the hydrogen value chain. There are three ingredients to this. The first is the cost of renewables, which as we know is falling fast. The other two factors are the cost of capital and the cost of electrolysers.

Access to cheaper capital

The industry needs capital, for instance to build electrolyser plants, so the cost of capital feeds into the price of hydrogen. I am optimistic about this because there is a lot of funding chasing sustainable investments, either because of ethical considerations or because exposure to the energy transition is thought to be a better investment strategy.

In addition, many hydrogen investments will be backed by policy drivers, which will help guarantee revenues. There is no commodity price exposure, such as that faced by power plants, which will lower the cost of capital further. And with its wide distribution of potential source regions, and its scalable and replicable model, hydrogen should require lower returns on capital than the existing fossil fuel industry.

Traditionally, oil and gas upstream projects have looked for returns above 10%, and arguably that should be even higher now to attract capital when so many seem inclined to divest and when, as the Bank of England highlights, risks to the business model such as stranded assets and CO_2 costs need to be accounted for. In contrast, renewable auctions are won at a 5% return on capital, with massive liquidity looking for lower-risk renewable opportunities.

Driving down electrolyser costs

Recently installed green hydrogen capacity is only between 100 and 150 MW. For comparison, we are installing 94 GW of solar capacity a year[31], around 500 times as much as all the cumulative green hydrogen capacity that has ever been built. But this is actually good news. It means economies of scale will quickly drive down prices.

We spoke to manufacturers and saw that some factories today are making just one big electrolyser a month. With such low volumes, industrialization hasn't happened at all; electrolysers are essentially still hand-made, This means the cost curve can go down and volumes can be ramped up very quickly.

The next generation of factories will build at least 10 times as many electrolysers as current ones. To get an idea of the room to optimise by scaling and automating, just think that only around 40% of the price of electrolysers today is the cost of the goods sold[32]– and even that overstates the cost of raw materials given that electrolyser-producers buy ready-made parts. As production scales up, so will the volume for suppliers along the value chain, which will further drive down the cost of the finished product.

Increasing demand will also support modular design, mass production and bigger, higher-power devices, which brings costs down because doubling the power of the electrolyser doesn't double the cost.

From today's cost of around $1 per watt, some firms reckon they could build electrolysers for $0.15 per watt under optimal conditions.

In terms of the speed with which this reduction will happen, we are assuming that every doubling of cumulative installed capacity should give a cost reduction of 12%. This number is known as the learning rate.

As a reference, onshore wind turbines have improved with a 12% learning rate in the last decade, while photovoltaic technology has achieved as much as 24%. Comparable analysis from BNEF has arrived at learning rates of 18% and 20% for alkaline and PEM electrolysis.

So an electrolyser learning curve of 12% is conservative. Other developments that could make it higher include the next generation of technologies such as solid oxide electrolysers (see *Appendix 2. How hydrogen works*).

The policy push

The learning rate for electrolysers, coupled with the expected cost curve for renewable power[33], gives us the essential numbers to work out how much demand is needed to get to the tipping point.

Using these inputs we have calculated that building 50 GW of electrolyser capacity by 2030 would get hydrogen to below our tipping point of $2/kg (see *Appendix 4. Electrolyser maths*).

That's not a huge number, but it is still quite a lot higher than the 3 GW pipeline of announced projects according to the IEA. So we do need some kind of push to get us to 50GW. Policies should initially be designed to address markets that already exist and don't require additional infrastructure investments, rather than waiting for the vehicle and household conversions that would require more upfront spend and changes in consumer behaviour.

The blending opportunity

A quick win would be to start by blending hydrogen with natural gas in the current network.

This would use existing infrastructure to deliver hydrogen to existing markets for natural gas. It doesn't require any behavioural changes, or any investments for infrastructure or industry users.

While studies are still being conducted with regards to how much hydrogen can be blended in which parts of the gas network and particularly whether it could be blended in underground storage, there are good reasons to believe that significant parts of the grid could carry a share of between 5 and 10%. And policies to mandate such a blend have the potential to create a lot of demand (and scale) for green hydrogen virtually overnight.

If Europe and Japan blended 7% of hydrogen into their natural gas networks, that would get us to well over 50GW of installed capacity.

The cost would be low. Say that you started the blending in 2020 and got to 7% in 2030, in 2030 the fully ramped up system would cost 0.02% of combined GDP, or less than $9 per capita, per year. This is much less than the cost of existing renewables incentives in Europe. Italy is paying €12bn a year for renewables, or €200 per capita per year.

This one measure could be enough to get hydrogen down below $2/kg, and tip the hydrogen snowball over the edge globally.

Light the afterburners

Our calculation implies that a blending policy alone could be enough to reach hydrogen's tipping point, but of course the future is never certain, and the uptake of hydrogen would also depend on a number of local circumstances and complexities. In any case the urgency of the climate crisis and the need to meet our carbon budget mean that the sooner we can decarbonise, the better.

So what other policies could accelerate the process of scaling up hydrogen?

Grey hydrogen in industry is another market that could be addressed, because grey hydrogen is relatively expensive and all the consumption infrastructure is there. It is also very grey indeed, because it emits 830 million tonnes of CO_2 per year, equivalent to the combined emissions of Indonesia and the UK. Green hydrogen would be well placed to replace this eventually, as electrolyser and renewable costs fall, but it can get a leg-up. If Europe decided to gradually increase the penetration of green in its hydrogen mix, to say 10% by 2030, that would require electrolyser capacity of 15 GW.

Heavy transport is another potential sector where green hydrogen could get a boost. This requires new infrastructure, but much less than passenger cars, and should be one of the first uses to be profitable. Truck-makers, who know the market best, believe this will happen if the €250 million investment by CNH in hydrogen truck-motor maker Nikola is anything to go by. If 10% of the European trucking fleet were hydrogen-powered, that would require 25 GW of electrolyser capacity.

Shipping is also a promising segment because, as Baroness Worthington highlights (see page 104) it has a global governing body, the IMO, that is very keen on decarbonisation. As a point of reference, if 5% of global shipping were hydrogen-powered through ammonia, that would add 100GW.

What about passenger cars? The business case for hydrogen isn't as strong as in trucks and ships, but I do think a Tesla of hydrogen could do for hydrogen cars what Elon Musk did for EVs. Perhaps it could be Wan Gang, the well-connected former Audi executive, widely considered to be the father of electric cars in China. He now thinks a hydrogen society is the next big thing, and cars are a central part of that.

How much hydrogen?

Electrolyser capacity required to generate required volumes of green hydrogen

o .... 7% blend in the European and Japanese gas grids	>50GW
o .... 10% of the current hydrogen market	15GW
o .... 10% of European trucking	25GW
o .... 5% of global shipping	100GW

As infrastructure build is such an important challenge in all this, two more important areas to look at are industrial clusters, which can aggregate demand for industry that uses hydrogen as a feedstock and also to provide heat, and city projects like Leeds, which are harder to roll out but bring hydrogen close to the consumer.

Requiring industry participants to produce, procure, blend or sell gradually increasing percentages of green hydrogen can get us way beyond the tipping point without creating disruption and without significant upfront costs for the economies involved. This is nothing new. Most European motorists are unaware that they are already paying extra at the pump for mandated biofuels, which are being blended with their petrol. Already, the EU has a target of 10% renewable penetration in transport by 2020, rising to 14% by 2030.

Who should do the pushing?

In theory some sort of international agreement, ideally setting a global carbon price, could highlight the niches where hydrogen is already competitive and gradually increase its penetration in the market. But that looks like a big ask given the unravelling global consensus on climate change, and the reluctance many emerging economies have to commit themselves to costly energy sources.

A better option would be for a group of Countries and regions at the forefront of the energy transition to form a coalition of the willing, and take it upon themselves to create a framework for the first hydrogen expansion. The coalition might be some subset of Europe, China, Japan, South Korea, Canada, and US States such as California, Hawaii and New York.

These countries could agree to put in place the policies and bear the modest cost required from now to 2030, to drive volumes and lower the cost of hydrogen technology for other sectors and other countries, to the point where hydrogen could compete on its own in a host of applications.

A coalition of the willing has a lot going for it. It minimizes the overall cost of the transition, exploiting market forces to reach deep decarbonisation. It is also simpler to enact, I think, than the massive industrial and social re-engineering implied by some of the "Green New Deal" policies, which address valid concerns but require complex policy reforms.

I think there is plenty that can be improved in the way we create and distribute wealth; and issues of social justice need a lot of attention. Growing inequality is the second existential challenge for our generation, and I like some of the ideas in the Green New Deal proposals. But taxes aren't always good or easy and social justice and global warming are distinct issues. We shouldn't think we have to solve capitalism to solve climate change.

And in fact our "Hydrogen Club of Countries" makes for a just energy transition, putting most of the burden on the wealthiest countries and those who have emitted the lion's share of the CO_2, as they bear the costs of the initial policies to drive hydrogen growth. Of course, policies applied internally by our hydrogen club can be structured to encourage other countries to follow suit. Europe, for instance, has huge market power and could easily impose some sort of border restriction, or tax the import of CO_2, adopting the idea advocated by a group of distinguished US economists in January 2019 (see *Appendix 5. A Nobel approach*). This would raise some money to support any loss of competitiveness in exports, reduce carbon leakage, and also encourage other countries to clean up their acts.

Blue and green

Will our low-carbon hydrogen be blue or green? Probably both. That's because the two routes to clean hydrogen will cost different amounts in different regions. In the sunniest and windiest areas of the world, green hydrogen would have a huge cost advantage, because the CapEx of the electrolyser is spread over a lot of hours of production.

By our analysis, 50GW of new hydrogen capacity gives you $2/kg green hydrogen because we have assumed an average load factor of 35%, But in the best areas, load factors may be 65% with a combination of solar, wind and batteries – cutting the cost to $1.6/kg[34] for the same capacity build.

Other regions, with cheap fossil fuels and geological storage space for carbon, may go for blue hydrogen instead. Take Russia, as an example. If you assume natural gas cash costs of $1/MMBTU, it could potentially produce blue hydrogen at a cost of less than $1.2 today – less than the cost of grey hydrogen in most regions.

This suggests that blue and green hydrogen will compete. Blue hydrogen can be a trailblazer for green, opening new markets for hydrogen (for example replacing diesel in trucks) and then being supplanted by green hydrogen as the cost of electrolysers falls. And if green hydrogen does take off, it will start displacing fossil fuels, making them cheaper, which in turn will lower the cost of blue hydrogen.

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[29] *https://blog.toyota.co.uk/toyota-mirai-safety-facts*

[30] *Internal analysis based on Eurostat (gas price at around $20/MWh), E4tech (CCS cost), H21 project (CO_2 transport and storage).*

[31] *IRENA, Renewable Capacity Statistics in 2018.*

[32] *This includes materials, parts, and direct labour costs.*

[33] *In our analysis we are using the optimized BNEF cost curves (which find the sweet spot between production, batteries and load factors), and which get us to around $23/MWh in 2030 and $14/MWh in 2050.*

[34] *BNEF: Hydrogen, the economics of production from renewables.*

7. Revolutions

> ***"Look at the world around you. It may seem like an immovable, implacable place. It is not. With the slightest push – in just the right place – it can be tipped."***
>
> **Malcolm Gladwell, *The Tipping Point***

When I trade thoughts about hydrogen with other people in the industry, some are enthusiastic, some are sceptical, and some are sensibly cautious. Many seem to think that the energy sector is not one for rapid change. But while energy is not as disruptive as IT, we have had our share of game-changers.

Shale shock

For instance, the energy world was upended by the shale gas revolution in the US. When I started working in energy in 2002, there was a lot of talk about peak oil, and especially peak gas, which had around 25 years of known reserves left in the world.

As a consequence, prices were very high. Russia, Europe's main gas provider, had a lot of power over us, as exemplified by the 2006 dispute with Ukraine. And the US was preparing to a 15-fold increase in LNG imports in the period from 2000 to 2019[35].

Fast forward to 2019, and shale oil (and gas) have made the US one of the world's largest natural gas exporters. Import facilities were quickly turned around to become export facilities, flooding the world with American gas, driving liquidity and lowering prices. What happened? The power of the market.

High gas prices led US maverick drillers to start extracting shale gas, which the industry had long known about but which was previously too expensive. And as they started, they innovated, rationalized, industrialized and scaled their operations and lowered production costs almost by a factor of 10.

Renewable boom

The other recent energy revolution started with a policy push. Driven by strong environmental ambitions, very high energy prices and a desire to strengthen security of supply, Europe decided to kickstart the renewable transition. Four countries, Germany, Italy, Spain and the UK, jointly committed subsidies to develop solar and wind. Having created a predictable and lucrative market for 100 GW of solar panels[36], more than 20 very ambitious and efficient Chinese companies set up to build panels for the European market competing fiercely between themselves. This drove down the cost of solar dramatically.

Straws in the wind

The third revolution is the consumer-led disruption to single-use plastic. It isn't directly an energy issue, but has huge

repercussions for the energy system. I am fascinated by the public rage against plastic, because the issue has gone from being something that we all know is bad, to public enemy number 1 in the space of a couple of years.

What happened? I think it may be a revolution that has been sparked by kids. About a year ago, I was in a bar with my daughter and ordered a coke. It came with a straw. She said, "Dad don't use that, it's bad". I said, "I know sweetie, plastic is terrible, but it is everywhere". And she said, "no really Dad, don't use it. Straws stay in the ocean for ever and ever, and turtles eat them". I put the straw back down, and took out my phone instead. Turned out she was right. I've always hated plastic, ever since I was a kid and saw a whole dump of plastic on a desert island. But I hadn't realised that straws were a particularly dangerous kind of plastic because they were so hard to recycle and ended up in fish.

Weeks later, almost every time I went into a bar I heard someone say something about straws. Months later, and straws in bars were replaced by paper or metal alternatives. In Italy, some bars are using straws made out of pasta.

One year down the line, and the UN has declared a war on single-use plastics. In 2018, the UK Royal Mail struggled to deal with the number of angry customers that sent their crisp packets back to manufacturers in protest about them not being recyclable. And then British naturalist and national treasure David Attenborough, in the final episode of the TV series Blue Planet II, devoted time to the terrible effect of plastic on the creatures of the ocean. The David Attenborough effect is credited with reducing single use plastic significantly.

I don't think many campaigns in history have done quite as well as the anti-plastics one.

The life of the climate change activist is tougher, because global warming is harder to see, and solutions are conceptually more nuanced. But I think the lesson here, about the power of the consumer and civil society, is one that we should take note of.

And coming up next…

In my mind, the development of hydrogen would probably look most like solar – a policy push and then a market reaction.

But we also want to harness the power of the consumer, which has never been higher than today. For that, we need to make CO_2 real. Enough with the gigatonnes of CO_2 emitted. And even telling the average consumer that they need to get their own annual energy-related emissions down from 4.6 tonnes today to 1.1 tonnes isn't terribly helpful. What we need is some sort of a 5-a-day labelling system, or something like a calorie counter for CO_2 indicating the percentage of daily allowance that is being consumed by each action or purchase. That could be a handy app on our phones.

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[35] *https://www.eia.gov/outlooks/archive/aeo06/supplement/pdf/supplement_tables(2006).pdf*

[36] *IRENA, Renewable power generation costs in 2017.*

8. Conclusions

> *"We should look into establishing a hydrogen society."*
> **Wan Gang, Chinese People's Political Consultative Conference, Beijing, June 2019**

I approached our work on hydrogen with a sense that we urgently need additional solutions to address climate change. While electrification, on the one side, and the push to reduce individual consumption through "flight-shame"-type initiatives, both have merits, neither is definitive.

The limits of both approaches, for me, were crystallized in the challenge of decarbonising winter heating, which is the core business of the gas grid. I couldn't see how electricity and electric storage were going to get us all the way to zero, as batteries cannot hold energy for long-enough periods. And I hoped we weren't going to have to sit in the cold.

With the seasonality challenge top of mind, I intuitively felt that green gas would be an important piece of the puzzle. Biomethane, to the extent that it is available, and hydrogen, which – while being more complex to imagine in a residential setting – has the advantage of being practically infinite.

However, having been involved with hydrogen almost 20 years ago, I was well aware of the challenges of getting it off the ground both in terms of cost and in terms of the time it would take to develop the infrastructure make it mainstream.

So when Snam embarked on a study of the potential of hydrogen, it was because we thought it was worth looking at as a long-term decarbonisation option for Europe and for our company.

Our work is yielding encouraging results.

We learned that the electrolyser industry is still in its infancy, with equipment still essentially hand-made. So a relatively small new capacity could reduce the cost of these devices – and of green hydrogen – significantly. This, coupled with the rapidly declining cost of renewables, gave us a line of sight to $2/kg hydrogen, the "tipping point" from where it may be competitive in large markets without subsidies.

And we learned that blending hydrogen in the existing gas network may provide a policy tool to scale up demand relatively quickly. Snam has experimented with 5% in a limited portion of the network, and we are working both to increase that percentage and to study and address constraints in other areas of the grid.

Policies to gradually increase the penetration of green hydrogen in other key sectors – like grey hydrogen, industrial use, heavy transport and even targeted local projects for heat – would also contribute to its scaling up, providing the demand boost that would lower prices, making clean hydrogen increasingly competitive.

Of course, getting the hydrogen ball rolling won't just be about costs. Every element of the value chain will need to be tested, and safety protocols developed.

Midstream companies will have a particularly relevant role to play, because they will need to ensure that their infrastructure can accept increasing blends of hydrogen. As hydrogen scales up, midstreamers will also be instrumental in aggregating supply, demand and getting new infrastructure built – like Snam and other pioneers did to get the natural gas market up and running in Europe almost 80 years ago.

Of course, as it penetrates different markets, a whole host of operational challenges will inevitably need to be addressed, concerning for instance resource constraints on water, on materials used for the electrolysers and so on.

So we're not looking at an easy job. But then, transforming our energy system to cut CO_2 emissions to zero isn't an easy task. And the development of green hydrogen gives us an option to decarbonise that is compatible with new businesses and new jobs – a greener and fairer world. The effort is worth it.

Contributions from thought leaders

Winning the hydrogen challenge will be far from straightforward. Every aspect of its production, transport and use presents complexities and opportunities that would need to be explored more fully than the space and timeline for this instant-book allow.

A wealth of thought exists on hydrogen today, thanks to leading experts in their fields who have put their time and effort into the subject. Their work is not just important because of the content that it adds, but also because of their energy and their commitment.

Hydrogen will only get off the ground if far-sighted thought-leaders can gain traction with the wider community. I am fortunate enough to have come into contact with a number of such thought leaders, and am delighted to host their expert contributions in the following pages.

Dr Gabrielle Walker makes an impassioned case for the need to rebuild trust between business and society to face the big challenges of our day.

Lord Turner digs deep into the hard-to-abate sectors, highlighting the work done by the Energy Transitions Commission to figure out a cost-efficient route to zero.

Baroness Worthington looks into shipping – a sector that doesn't get as much attention as it deserves and that can be a candidate to lead the way on hydrogen.

Luigi Crema, of the Fondazione Bruno Kessler, gives us an insight into the upcoming technologies that might yet disrupt hydrogen production.

Bernd Heid and the **McKinsey** team explain how, according to their analysis, hydrogen is not a question of "if" but of "when".

Hydrogen: the great connector

by Dr Gabrielle Walker

I vividly remember the first conversation about climate change that I had with Marco, as we climbed up the side of that Norwegian mountain 12 years ago. We mainly talked about the science. I recall describing the bubbles of air that had been trapped in Antarctic ice, the deepest ones nearly 800,000 years old, and how I was present at the field station when scientists drilled down to release through the ice to excavate these bubbles, layer by layer. The tiny pieces of air they collected spanned all of human history and more. They contained a true record of all the changes our atmosphere has experienced since before homo sapiens sapiens appeared on the scene. And that record shows us beyond doubt the dramatic change that took place after the industrial revolution, when we started flooding the air with greenhouse gases. For me this was the concrete proof that the forms of energy we had been using to make our collective living on earth were causing a radical change to our own life support system.

We talked about other parts of the science too, how, in lockstep with the rising greenhouse gas concentrations, we could also see the Earth's temperature changing year by year; and about the potential implications of this for fires, droughts, floods, storms

and famines. But back then, much of this still seemed as if it lay in the future. The argument that convinced Marco, and others at the time, that we should act on all this was more as an insurance policy than as a clear and present danger.

Now such a conversation seems almost quaint. Climate change is already here – and it's not subtle. When I prepare slides to give talks on this topic to business executives like Marco, the hard thing these days is not finding images to illustrate the dangers – but choosing which ones to use. Should I show the unprecedented wildfires that recently tore across California, or Chile, or Russia, or Sweden? Should I show hurricane Harvey dumping so much rain on the city of Houston that it actually sank by several centimetres? Or hurricane Irma sweeping across the island of Barbuda with so much force that there was literally nothing left standing? And which of the heat waves in Australia, in Europe, in northern Russia, in Greenland, as temperatures the world over break record after record? Even the migrations that have been wreaking such geopolitical havoc on Europe and the USA can trace their origins in part to drought, and they look set to get much worse. One military general told me that the human migrations we are experiencing now will look like a "walk in the park" compared to what will happen if we let climate change take greater hold.

Though I am a scientist by training, and we are a cautious bunch when it comes to apocalyptic predictions, I no longer talk about an insurance policy. Now, I talk about a full-on, existential crisis.

So, what do we do about it? Well, we already have a whole toolbox of potential solutions many of which, frustratingly, have been with us for decades without being deployed at anything like the scale we need. The challenge now is not just scale but also urgency. It's hugely important to remember that climate change is a "stock" problem not a "flow" problem. In other words, what matters is how much additional CO_2 and other greenhouse gases get into the atmosphere, not how quickly they get there. And that means we have to do everything we possibly can to reduce emissions now.

To my mind, this means that we can't afford to wait for some mythical perfect solution. We need to get all options on the table as quickly as we can, and scale them up as quickly as we can.

Which brings me to hydrogen. There used to be a lot of talk about the "Hydrogen Economy" in the early noughties, mainly focused on cars that could be powered by hydrogen fuel cells and produce in the way of emissions nothing but pure water. But as the appetite for electric vehicles took hold, it seemed that hydrogen had fallen away.

I'm so glad it's back, and this time with a much bigger remit. Now it's clear that hydrogen can provide climate solutions that go far beyond cars. It could be used to decarbonise heating, fuel ships and short-haul planes, solve some of the hardest climate problems in heavy industry, store up renewable energy from season to season and place to place and yield the stored energy exactly just when and where it's needed. It is the great connector; the miracle molecule.

Elsewhere in this book there are many more details about all these opportunities and more. And in addition to demonstrating the many roles that hydrogen can play in solving the climate crisis, this book also highlights what has been stopping the use of hydrogen, and how to break down those barriers. To the many barriers and strategies described elsewhere, involving policy, economics, technical issues and the like, I would add one further crucial requirement for scaling hydrogen as a climate solution: the need for passionate champions for hydrogen from all the different sectors that will have to be involved.

That's because, in my experience, hard things only happen when influential people spend all their waking hours trying to make them happen. I believe we need new cohorts of hydrogen champions who understand and care deeply about the potential, to be urgently seeking the opportunities, pushing for the policies, securing the financing and telling the hydrogen story, in order to realise this vision.

These champions also have to be willing to form new alliances across ideological divides.

It is so maddening that we have taken so long to pour energy into technological solutions to the climate crisis that were already available that lately I have been asking myself why. I found some answers in Nathaniel Rich's book *Losing Earth: The Decade We Could Have Stopped Climate Change*. Rich traces the actions and missteps on climate throughout the 1980s, and some of them are them are astonishing. In the wildly polarised world of today, it's easy to forget not just that we knew all about global warming even then, but that it was also considered a fully bipartisan issue, all the way to the top. George W. Bush even said in 1988 that "those who think we are powerless to do anything about the greenhouse effect are forgetting about the White House effect."

I believe that one of the unsung reasons we missed so many chances to act decisively in the past is the way the efforts to fight climate change became so polarised, with different tribes giving certain technologies favoured status and vilifying others. What's more, the atrocious and cynical disinformation campaigns and targeted denialism of the 90s didn't just cost us precious time – they also reinforced these divides and made collective action even harder.

And yet, to fight off climate disaster we will need radical new collaborations, between business, unions, NGOs, policy makers, storytellers and everyone else with a stake in the survival of humanity. And that can't happen if we all paint ourselves into our own respective corners. Moreover, I am worried about a burgeoning divide between climate activists (who are bringing the urgency and seriousness of the problem brilliantly out into the open) and businesses (who are often mistrusted, but will need – in many cases – to be the delivery arms of the solutions we are trying to scale).

That's why, while many others are working on the technical part of the issue, the policy, economics and technology, my work since that conversation with Marco twelve years ago has been increasingly focused on creating energised climate champions, building trust and bridging ideological divides; I am trying to help turn some of the most important climate narratives from "saints and sinners" to putting some of the world's smartest people round the same tables, so they can find collective solutions together.

Hydrogen has many advantages in this regard. It's not just the great connector from a technical point of view (uniting many different climate solutions). It's also never been owned, or stigmatised, by any individual sector. Hydrogen really does have something for everyone. It can be an enabler of renewable energy (through its storage capacity); it can be introduced incrementally, using existing infrastructure such as pipelines and gas turbines; and it might also be able to help us realise the most unloved, unwanted and vilified climate technology of all – carbon capture and storage (CCS).

CCS actually covers a small army of technologies, all of which involve capturing carbon dioxide from big point sources (such as cement or steel factories, fossil fuel power plants and the like), transporting the carbon dioxide, and burying it in geological formations. And although climate scientists have been saying for years that we will need this technology to close the emissions gap, it has struggled repeatedly to get beyond the pilot stage.

Over the past year and a half, I have been leading a project on CCS called the "Alliance of Champions", specifically designed to try to understand the non-technical reasons why CCS has never happened at scale. My colleagues at Valence Solutions and I have spoken to more than 130 people in Europe and North America, hailing from organisations as diverse as Greenpeace and the oil and gas industry. We have also run several cross-sectoral workshops. And we have come to the conclusion that one of the biggest barriers facing CCS is lack of trust.

Much of this distrust has been well earned. Companies don't trust the government to follow through on their policy promises since they have had the rug pulled from under them too often in the past. NGOs realise that CCS will have to be delivered by the only industry in the world that understands how to transport and bury molecules in geological formations – the oil and gas industry. And they remain suspicious that any support by oil and gas companies for CCS could just be a delaying tactic, or a way to prolong the use of fossil fuels.

And yet, in each of our workshops, in the end, everyone has agreed that we will need at least some CCS to solve climate change. Now the challenge is to build the trust and broker the collaborations that could make it happen.

Hydrogen plays a fascinating role in this story. First, as Adair Turner points out on next page, we already make large amounts of hydrogen for chemical purposes, using methane as a feedstock. One of the waste products of this process is a very concentrated stream of carbon dioxide. Bolting on CCS would help to neutralise its climate impacts by removing most or all of the emitted carbon dioxide, providing a stream of clean hydrogen that could help kickstart the hydrogen economy. This could also, in turn, promote the development of CCS itself, which we will need for certain solutions that other climate technologies can't reach. Win, win.

None of this will be easy – but I believe we have to make it happen. Because we don't have time to argue any more. This is an emergency. I am excited about hydrogen for all of the reasons scattered throughout this book. But perhaps most of all because it is the ultimate connector. Polarisation and divisions have got us into much of this mess. Perhaps this little molecule that often slips through the cracks could be one of the instruments that helps us bring together all the people of good will and brain who are genuinely fighting the climate crisis, to accelerate action before it really is too late.

Mission Possible

by Lord Turner

The mission is clear.

In line with the commitments taken in Paris at the COP21, and in line with the recommendations of the latest IPCC report, we need to limit global warming to well below 2 °C, and as close as possible to 1.5 °C.

What is often called into question is whether achieving these targets is actually possible. The answer is yes, but we need to apply an ample and diversified toolkit of technologies to get there.

As the Energy Transitions Commission (ETC), the coalition of business, finance and civil society leaders from across the spectrum of energy producing and using industries which I am currently chairing, has demonstrated, reaching net zero CO_2 emissions is possible – by 2050 in developed economies and 2060 in developing economies.

A key pillar of this effort will be using less energy. We should also seek to decarbonise power and gradually electrify as much of the economy as possible. In 2017, the Energy Transitions Commission's first report – Better Energy, Greater Prosperity – tackled these challenges, demonstrating that dramatic reductions in the cost of renewable electricity generation and of energy storage options now make it possible to plan for cost-competitive power systems which are nearly entirely dependent on wind and solar (e.g. at 85-90%).

But green electricity will only get us part of the way there. One of the biggest challenges to reaching a fully decarbonised economy stems from what we have labelled the "harder-to-abate" sectors.

These are the sectors of heavy industry (in particular cement, steel and chemicals) and heavy-duty transport (heavy-duty road transport, shipping and aviation), which currently account for 10Gt (30%) of total global CO_2 emissions. On current trends, their emissions could account for 16Gt by 2050 and a growing share of remaining emissions as the rest of the economy decarbonises. Despite the magnitude of their impact, many national strategies – as set out in Nationally Determined Contributions (NDCs) to the Paris agreement – focus little attention on these sectors.

The good news is that reaching net-zero CO_2 emissions in these sectors by mid-century is possible – and not as costly as one might imagine.

The technologies required to achieve this decarbonisation already exist: several still need to reach commercial viability, but we do not need to assume fundamental and currently unknown research breakthroughs to be confident that net-zero carbon emissions can be reached.

Moreover, the cost of decarbonisation can be very significantly reduced by making better use of carbon-intensive materials (through greater materials efficiency and recycling) and by limiting demand growth for carbon-intensive transport (through greater logistics efficiency and modal shift).

Indeed, the ETC has found that it is technically possible to reach net-zero CO_2 emissions in the harder-to-abate sectors by mid-century at a cost to the economy of less than 0.5% of global GDP with a minor impact on consumer living standards.

Three routes to decarbonisation in harder-to-abate sectors

In more depth, the route to decarbonisation involves three complementary sets of actions:

1. Reducing demand for carbon-intensive products and services, which can greatly reduce the cost of industrial decarbonisation and, to a lower extent, of heavy-duty transport decarbonisation. A circular economy – based on greater material efficiency and recycling – can reduce CO_2 emissions from four major industry sectors (plastics, steel, aluminum and cement) by 40% globally, and by 56% in developed economies like Europe by 2050, whilst modal shifts and logistics efficiency could reduce emissions by 20% in heavy-duty transport.
2. Improving energy efficiency, which can enable early progress in emissions reduction and reduce overall decarbonisation costs. In the industrial sector, opportunities for energy efficiency within existing processes (through advanced production techniques or the application of digital technologies) can enable short-term emissions reductions. They are unlikely to exceed 15-20% of energy consumption, but will be essential to reduce emissions from existing, long-lived industrial assets, in particular in developing countries.
3. Applying decarbonisation technologies, which will be essential to achieving net-zero CO_2 emissions from the energy and industrial systems. In each sector, there are four main pathways for the decarbonisation of production:
    - Electricity – direct and indirect electrification (through hydrogen) – will likely play a significant role in most sectors of industry and transport, leading to a sharp increase in power demand – growing 4-6 times from today's 20,000 TWh to reach around 100,000 TWh by mid-century.
    - Bioenergy and bio-feedstock will be required in several sectors, but will need to be tightly regulated to avoid adverse environmental impact (such as deforestation), and its use should be focused on priority sectors where alternatives are least available, such as aviation.
    - Carbon capture (combined with use or storage) will likely be required to capture process emissions from cement and may also be the most cost-competitive decarbonisation option for other sectors in several geographies. However, it does not need to play a major role in power generation, where a range of storage and grid management technologies can limit the need for peaking capacity.
    - Hydrogen will play a major role, leading to a 7-11x demand increase by mid-century.

A major role for hydrogen

Hydrogen is likely to be a pillar of cost-effective decarbonisation in several of the harder-to-abate sectors and may also be important in residential heat and flexibility provision in the power system. Achieving a net-zero-CO_2-emissions economy will require an increase in global hydrogen production from 60 Mt per annum today to something like 425-650 Mt by mid-century, even if hydrogen fuel-cell vehicles play only a small role in the light-duty transport sector.

It is therefore essential to foster large-scale and cost-effective production of zero-carbon hydrogen via one of two major routes:

Electrolysis using zero-carbon electricity: This will be increasingly cost-effective as renewable electricity prices fall and as electrolysis equipment costs decline. If 50% of future hydrogen demand were met by electrolysis, the total volume of electrolysis production would increase 100 times from today's level creating enormous potential for cost reduction through economies of scale and learning curve effects.

- And it preserves energy. A lot of electrical power is lost as it is transported over long distances, and storing electricity is relatively costly, while the gas system can carry and store energy cheaply with barely any loss.
- The application of carbon capture to steam methane reforming, and the subsequent storage or use of the captured CO_2: This may be one of the most cost-effective forms of carbon capture given the high purity of the CO_2 stream produced from the chemical reaction, if energy inputs to the process are electrified. For hydrogen from SMR plus CCS to really be near-zero-carbon, however, carbon leakage in the capture process, as well as methane emissions throughout the gas value chain, would have to be brought down to a minimum. If 50% of future hydrogen demand were met using SMR with carbon capture on chemical reaction, the related carbon sequestration needs would amount to 2-3Gt.
- Biomethane reforming: SMR could also in principle be made zero-carbon if biogas were used rather than natural gas, but this route is unlikely to play a major role, given other higher priority demands on limited sustainable biomass resources.

Feasible pathways

In practical terms, all these pathways translate into the following shifts.

In heavy-duty transport, electric trucks and buses (either battery or hydrogen fuel cells) are likely to become cost-competitive by the 2030s, while, in shipping and aviation, liquid fuels are likely to remain the preferred option for long distances, but can be made zero-carbon by using bio or synthetic fuels. Improved energy efficiency, greater logistics efficiency and some level of modal shift for both freight and passenger transport could reduce the size of the transition challenge.

In industry, more efficient use of materials and greatly increased recycling and reuse within a more circular economy could reduce primary production and emissions by as much as 40% globally – and more in developed economies – with the greatest opportunities in plastics and metals. Reaching full decarbonisation will therefore require a portfolio of decarbonisation technologies, and the optimal route to net-zero carbon will vary across location depending on local resources.

Investments will also be required, but on a scale that does not threatens economic viability.

At European level, incremental investment could be 25% higher than in a business-as-usual scenario, with the greatest investment required not in transport infrastructure or industrial assets, but in the power sector to enable very high increases of power use across the economy. For example, in heavy-road transport, the European Commission estimates suggest that the investments required for recharging or hydrogen refueling infrastructure would be less than 5% of business-as-usual investment in transport infrastructure.

The impact of decarbonisation on prices faced by end consumers will vary by sector, but will overall be small. For example, green steel use would add approximately $180 on the price of a car; green shipping would add less than 1% to the price of an imported pair of jeans, and low-carbon plastics would add $0.01 on the price of a bottle of soda.

How to get there – overcoming the challenges and designing a strategy

Achieving net-zero CO_2 emissions by mid-century, at low cost to the global economy and to the end consumer, requires recognising and resolving the different sets of challenges which represent the main obstacles to decarbonisation.

Technical challenges

The most pressing challenge to decarbonisation is that many of the relevant technologies are not yet commercially ready. While electric trucks could be cost-competitive by 2030, cement kiln electrification may not be commercially ready till a decade later. Hydrogen-based industrial processes also require significant development. Accelerating development and scaling deployment of key technologies is therefore vital.

Economic challenges

Since most decarbonisation routes will entail a net cost, market forces alone will not drive progress; and strong policies – combining regulations and support – must create incentives for rapid decarbonisation. A particular difficulty is to create strong enough financial incentives today to trigger the search for optimal decarbonisation pathways without imposing a disproportionate burden on sectors for which full decarbonisation technologies are not yet available.

In heavy industry, very long asset lives will delay the deployment of new technologies, unless there are strong policy incentives for early asset write-offs. In steel, for instance, a switch from blast furnace reduction to hydrogen-based direct reduction may require scrapping of existing plant before end of useful life.

High upfront investment costs may also act as a barrier to progress even where carbon prices make a shift to zero-carbon technologies in theory economic, in particular in sectors or companies facing low margins. Direct public investment support may therefore be required.

Furthermore, although beneficial on an aggregate scale, the transition to a zero-carbon economy will inevitably create winners and losers, impacting local economic development and employment in some regions. It is therefore important that policy anticipates and compensates for these distributional effects through just transition strategies.

Institutional challenges

Finally, institutional challenges also emerge. Current innovation systems are poorly connected, with little coordination between public and private R&D, and a lack of international forums to carry an innovation agenda focused on harder-to-abate sectors. In sectors exposed to international competition, domestic carbon prices or regulations could produce harmful effects on competitiveness and movement of production location. This implies the need for international policy coordination, or alternatively the use of downstream rather than upstream taxes, border tax adjustments, or free allocation within emissions trading schemes or compensation schemes (combined with increasingly ambitious benchmark technology standards). Furthermore, some industries, like shipping or construction, are so fragmented that incentives are split. Even cost-effective efficiency technologies and circular practices are not easily deployed. In these sectors, innovative policy should strengthen incentives.

Given these technical, economic and institutional barriers, transition paths will vary significantly by sector. For example, in the industrial sectors, progress to full decarbonisation will inevitably take several decades. Public policy must provide strong incentives for long-term change, established well in advance, whether via carbon pricing, regulations, or financial support. Proactive action from industries over the next decade would reduce costs of subsequent decarbonisation efforts.

On the other hand, in the transport sectors, transition paths are less complicated. In heavy road transport, considerably shorter asset lives could allow rapid decarbonisation of truck fleets once alternative vehicles (whether battery electric or hydrogen fuel-cell) become cost-competitive at point of new purchase. In long-distance shipping and aviation, the likely route to full decarbonisation entails the use of zero-carbon fuels within existing engines, meaning that the pace of transition will be determined by the relative costs of zero-carbon versus conventional fuels.

Every sector will require an adapted and different response, but overall, these will all be determined by efficiency improvement and demand-side reductions. These steps are essential not only to deliver short-term emissions reductions, but to decrease the cost of long-term decarbonisation by reducing the volume of primary industrial production or mobility services to which supply-side decarbonisation technologies need to be applied.

Working together to win the climate war

Winning the climate war would not only limit the harmful impact of climate change; it would also drive prosperity, through rapid technological innovation and job creation in new industries, and deliver important local environmental benefits. National and local governments, businesses, investors and consumers should therefore take the actions needed to achieve this objective.

It will be key to encourage collective action. Energy companies must commit to producing low-cost zero-carbon energy; investors must finance low-carbon industrial assets as well as energy and transport infrastructure; consumers (businesses, public procurement services and end consumers) must demand zero-emissions materials and mobility; policy-makers must drive and support a green industry revolution; and harder-to-abate sectors must prepare for a profound transformation.

In the wake of the IPCC's urgent call for action, the "Mission Possible" report sends a clear signal to policymakers, investors and businesses: full decarbonisation is possible, making ambitious

climate objectives achievable. Key policy levers to accelerate the decarbonisation of harder-to-abate sectors include:

1. Tightening carbon-intensity mandates on industrial processes, heavy-duty transport and the carbon content of consumer products.
2. Introducing adequate carbon pricing, strongly pursuing the ideal objective of internationally agreed and comprehensive pricing systems, but recognising the potential also to use prices which are differentiated by sector, potentially applied to downstream consumer products and defined in advance.
3. Encouraging the shift from a linear to a circular economy through appropriate regulation on materials efficiency and recycling.
4. Investing in the green industry, through R&D support, deployment support, and the use of public procurement to create initial demand for "green" products and services.
5. Accelerating public-private collaboration to build necessary energy and transport infrastructure.

Together, through shared responsibilities and collective action, the world can win the climate war and achieve net-zero CO_2 emissions.

Getting Shipshape

by Baroness Worthington

A global market in hydrogen based fuels could be about to emerge – can it help avert a climate crisis?

The escalating climate emergency is now hard to ignore. The scale and speed of the observable impacts of a warming planet are taking even the most pessimistic climate scientists by surprise. The last 50 years of industrial growth in particular has contributed a huge and growing volume of emissions of greenhouse gases to the atmosphere which have not yet showed any signs of slowing and we now are deep into uncharted climatic territory. What is becoming clear is the global experiment we are now conducting will have serious consequences for all inhabitants of this our shared and only home.

The key question is what can be done about it? What needs to happen to apply the brakes quickly? And how can this be done with minimum negative impact on the poorest in our society?

First and foremost we need to turn off the tap of manmade greenhouse gas emissions. In terms of impact the quickest and easiest way to do this is to focus on phasing out coal from the global power sector. Despite great progress this sector has contributed the lion's share of the build-up of emissions and is still contributing the most to the problem. By focusing on cleaning the power sector other options for decarbonising other sectors are opened up. Clean electricity can directly replace fossil fuel use in transport and heat markets through electrification – and this is applicable in more sectors than we might first imagine – large electric ovens can be used to replace kilns, arc furnaces forge metals from recycled content, even long distance trucks can be electrified using overhead cabling on major roads and motorways.

But where electricity on its own is not a practical alternative to fossil fuel use, it can also be used to make combustible fuels by using excess electricity to create hydrogen and combining hydrogen with nitrogen from the air to manufacture ammonia. Both hydrogen, and hydrogen rich ammonia, can be used immediately in conventional combustion engines, with little modification, or later, in specially designed fuel cells. Both are also well-known, globally traded commodities. Neither produces any greenhouse gases at point of use.

An additional route to a hydrogen fuel based economy opens up if fossil fuels are used in processes that strip out and sustainably bury the greenhouse gases to produce the hydrogen. The cost comparisons between the two routes will vary depending on many starting conditions. Where, for example, natural gas is abundant and easily extractable a carbon capture to hydrogen route may be most cost effective. In places where there is abundant untapped renewable electricity capacity, hydrogen fuel production could offer the better investment returns.

So with so much potential what's stopping this emissions free energy system from emerging? The answer is cost.

Put simply these alternative energy supply chains are highly capital intensive and cannot compete with the highly mature incumbent industries. To bring hydrogen based solutions to market will therefore require a concerted effort. Government intervention will almost certainly be needed. But just how and where will the political capital be found to kickstart the deployment of these solutions at scale such that repeated deployment and economies of scale can bring them down the cost curve?

A relatively obscure corner of the UN provides an answer: international shipping, regulated by its own international governing body, can be the key to unlocking large-scale investment in clean energy developments across the world. It is responsible every year for about the same amount of greenhouse gas emissions as the entire German economy. It's agreed it needs to decarbonise. It has also already helped reduce the cost of electrolysis to generate hydrogen, thanks to new requirement on fuel suppliers to strip the Sulphur out of maritime fuels – a process that commonly uses hydrogen.

But shipping could prove a much more significant catalyst. There is no shortage of capital in the world seeking a home but investor confidence in clean energy is still low. In many places with abundant renewable potential, there is not enough reliable energy demand for investors to put their money into large-scale projects. But the solution to this problem, unlocking trillions of dollars in new investments, could come from international shipping. The energy demand from large ocean going vessels is large and consistent – many routes are regular and many of the least developed countries, lacking traditional energy infrastructure, have well established ports.

Shipping fuel today is a chunky porridge of unrefined petroleum, almost raw from the well. As well as greenhouse gases it produces smog-forming nitrogen oxides, lung-clogging particulates and climate-polluting black carbon. The visible blight this bring to cities with port terminals is hard to ignore. Yet 90,000 ships use this fuel to ply the world's oceans, carrying everything from grain to toys to car parts all over the globe.

At the moment, the bulk of the filthy maritime fuel is sold from just a handful of mega ports but the need to move away from fossil fuels towards cleaner alternatives opens up the potential for many more ports and fuel providers to enter the market to provide clean hydrogen based "electrofuels", i.e. fuels such as hydrogen and ammonia that can be derived from renewable electricity. The ability to create a combustible fuel from sunlight (or wind, or water) to create hydrogen separated out of water, combined with nitrogen taken from the air, opens up a huge potential market to a range of new actors. Our recent report Sailing on Solar[37] included a close look at the potential for fuels for ships to drive investment in Morocco and we plan a follow up study centred on Chile. But the potential benefits also extend to Europe where untapped renewable potential in the north and the south could be brought to market in the service of ships of all classes. In the UK and Norway excess wind and hydro power is already being converted for use in ferries and there is huge potential in the Mediterranean for supply chains based on solar and wind.

There are of course caveats to the proposed use of hydrogen derived fuels in the shipping industry. One is the safety implications, while both hydrogen and ammonia are carried at sea at the moment with established safety protocols, if these fuels are to be used more widely, then broader safeguards need to be considered. Further, these fuels are only climate friendly if they are produced using renewable electricity as discussed here, or through use of fossil fuels with permanent carbon capture and storage, so any support needs to be carefully targeted using robust accounting rules that account for the full impacts of the supply chain. However, neither of these caveats presents an insurmountable challenge and indeed, can be easily overcome through sensible regulation.

International shipping is lucky, it has its own dedicated UN agency: the International Maritime Organization (IMO). This is where global shipping policy is developed, allowing shipping to sit outside much of the standard political dynamics that are holding back multilateral cooperation on climate issues. But little progress has been made on climate at the IMO to date because for years it was thought that there was little shipping could do as a servant of international trade – if trade increased, shipping's emissions increased. But recent studies have shown that the move to electrofuels can begin almost immediately, the technology is available and both hydrogen and ammonia are known commercial products. It is time to start getting demonstration projects deployed.

The world has been trying to figure out how to fight climate change for decades now so we have a fair idea of which policies work in which scenarios. At the moment building out ammonia or hydrogen supply chains for shipping looks astronomically expensive compared to the status quo and no shipping company has any incentive to do so. So an obvious first solution is to put a price on the damage that the emissions of the use of current fossil fuels causes. The second part, which is not always as obvious, is to spend the money collected from that price developing early hydrogen and ammonia supply chains for shipping to help bring costs down through repeated deployment. This has worked extremely effectively in the solar and wind industries which have now reached price parity with fossil based electricity production in many places. There are no legal impediments to the IMO introducing a policy that funds the rapid scaling up of clean shipping fuels – in fact the IMO has a good track record of implementing globally standardised environmental regulations. Having recently adopted a strategy to at least halve emissions by mid-century the focus in upcoming meetings of parties is now on determining the policies to get us there.

If ship owners, shippers and port states can be convinced to adopt a sensible policy framework that incentivizes new clean fuel supply chains and vessel modifications, the global maritime sector could usher in a new era of clean abundant energy, sustaining global trade and boosting international development. In doing so it will help to drive change among a handful of powerful actors controlling existing fossil fuel supply chains who have thus far shown little sign of taking the existential risk of climate change seriously. A new market in clean fuels will help decide the relative role fossil fuels with capture and storage will play compared to a zero carbon electricity plus water (and air) supply chain and may the best providers win.

As the IMO gathers annually to discuss potential climate policies it is entirely possible that with couple of years a new incentive derisking investment can be agreed and implemented early in the new decade. A hydrogen-based economy is within our grasp but a concerted effort will be needed to make it a reality. All those who want to move on from this reckless era of manmade impact on our climate would do well to turn their attention for a little while to the negotiations taking place there. A seismic shift in transport fuels could be about to occur there – and it would be highly fitting for shipping, with its inherent efficiencies and long history of zero carbon propulsion, to re-occupy the green moral high ground and lead the fight against climate change. But it will require those of us committed to bending the curve in global greenhouse gas emissions to engage. So we look forward to seeing you at the IMO.

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[37] *https://europe.edf.org/news/2019/02/05/shipping-can-reduce-climate-pollution-and-draw-investment-developing-countries*

Potentially disruptive technologies for clean hydrogen

by Luigi Crema, Fondazione Bruno Kessler

The cheapest and most widely used hydrogen-production methods are far from green. The International Energy Agency (IEA) estimates that hydrogen production globally releases 830MtCO_2 per year – equivalent to 2.2% of global emissions in 2018, because it is produced almost exclusively from fossil fuels with no carbon capture and storage.

One route to low-carbon hydrogen is, of course, to add Carbon Capture and Storage to existing hydrogen production methods. And green hydrogen can also be produced using electricity, through electrolysis of water, as liquid or steam. But while significant high efficiencies exist, at the moment this process is not always competitive economically with the fossil-fuel route. Electrolysis therefore plays a minor role in current hydrogen production, accounting for only 4%.

There are five other "clean" technologies, currently at an earlier stage of development, that could in future produce hydrogen without emitting CO_2. Three of them derive the hydrogen from methane, and two from water.

Methane thermal cracking

This is the first of two processes that extract hydrogen from methane and provides an alternative to steam methane reforming. In this case, the reaction of thermal catalytic decomposition induces the cracking of methane from which hydrogen and solid carbon result. This type of reaction, which is a one-step reaction, does not produce CO_2 during its process.

Due to the chemical stability of the methane molecule, reactions aimed at splitting it usually require very high temperatures – reaching about 1200 °C. But, by using catalyst materials, cracking temperatures can be significantly reduced to well below 700 °C. A great energy saving. Furthermore, the energy requirements for catalytic cracking of methane are about half of those required for steam reforming.

The setback is that, unfortunately, metals and oxides suffer from coking and are intolerant to sulphur poisoning. The carbon produced by the cracking of methane therefore usually occurs in the form of carbon black or graphite.

Research underway seems to point to processes capable of producing higher-value carbon forms such as nanotubes or Graphene. These still need to be developed fully.

Plasma methane cracking

Another process which aims to extract hydrogen from methane is through plasma cracking. Here, the decomposition of methane using plasma is based on non-thermal processing which employs high-energy electrons to begin the decomposition of methane, thus also significantly lowering the temperature requirements. Amongst these, some very advanced processes, such as low-pressure plasmas, can even crack the methane molecule at room temperature, therefore requiring very low energy inputs. And the good news is that these plasma-cracking processes seem to have a relatively good ratio of success, with around 50-60% resulting effective.

Although they demonstrate great potential, these processes nonetheless require equipment which is much more sophisticated than mere thermochemical reactors. For example, one must use plasma sources with generators from microwave, radio-frequency or medium-frequency systems. These plasma generators must then be implemented in reaction chambers that sometimes require complex technologies such as vacuum technologies.

Although the carbon produced by plasma methane cracking is usually carbon black or graphite, there are processes under development that seem able to produce forms of higher-value, such as hard amorphous carbon, nanotubes or Graphene. Yet these are still in a highly experimentation phase. Furthermore, for now, most of these processes are made by *Chemical Vapour Deposition*, which is mainly used in the production of carbon-based materials but not for the production of hydrogen.

Metal hydrolysis

Another promising approach for generating small (every bit helps) amounts of H_2 are through water-metal reactions. The most prominent among these is the water-magnesium reaction. In this context, aluminum, magnesium and manganese have been identified as the most effective "combustible metals" for Hydrogen generation.

These processes offer great promise, but their main limitation is that they are not capable of producing Hydrogen in large amounts, and that the reversibility of the compounds produced is difficult and it would require a large-scale chemical conversion plant.

Photocatalysis hydrolysis

Also aiming to extract hydrogen from water in an alternative way, photocatalysis is a process that achieves water hydrolysis through the use of sunlight and catalyst materials within the photoelectric cell.

Unlike electrolysis, the cell does not need to be provided with an electrical current to activate the process of water hydrolysis. The cathode is usually coated with a photo-active ceramic and exposed to sunlight. Sunlight induces the formation of surface excitons that promote reductive oxide reactions with water. This results in the conversion of water into oxygen and hydrogen.

The advantage of this technology lies in the fact that a direct conversion of hydrogen solar energy can be achieved. However, it is not without limits. Unfortunately, the technology still has a low conversion efficiency, currently as low as 2%, and only in small scale and short-term tests at a slightly higher conversion value. Nonetheless, research continues, and significant improvements have already been achieved in terms of efficiency using novel materials.

Solar thermochemical gas splitting

Finally, an emerging and fascinating technology, that could provide the ultimate breakthrough, is "solar thermochemical gas splitting" (STGS), also known as the solar thermochemical separation of gases. The process is based on a thermochemical reaction that is triggered by the sun's energy. Here, sunlight is diverted onto thermochemical reactors containing water vapour and a ceramic catalyst such as Ceria. The reaction leads to the formation of hydrogen and carbon monoxide. The latter can be used for the production of solar fuels.

In the STGS, the reaction takes place in two stages: the concentrated sunlight leads to the reduction of a metal oxide, and oxygen is released. The advantage of this technology lies in the fact that there is a direct production of hydrogen from water by means of thermochemical cycle, where solar energy is used to regenerate the catalyst. However, this process too is not without limits, which once again lies in the technology's low efficiency.

Given their respective limits, there are still some obstacles to many of these processes used as alternatives to the traditional methods for hydrogen production. However, if and once they reach completion, their potential as disruptors in the hydrogen production of the future is infinite.

As things stand, the technology that seems to be the closest to commercial maturity – and thus to more widespread use – is methane thermal cracking. This is because the technologies used in the process, such as the thermochemical reactors, which function at temperatures between 400 and 700 °C, are already on the market, and the raw material they use, methane, is already widely available. Thermal methane cracking process could therefore become a viable substitute for steam methane cracking in the short term, offsetting a large part of hydrogen production emissions. Yet the technology still requires some engineering steps to be applied commercially. Meanwhile, research and development on the other processes is also advancing. For example, plasma technologies, that are also looking technologically interesting, could find application from 2025.

Building momentum for a global hydrogen market – the McKinsey view

by Bernd Heid, Markus Wilthaner
and Alessandro Agosta, McKinsey

Can the stuff that powers stars fuel a cleaner future for our planet? Hydrogen is the most plentiful element in the universe but one of the least utilised sources of green energy on Earth. Recent developments suggest that's about to change, however.

Industry is jointly investing in a variety of large-scale flagship projects involving hydrogen, with initiatives ranging from developing hydrogen-powered fuel-cell trucks to producing "green," carbon-free steel. Other projects aim use hydrogen to heat buildings, produce ammonia as a shipping fuel and as an input to low-carbon fertilizer production, for storing and generation carbon-free electricity, and to create liquid hydrogen supply chains. But hydrogen has been talked about a lot previously – so what is fueling the unprecedented momentum we see now?

It's a matter of when, not if.

Three key factors are accelerating global hydrogen deployment. The first, and maybe most important, driver is the sharp drop in the costs of renewables – a decline in the cost of renewables implies a direct decline in costs of green hydrogen.

As wind and solar power are deployed at large scale, their costs are falling dramatically. The trend has historically been tremendously underestimated: today's forecast for photovoltaic capacity in 2030 is 14x that of the forecast from 2006 for the same year. Regularly, auction results are breaking records – recently with a €15/MWh bid for solar in Portugal and a $18/MWh bid for onshore wind in Saudi Arabia. And while these are best cases, we expect the average cost of a newly installed megawatt-hour (MWh) of solar power production in 2030 to be 80% lower compared to 2010.

At such costs, generation from renewables becomes competitive with power production from natural gas. This is great news for hydrogen made from electrolysis, since 70% of its cost depend on the price of the input energy. If fed from renewable sources, hydrogen produced with electrolysis is also carbon free. And while global electrolyser capacity is limited today, we expect it to increase steeply over the next several years. Looking at announced projects, for example, a doubling of capacity is likely by 2020 and a staggering 35-fold increase has been announced until 2025.

The second driver is the renewed commitment by many governments to limit carbon emissions, supported by rising awareness and interest of citizens to reduce global warming. When targeting a significant reduction of carbon emissions, as experts deem required to remain below 1.5 degrees of global warming, hydrogen is a key technology without which such deep decarbonisation is unlikely to be achieved.

Combining this necessity of hydrogen in the future with the prospect of developing new industries and employment, has led a number of governments to embrace the technology. China, Japan, Korea, Germany, France, Norway, the Netherlands, Australia and a number of other countries – among which we hope to see Italy soon – have now put forth hydrogen roadmaps or national plans. Some have laid out ambitious deployment figures, others focus more strongly on R&D and market activation. China, for example, which had been a laggard on fuel cell and hydrogen technology, has leapfrogged to be the biggest market for hydrogen trucks in only 18 months. The national FCEV fleet deployment targets for 2030 for China, Japan, California, and South Korea began at 1 million vehicles two years ago and have reached 4 million today. South Korea has set itself an ambitious target for FCEV production of 6.3 million vehicles per year by 2040.

The final energising element in this equation involves industry alliances. In many countries and at a global level, industry alliances to further the development and deployment of hydrogen have formed. On the global level, the Hydrogen Council has formed in January 2017 with 13 members, out of which five were European, Japanese and Korean automotive OEMs and two Oil&Gas majors. Today, the Council has 60 members, represents more than $1.7tn market capitalization, and includes 6 more Oil&Gas companies as well as companies interested in decarbonising steel, rail and aviation, to name a

A primer on hydrogen production

Today, almost 95% of the hydrogen produced globally comes from **reforming** and **gasification** of fossil feedstocks. The key production technology used is steam methane reforming (SMR), and the most prevalent feedstocks are natural gas, naphtha and coal.

Their cost depend mostly on the used feedstock and the produced hydrogen has different carbon footprints, depending on the feedstock and process. These production pathways could be combined with carbon capture and storage (CCS) for removing carbon dioxide.

Alternative reforming processes, for example autothermal reforming (ATR), could prove useful in this context, as they allow for a higher share of carbon capture. CCS would slightly increase the capital (CapEx) and operating expenditures (OpEx) of hydrogen production, and slightly lower efficiency.

Low-carbon and carbon-free hydrogen can also be produced by using biomass or biogas as feedstocks.

Electrolysis is currently used in about 5% of hydrogen production. Three technologies are employed.

The first, alkaline electrolysis, is a mature technology.

The second, polymer electrolyte membrane (PEM) electrolysis is currently more expensive, but has strong cost reduction potential via industrialization.

The third is the so-called "high temperature" approach using a solid oxide electrolyser cell (SOEC). It can achieve the highest efficiencies out of the three technologies, but it's difficult to build SOEC electrolysers at large scale due to the size limitations for the ceramic membranes.

The carbon content of hydrogen from electrolysis depends on the used carbon content of the used electricity and can be very low if powered from renewables.

Besides these, several other production technologies are in a research stage. These include biological and bacterial production, direct solar water splitting and pyrolysis (the thermal decomposition of materials at elevated temperatures).

few examples. Such alliances can play outsized roles during the tenuous early days of a new market, as few companies have the resources (or the commitment) to "go-it-alone" when it comes to building up supply chains and deploying solutions in lockstep.

Out of the three drivers, the underlying cost-competitiveness of hydrogen is probably the most important and will prove decisive to the speed of the deployment of hydrogen solutions.

Hydrogen supply costs are falling fast

The momentum in hydrogen will create new hydrogen demand. Given its lower relative cost, technological maturity and availability at scale, hydrogen production via SMR is likely to provide a sizable share of that new demand in the short term. Electrolysis, however, has big disruptive potential. It can provide the link with the power sector, stabilize grids and make use of intermittent renewable power supply. It can produce hydrogen at small scale, close to the point of use, for example in refilling stations.

The costs for hydrogen from electrolysis will be reduced by lower cost renewables and cheaper electrolysers. Combining electrolysers directly with renewables avoids the costs of transmission and distribution grids and allows electrolysers to profit directly from cost reductions in renewables. For this to work out, however, electrolysers also need to get cheaper.

Electrolysers are produced today in relatively low volumes and even a small share of the future hydrogen market provides sizable growth prospects for electrolysers. This growth will drive the industrialisation of the manufacturing process, a scale up of the value chain for electrolysers and thereby significantly reduce costs. Globally more than 650 MW of electrolyser projects have been announced for the next few years and we have already observed drastic cost reductions.

Besides hydrogen production, its distribution and retail will also fall with a scale up. For the transport applications, for example, green hydrogen from the pump could fall by more than 50% in costs between 2020 and 2030. The cost reduction in production is only partially responsible (15%) – the bigger share of reduction comes from large, better utilised refueling stations (40%) and more efficient distribution (10%). Where production takes place on-site or a pipeline network is available, costs will be even lower.

As hydrogen cost declines, solutions become competitive

With renewables and electrolyser costs falling we can see a pathway to hydrogen below $2/kg (roughly $50/MWh) where access to good renewables is possible. This already brings a number of hydrogen applications “into the money”: on a total cost of ownership (TCO) basis, and at scale, we estimate that medium- and heavy-duty transport, buses and even light-duty fuel cell vehicles for fleet applications can break even at hydrogen production costs of around $100/MWh. Trains, ships, backup power solutions, forklifts and many other applications are also in or close to break even at such cost levels. At $50/MWh, green hydrogen becomes cost-competitive with hydrogen from natural gas in some regions, opening a large and already existing market.

This is not a done deal yet. Hydrogen still needs to overcome barriers to adoption – infrastructure needs to be built, value chains and manufacturing scaled up and products brought to market. But the underlying drivers are reducing production costs rapidly, and pointing towards a very large opportunity indeed.

Industrialization will drive reduction in electrolyser costs

Through analogies and our marker researches we estimate that the learning rate for electrolysers in the coming decade is at least 12%. That means, for every doubling of cumulative installed capacity, we expect electrolyser costs to drop by at least 12%. To estimate the learning rate, we have both looked at electrolyser cost from a bottom-up point analysis as well as by applying analogous learning rates from other industries to the main components of an electrolyser. We expect the biggest lever to be the increase of the stack size, which reduces not only the cost per capacity of the stack, but also decreases the costs of the balance of plant, including the rack, electronics, etc. Significant cost improvements are also possible through the scale up of manufacturing and the value chain.

We believe there is room for even faster improvements, in particular in the early years of electrolysers. Cell stack design and size are still at an early stage, companies are aggressively investing into research to build one, two and even five MW modules, and improvements could lead to step changes in cost. Compared to other technologies, a learning rate of 12% is on the conservative side: onshore wind turbines have improved with a 12% learning rate in the last decade, while photovoltaic technology has achieved as much as 24%. Comparable analysis from BNEF has arrived at learning rates of 18% and 20% for alkaline and PEM electrolysis, suggesting more potential upside than we see here.

Dr Gabrielle Walker is a strategist, author and speaker focused on climate change. She works as an advisor at boardroom-level with a wide range of global companies and has covered many different sectors. Her team at Valence Solutions helps to build bridges between stakeholders in the climate space, restructuring narratives and identifying broadly supported solutions to non-technical barriers.

Gabrielle has presented dozens of TV and radio programs for the BBC, reporting from all seven continents, and has written very extensively for international newspapers and magazines, including The Economist, The Wall Street Journal and The New York Times. She has written four books including co-authoring the bestselling book The Hot Topic, how to avoid global warming while still keeping the lights on, which was described by Al Gore as "a beacon of clarity" and by The Times as "a material gain for the axis of good". Gabrielle has a PhD from Cambridge University and has taught at both Cambridge and Princeton Universities.

Lord Turner chairs the Energy Transitions Commission, a diverse group of individuals from the energy and climate communities: investors, incumbent energy companies, industry disruptors, equipment suppliers, energy-intensive industries, non-profit organisations, advisors, and academics from across the developed and developing world. Its aim is to accelerate change towards low-carbon energy systems that enable robust economic development and limit the rise in global temperature to well below 2 °C and as close as possible to 1.5 °C.

He is a businessman, academic and former chairman of the Financial Services Authority. He has chaired the Pensions Commission, the Low Pay Commission, and the Committee on Climate Change in the UK. During his time at McKinsey (1982-1995) he built McKinsey's practice in Eastern Europe and Russia (1992-1995). From 1995-1999, he was director general of the Confederation of British Industry and vice chairman of Merrill Lynch Europe from 2000-2006. He was also non-executive director of a number of companies, including Standard Chartered plc, and currently holds this position at OakNorth and Prudential plc. As well as being chairman of the Institute for New Economic Thinking, Adair is a visiting professor at the LSE and Cass Business School.

Baroness Worthington is the Executive Director of Environmental Defense Fund Europe. She was appointed a life peer to the British Parliament's House of Lords in 2011. She is a leading expert on climate change and energy policy and carbon trading. She recently served as the Shadow Minister for Energy and Climate Change in the House of Lords, leading on two Energy Bills for the Shadow Ministerial team. In 2006, Bryony helped launch a Friends of the Earth campaign for a new legal climate framework, which led to her selection as a lead author on the United Kingdom's Climate Change Act. In 2008 Bryony then founded the Sandbag Climate Campaign, a group dedicated to scrutinising the EU's Emissions Trading Scheme.

Bryony also worked for the UK's Department for Environment, Food and Rural Affairs and worked for energy company Scottish and Southern Energy, advising them on sustainability issues.

Luigi Crema is Head of Applied Research on Energy Systems (ARES unit) at the Fondazione Bruno Kessler. The Fondazione Bruno Kessler is a leading Italian non-profit research institute, founded more than 50 years ago. It aims to achieve excellence in science and technology, with particular emphasis on interdisciplinary approaches and applications.

Bernd Heid, Senior Partner in the Cologne office, leads McKinsey's global Hydrogen Service Line, focusing his work on hydrogen mobility and alternative powertrain solutions including fuel cells.

Thereby he helps his clients in the transport, industrial and energy sector develop and implement decarbonisation strategies. In addition, Bernd is a member of the leadership team of McKinsey's automotive sector.

Markus Wilthaner is an Associate Partner in the Vienna office and a member of McKinsey's Center for Future Mobility, where he leads the Hydrogen and Battery Teams. He brings his deep expertise to clients in automotive, power, oil and gas, and cleantech to master the complex challenges arising from the energy and mobility transition. He holds an MA from Johns Hopkins SAIS and a MSc from the Vienna University of Technology.

Alessandro Agosta, Partner in the Milan office, leads the development of McKinsey's natural-gas knowledge, helping to build a distinctive perspective on gas-market discontinuities, the role of natural gas in the energy transition, and LNG, and serves clients globally on their most complex strategic challenges.

Glossary

Adapted from the National Academy of Sciences Energy Glossary

AC

Alternating current.

British thermal unit

A unit of measure for the energy content of fuels. One Btu is the amount of energy needed to raise the temperature of a pound of water by 1 °F.

Carbon capture and storage (CCS)

The act of capturing gaseous carbon, usually in the form of CO_2, and placing it into a stable carbon store such as a disused oilfield.

Carbon dioxide (CO_2)

A colourless, odourless, non-poisonous gas consisting of one carbon and two oxygen atoms. A by-product of fossil fuel combustion and other industrial processes, it is a greenhouse gas because it traps infrared energy radiated from Earth within the atmosphere. CO_2 is the largest contributor to human-induced climate change.

Carbon tax

An approach to limiting emissions by establishing a tax on goods and services based on the amount of carbon released in their creation and delivery.

Climate change

The process of shifting from one prevailing state in regional or global climate to another. Climate change is a less narrow term than global warming because it encompasses changes other than rising temperature.

Electric vehicle (EV)

A vehicle powered entirely by electricity stored in on-board batteries. Batteries are recharged by plugging them into an electricity source while the vehicle is parked.

Energy

The capacity for doing work; usable power (as heat or electricity); the resources for producing such power.

Energy content

The total amount of energy stored within a given quantity of fuel.

Energy conversion

The transformation of energy from one form to another. For example, when coal (chemical energy) is burned, it produces heat (thermal energy) that is then captured and used to turn a generator (mechanical energy), which produces electricity (electrical energy).

Energy efficiency

A measure of how much energy is needed to provide by an end use. Higher energy efficiency is exemplified in a wide variety of applications—from improved lighting and refrigeration to less energy-intensive industrial and manufacturing processes.

Fossil fuels

Fuels formed in the Earth's crust over millions of years from decomposed organic matter. The most widely known fossil fuels are petroleum (oil), coal, and natural gas.

Gigawatt

One billion watts, a watt being a unit of measure of power, or how fast energy is used. Gigawatts are typically used to describe very large quantities of power, such as the power carried by a major section of a national electrical grid.

Global warming

Earth's rising average near-surface temperature. Although such fluctuations have occurred in the past due to natural causes, the term is most often used today to refer to recent rapid warming. Scientists have concluded that this is almost certainly due to the increase in human-generated greenhouse gas concentrations in the atmosphere.

Greenhouse gas

A gas which, like a greenhouse window, allows sunlight to enter and then prevents heat from escaping – in this case, from Earth's atmosphere. The most common greenhouse gases are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons, and ozone (O3).

Grid

The network connecting electricity producers to consumers. The boundaries of the grid can be drawn differently but may include electricity generators, high power transmission wires, lower power distribution wires, and end users such as homes and businesses as well as the regulatory and market structures that affect electricity transactions. The grid is a physical infrastructure transmitting electricity and is also an economic entity that responds to supply and demand communicated through prices.

Hydrogen fuel cell

An emerging technology that uses hydrogen and oxygen to generate electrical current, giving off only water vapour as a by-product.

Intermittent energy source

An energy source characterized by output that is dependent on the natural variability of the source rather than the requirements of consumers. Solar energy is an example of an intermittent energy source since it is only available when the sun is shining. Wind is also an intermittent energy source.

Kilowatt

One thousand watts, a watt being a unit of measure of power, or how fast energy is used. Kilowatts are typically used to describe intermediate quantities of power, such as power usage in a home.

Kilowatt hour (kWh)

A unit of measure for energy, typically applied to electricity usage. It is equal to the amount of energy used at a rate of 1000 watts over the course of one hour. One kWh is roughly equal to 3,412 British thermal units (Btu).

Megawatt

One million watts, a watt being a unit of measure of power, or how fast energy is used. Megawatts are typically used to describe large quantities of power, such as the power output of an electrical generating plant.

Mtoe

Million tonnes of oil equivalent.

Natural gas

A gas mixture that occurs naturally in underground deposits. It is composed mainly of methane and may contain other hydrocarbons, carbon dioxide and hydrogen sulfide. Commonly employed as a fuel for electricity generation, it is also used for space heating, industrial processes, and as a starting material for the manufacture of chemicals and other products.

Particulate matter

Extremely small particles of solid or liquid droplets suspended in either a liquid or gas. Particulate matter is a common emission from the combustion of fossil fuels and can increase the risk of health problems. Examples include dust, smoke, aerosols, and other fine particles.

Photovoltaic (PV) cell

Sometimes referred to as a solar cell, a device that utilises the photoelectric effect to convert incident sunlight directly into electricity. This can be distinguished from solar thermal energy, which is sometimes used to create electricity indirectly.

Plug-in hybrid electric vehicle (PHEV)

A vehicle that contains a gasoline powered engine as well as batteries that can be charged when plugged into an electric power source. The vehicle typically runs on battery power until the charge has been depleted and then uses the gasoline engine for extended range.

Primary energy

Energy that has not undergone transformation to another form. This may include fuels such as natural gas or oil, or other forms such as solar or wind energy.

Renewable energy resource

An energy source that is naturally replenished. Examples include biomass, wind, geothermal, hydro and solar energy.

Secondary energy resource (or source)

A source of energy that is dependent on a primary source of energy for its power. As the production of electricity depends on the use of fossil fuels, nuclear power or renewable sources, it is referred to as a secondary energy source.

Smart grid

An electric grid that is able to use two-way communication and computer processing to provide increased reliability and efficiency. Smart grids may be able to automate and control more functions than the current electric grid.

Smog

A photochemical haze that is produced when sunlight reacts with hydrocarbons and nitrogen oxides in the atmosphere. Mainly caused by excess automobile exhaust, it is a form of air pollution that can be threatening to human health.

Solar energy

Radiant energy from the Sun.

Sustainability

Sustaining the supply of energy and materials needed to support current levels of consumption, making them available where most needed, and addressing the environmental problems resulting from their extraction, consumption, and disposal.

Syngas

A mixture of carbon monoxide, hydrogen, and sometimes other gases that can react to form higher hydrocarbons, natural gas, or methanol. Syngas is short for synthesis gas.

Watt (W)

A unit of measure for power, or how fast energy is used. One watt of power is equal to one ampere (a measure of electric current) moving across one volt (a measure of electrical potential).

Wind farm

A collection of wind turbines used to generate electricity.

Appendix 1. Bite-size climate science

Global average temperatures are now about 1 °C higher than they were a century ago. That figure comes from thousands of local temperature records, and in recent decades from satellite data (checked against ground-based weather stations).

This is a very sudden change. Scientists can trace past temperature by analysing the chemistry of tree rings, ice cores, corals and ocean sediments. The recent rise is bigger than any changes over the past 10,000 years, and seems to be faster than anything for millions of years.

Natural climate variations – for example from changes in solar activity and the Earth's orbit, volcanic eruptions and ocean circulation – are all too small to explain this jump in temperature. It is almost certainly due to human activity[38].

Since the industrial revolution, we have been injecting extra CO_2 into the air, mainly by burning fossil fuels and cutting down forests. Along with other greenhouse gases including water vapour, CO_2 helps to keep the Earth warm by trapping solar heat. Without it, we would freeze. But with too much, we will boil. The concentration of CO_2 has now built up to about 410 parts per million, far higher than at any time in the last 800,000 years at least, and it is still rising rapidly.

More bad news is that the Earth has inertia. The oceans have been acting as a sponge, absorbing both CO_2 and heat. This has kept the atmosphere cooler that it would otherwise have been; but it will catch up with us. Even if emissions stopped tomorrow, temperatures would keep rising, by about another 0.5 degrees.

So you don't need a sophisticated climate model to work out that the future is likely to be warmer still. Of course we do have sophisticated climate models, based on the known physics of the atmosphere and oceans. There are gaps in our knowledge, but models are constantly being tested against observations, and according to the Intergovernmental Panel on Climate Change, there is very high confidence that models reproduce long-term trends in temperature.

Models confirm the picture, predicting warming by roughly 4 degrees in 2100 if emissions are unrestrained. That would probably be catastrophic, making large areas of the planet uninhabitable, with far more extreme droughts, heatwaves, rainstorms and hurricanes, and sea levels inexorably rising. Four degrees would probably take us past climate tipping points; irreversible changes such as the Amazon rainforest drying out and dying off, the Greenland and the West Antarctic ice sheets collapsing (bringing a total sea level rise of more than 10 metres, albeit over a few centuries), and perhaps worst of all, tundra and marine sediments releasing huge amounts of the potent greenhouse gas methane, heating the planet further.

So four degrees would be very bad. What would be good, or at least acceptable? There is no exact answer, but the consensus is that we should try to stay below two degrees (ideally, well below), to avoid highly dangerous warming. That means a tight budget on further emissions, allowing us only about another 700 billion tonnes of CO_2, which is 17 years worth at the current rate.

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[38] *https://iopscience.iop.org/article/10.1088/1748-9326/11/4/048002*

Appendix 2. How hydrogen works

Hydrogen, the element, was created during the Big Bang. The first, simplest and lightest element in the periodic table accounts for 75% of all the conventional matter in the universe. Chemically combined with oxygen, it is the main component of water (H_2O), which covers three quarters of Earth's surface and makes up around 60% of our bodies. Hydrogen, which means water-forming in Greek, is colourless, odourless and so light that it can escape the world's gravitational pull and shoot off into space, which is why on our planet you usually find it bound with other elements in bigger molecules. When we refer to hydrogen in the context of the energy transition, we mean a molecule made of two atoms of hydrogen (H_2), usually in gaseous form.

Production

Electrolysis of water

In this process, which was invented by two British chemists in 1800, electricity is used to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyser, with two noble-metal-coated electrodes, separated by a conductive substance called electrolyte or a membrane.

There are 3 types of electrolyser, differentiated by the electrolyte type with different maturity levels. Alkaline electrolysers are the most common and robust, with well-developed cost models as they have existed for several decades. The production of hydrogen occurs in a strongly basic aqueous electrolyte, allowing the use of low-cost catalysts coating the electrodes (nickel, zinc) and electrode material (steel).

Electrolysers with proton exchange membrane (PEM) have been known for several years. They have technical advantages such as a higher achievable current density and a low electrical resistance. A PEM electrolyser uses an ionically conductive solid polymer membrane. However, they require more expensive catalysts such as iridium and platinum.

Solid oxide electrolysis cells (SOECs) work at a high temperature (800 °C) and have the best efficiency of electric-hydrogen conversion with a ceramic electrolyte. However, this is still a young technology, with only some prototypes and demonstrators operating.

Reforming

This is the most widely used technology for making large volumes of hydrogen, by extracting it from natural gas or other fossil fuels. Steam methane reforming (SMR) and autothermal reforming (ATR) exploit reactions between hydrocarbons (mainly methane) and water vapour at high temperatures, generating hydrogen and CO_2.

In a typical SMR reactor, the reaction heat is supplied externally by the additional combustion of additional fuel gas (methane); in an ATR reactor, combustion takes place inside the reactor. SMR requires conversion temperatures between 500 °C and 900 °C; ATR requires 900-1150 °C. Between 10 and 15 kg of CO_2 is emitted per kg of H_2 produced (for comparison, the coal gasification process produces between 18 and 25 kg of CO_2 for each kg of H_2).

If carbon capture is used, the quantity of CO_2 that can be captured varies between 60% to 90%. ATR has the potential for > 90% capture, because its exhaust gases have a high concentration of CO_2.

Methane cracking

A less developed technology, methane cracking can produce low-carbon hydrogen without the problem of gaseous CO_2 capture and storage. It is based on the decomposition of methane into gaseous H_2 and solid carbon.

The reaction can be achieved by heating methane to 1200 °C (or 700 °C using specific materials), but this process is very sensitive to sulphur contamination. To avoid that problem, decomposition by plasma is being investigated. This could make the reaction happen at ambient temperature, but the energy required for the high energy electrons gives an efficiency of only about 50 to 60%. Moreover, the hardware is sophisticated, requiring vacuum technologies and plasma generators.

The economics of the process depend on generating high-value solid carbon such as graphene or nanotubes, and the technology still needs a lot of investment in R&D.

Extraction from oil fields

In August 2019, Canadian engineers announced a method of extracting hydrogen from oil sands and oil fields, which they say will be cheap and environmentally friendly. They inject oxygen, which raises the temperature and releases hydrogen. It could be used on the remnants of oil in abandoned fields, or on working fields to extract hydrogen instead of oil, leaving the carbon underground. This could produce hydrogen for between $0.10 and 0.50, according to Grant Strem, CEO of Proton Technologies, which is commercialising the process. Field testing is still needed.

Power-to-Liquids

Power-to-Liquids (PtL) is a production pathway for liquid hydrocarbons based on hydrogen and CO_2 as resources.

There are two principle pathways to produce renewable PtL jet fuel:

- Fischer-Tropsch (FT) synthesis and upgrading.
- Methanol (MeOH) synthesis and conversion.

PtL production comprises three main steps:

- Hydrogen production from renewable electricity using the electrolysis of water.
- Provision of renewable CO_2 and conversion.

- Synthesis to liquid hydrocarbons with subsequent upgrading/conversion to refined fuels.

Transportation

There are various ways to transport hydrogen:

- Blend with natural gas so it can be carried in the existing natural gas grid. This has the advantage of being based on existing infrastructure, limiting the investment needed – although some sensitive grid auxiliaries or final uses cannot accept a hydrogen blend above a threshold. It also faces standards and regulation issues. Gas transmission system operators are working on solutions to overcome these limitations.
- Pump pure hydrogen gas. This would require new infrastructure or investments to adapt the existing infrastructure.
- Move compressed or liquefied hydrogen in tanks.
- Use hydrogen carriers such as ammonia or liquid organic hydrogen carrier (LOHC).

To move pure hydrogen in small and medium quantities, the best solution is cylinders or tanks. For short distances compressed hydrogen is suitable, with transport costs about \$0.5 to 2/kg for 100 km. For longer distances liquid hydrogen in cryogenic tanks is more economical, costing about \$0.3 to 0.5/kg for 100 km.

For large quantities, the distance is again critical. Under 4000 km, building a dedicated hydrogen transport network would be the best option (about \$0.1 to 1/kg for 100 km) despite the high initial investments (\$0.2-1 million/km). It is possible to create local transport networks (micro-networks) or regional ones. Globally in 2016 there were more than 4500 km of hydrogen pipelines, the majority managed by hydrogen producers. The longest hydrogen pipelines are located in the USA, in particular Texas and Louisiana.

For long distances, over 4000 km, carrying liquid hydrogen in tankers remains one of the most promising options. In a tanker carrying 9000 m^3 this would cost about \$1.8 to 2/kg for 100 km. Ships could use fuel cells for propulsion.

For long-distance transport and storage, ammonia and LOHC are candidates. The hydrogen is transformed into another substance (eg. ammonia) before shipping and is then regenerated close to the delivery point. This reduces yield but transportation would be cheaper and is known to be reliable – the global ammonia supply chain handles hundreds of thousands of tons of NH_3 per day.

Storage

This falls into two categories: centralised storage for seasonal timescales, and distributed short-term storage.

Seasonal storage involves huge amounts of hydrogen, and the only solution is centralised, underground reservoirs. Former salt mines could provide the volume required. Depleted gas or oil fields are not as suitable due to contamination from residues, including sulphur-based compounds and hydrocarbons, although they could be used if extracted gas is then purified. Underground storage should have quite low costs, depending on the specifics of the site, roughly between \$10 and 15 per MWh capacity.

For intra-day timescales, distributed storage could be placed close to locations with high hydrogen consumption to absorb peak demand. This could be done within gas transmission and distribution lines, or using silos or tanks at nodes of the gas network. Large vertical cylinders at 50-80 bar would mean compression is not necessary for introducing gas to the transmission network. A 400 kg cylinder costs about \$210,000, which means an investment of $13/kWh. Alternatively, tanks in steel or composite materials, with H_2 at pressures up to 430-500 bar, would be more capital intensive, between $63/kWh and $85/kWh.

Uses

Combustion

Hydrogen can be burned directly in boilers or to drive turbines. The first commercial gas turbines have been developed for producing electrical power directly from pure hydrogen or from mixtures. Some turbine systems on the market, such as the Enel plant near Venice, can use natural gas mixed with up to 50% hydrogen. Several companies are also developing burners compatible with pure or mixed hydrogen, to provide boilers for domestic use.

The combustion of hydrogen, when compared with that of fossil fuels, also presents problems, such as the difficulty of detecting the flame and the high speed of flame propagation.

Fuel cells

Fuel cells are the opposite of electrolysers: recombining hydrogen and oxygen to generate power.

The principal applications are for vehicles – powering cars, buses, trucks, trains, ships and maybe planes and whatever the exciting future brings – and for small-scale electricity generation.

They are based on two bipolar plates, one distributing oxygen and the other evacuating water. Two electrodes allow the electric current to circulate, and a membrane serves as an electrolyte allowing ion exchange. The reactions take place in what is commonly called a stack that can produce only a low voltage (linked to the potential of the electrochemical reaction exploited). The challenge is to put many stacks together to generate a high enough voltage.

There are a lot more electrode combinations than for electrolysers, allowing fuel cells to work with other fuels, but for hydrogen the main technologies are proton exchange membrane, solid oxide, and alkaline.

A proton exchange membrane fuel cell (PEMFC) is based on the exchange of protons (positive hydrogen ions). Hydrogen injected on one side (anode) is oxidised, producing protons and electrons ($2H_2 \rightarrow 4H^+ + 4e^-$). Protons pass through the membrane to the other side of the cell while electrons move from the anode to the cathode generating the current. On the other side (cathode) oxygen is injected. It combines with protons arriving through the membrane, and the electrons that have provided current, to form water ($O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$).

In a solid oxide fuel cell, the principle is the same but the electrolyte is a ceramic, and instead of protons it lets negative oxygen ions through. On the anode side, hydrogen is still injected and oxidised to produce protons and electrons; the electrons move to the cathode side and react with the oxygen to produce oxygen ions that pass through the solid oxide to combine with hydrogen on the other side. Solid oxide cells operate at very high temperature to increase the conductivity of the electrolyte. Due to this high temperature, start-up and shut-down procedures are very time-consuming, so these devices are not as flexible as PEMFC, making them unsuitable for vehicles, where demand can change rapidly. But solid oxide cells are extremely interesting for stationary uses because they have higher efficiencies than PEMFC. The development of low-cost materials (especially interconnections) with high durability at high temperatures is the key technological challenge.

Alkaline fuel cells (AFCs) use a liquid electrolyte (generally potassium hydroxide or KOH). At the anode hydrogen combines with hydroxyl ions, while at the cathode oxygen reacts with water producing hydroxyl ions. The biggest disadvantage of this technology is that it needs pure oxygen (while others can use air) to avoid contamination of the electrolyte solution with CO_2.

Industry

Industrial applications account for about 98% of global hydrogen consumption, about 115 million tonnes per year. Around 70 million is in pure form, mostly for oil refining and ammonia manufacture for fertilisers. It is almost entirely supplied from natural gas, coal and oil, generating considerable greenhouse gas emissions. The remaining 45 million is used in industry without prior separation from other gases.

The top three uses are oil refining (33% of total consumption), chemicals (40%), and steel production via the direct reduction of iron ore (3%), with many more uses including food processing.

Oil refining

Turning crude oil into various end-user products such as transport fuels and petrochemical feedstock uses 38 million tonnes of hydrogen per year, or 33% of the total global demand. It is consumed as feedstock, reagent and energy source.

Hydrogen is mainly used to remove sulphur and other impurities from crude oil, and to upgrade to refined fuels, including gasoline and diesel, through the processes of hydrotreatment and hydrocracking.

Today refineries remove around 70% of the naturally occurring sulphur from crude oils. With concerns about air quality increasing, there is growing regulatory pressure to further lower the sulphur content in final products. And refineries' existing large-scale demand for hydrogen is set to grow.

Chemicals

Hydrogen is part of the molecular structure of almost all industrial chemicals, but only a few primary chemicals require large quantities of hydrogen feedstock. Ammonia production uses 31 million tonnes of hydrogen per year; methanol 12 million tonnes.

Other comparatively minor applications take the overall sector demand to 46 million tonnes, or 40% of total hydrogen demand.

Ammonia (NH_3) is obtained on a large scale by the Haber-Bosch process, which combines hydrogen and nitrogen together directly. Nitrogen is obtained by low-temperature separation of air, while hydrogen originates today from natural gas steam reforming. Around 80% of ammonia is used to make fertilisers, such as urea and ammonium nitrate.

Methanol (CH_3OH) is produced by catalytic hydrogenation of carbon monoxide. Methanol is used to produce several other industrial chemicals, and to produce gasoline from both natural gas and coal.

The chemicals industry also generates by-product hydrogen, but the vast majority of hydrogen that the sector consumes is produced from fossil fuels.

Metals

About 4 million tonnes of hydrogen is used as a reducing agent in the metals industry, in particular for iron and steel production.

The blast furnace-basic oxygen furnace method accounts for about 90% of primary steel production globally. Blast furnaces produce hydrogen as a by-product of coal use in a mixture known as works-arising gases (WAG), which includes carbon monoxide. WAG is used for various purposes on site, and also transferred for use in other sectors including power generation and methanol production.

The direct reduction-electric arc furnace method accounts for 7% of primary steel production. It uses a mixture of hydrogen and carbon monoxide as a reducing agent. Here, hydrogen is produced in dedicated facilities, around 75% by natural gas reforming and the rest by coal gasification.

Appendix 3. The world of green gas

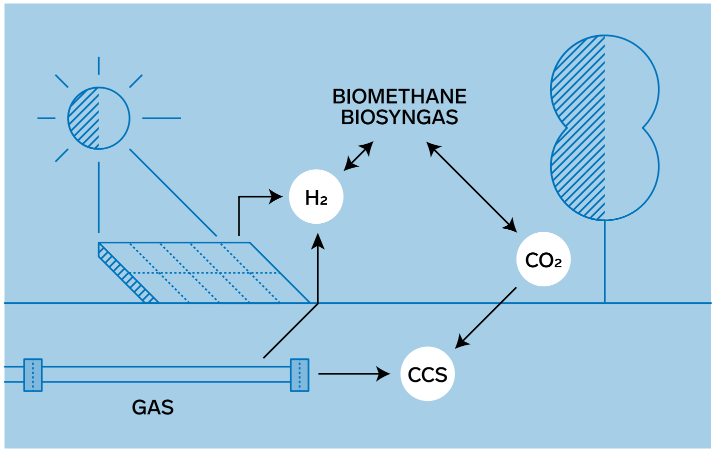
Hydrogen, whether from renewable power or fossil fuels with some sort of carbon capture, is just one of the renewable and low-carbon gases available.

Others include biogas and biomethane, which are renewable gases made from agricultural or urban organic waste, through either anaerobic digestion or gasification; biosyngas, which is synthetic gas made from renewable hydrogen and CO_2 released from natural processes (a process called methanation) and low-carbon natural gas, which is made by capturing the CO_2 from natural gas after it has been combusted.

Biomethane and biosyngas are chemically identical to natural gas (CH_4); while biogas needs additional upgrading to be injected into the gas grid.

The bio contingent (biomethane and biogas) count as carbon neutral because burning them emits carbon that the plants would have emitted anyway as they rotted.

The low carbon gas puzzle



Natural gas with CCS counts as almost carbon neutral, given high post-combustion capture rates.

The good thing about a clean gas that is chemically identical to natural gas is that it allows you to decarbonise sectors that currently run on natural gas without changing anything at all except for the source of the gas itself. The downside is that to be sustainable – not without competing with food – production of biogas, biomethane and biosyngas is constrained by how much agricultural and urban waste there is.

Meanwhile, while swapping existing fuels with hydrogen will require investments over and above the production of hydrogen, the advantage is that it is theoretically infinite and also hugely scalable, so production costs will likely come down to a level which makes it competitive even accounting for the additional investments it requires.

The precise combination of low-carbon gases in final consumption will differ region by region.

Areas of the world with lots of wind and sun (or cheap fossil fuels and room to store CO_2) will probably turn up the dial on hydrogen, while agricultural areas will have a greater availability of biomethane.

In addition, areas of the world with plastic pipes in their gas networks, like the UK, may see hydrogen as a good option for heating homes, while in other areas biomethane may be the preferred clean gas.

The choice of fuels will also depend on what else is being done in the vicinity, in terms of consumption and production.

For example, retail consumption that is close to an industrial “hydrogen cluster” will probably use existing infrastructure for hydrogen. Where they would need to provide the aggregate demand to justify new infrastructure, it may be more of a biomethane market. The synergies in the production of biomethane and biosyngas may also support the methanation of hydrogen in areas where biomethane is produced.

Hydrogen-assisted biomass-to-methane processes. Biomass-based technologies can be coupled with hydrogen-based conversion technologies to achieve higher biomass energy conversion efficiencies and a more sustainable land use at a lower overall costs.

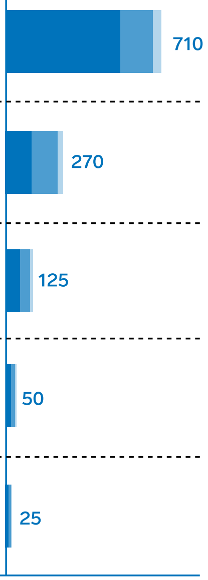
H_2-enriched biomethane plant. Biogas (a mix of CO_2 and CH_4) from anaerobic digestion can be enriched with electrolytic H_2 and fed into a methanator to produce a bio – synthetic natural gas (Bio-SNG). With respect to a non-hydrogen coupled production process, this has the advantage of achieving at the same time a higher CH_4 yield, a higher energy efficiency as the waste heat from the electrolyser can be recycled into the digestor, and substantial capital cost saving.

H_2-enriched biomass gasification plant. Biomass gasification plants can produce almost any type of synthetic fuel through the intermediary production of syngas, which can be enriched with electrolytic H_2 and fed into a methanator to produce Bio-SNG. Both the oxygen co-produced and the waste heat from the electrolyser can be recycled into the gasification process to enhance its efficiency.

H_2-enriched sewage fermentation plant. Sewage plants and landfill sites emit large amount of CO_2 during fermentation, which can be fed together with H_2 into a methanator. Oxygen from the electrolyser and the waste heat from the methanator and/or electrolyser can be recycled to enhance the fermentation process performance.

Appendix 4. Electrolyser maths

	Renewable generation (solar PV + batteries)	Electrolyser (PEM)			Levelised cost of hydrogen (LCOH)
Time horizon	Generation costs $/MWh	Utilisation	Capex $ per kW[2]	Efficiency	LCOH $/MWh
2010	360	20%[1]	2.000	57%	710
2014	79	20%[1]	1.750	60%	270
Today	53	35%	1.200	63%	125
10 years from now	23	35%	390	70%	50
Large scale adoption	14	35%	180	70%	25

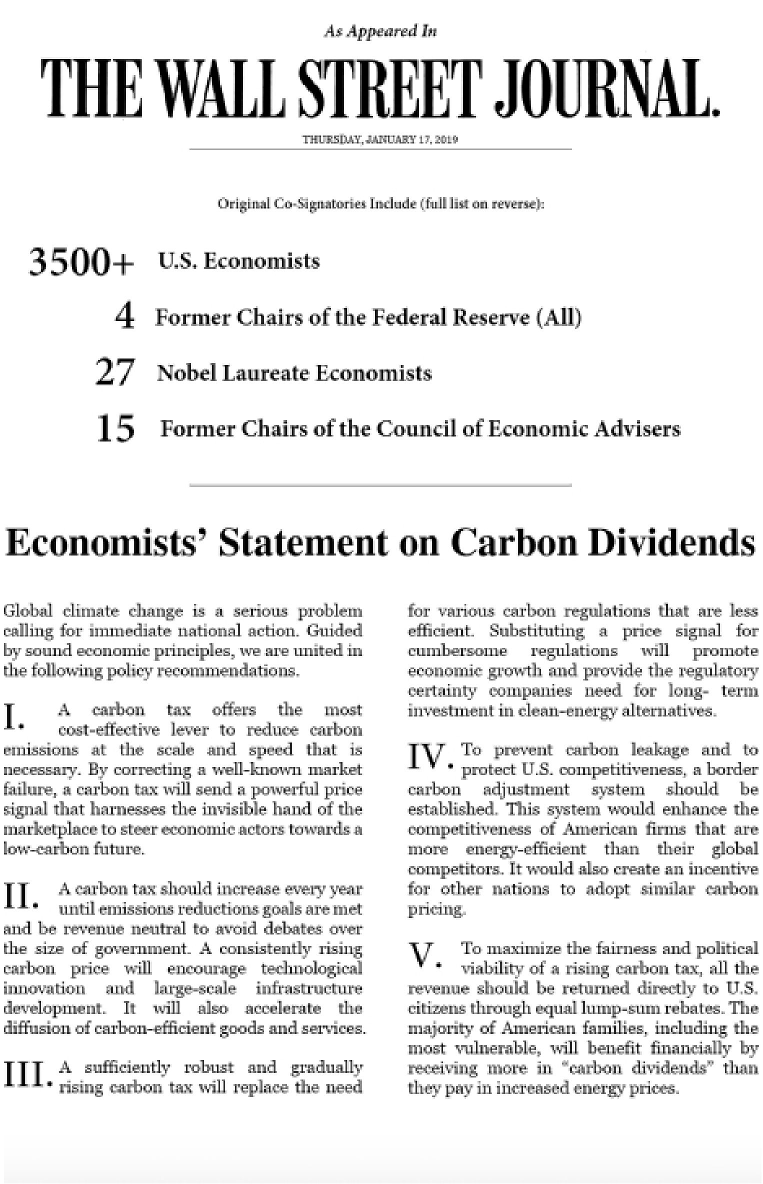


▬ Electricity ▬ Capex ▬ Opex

1 Without battery
2 Equipment and installation included

source: McKinsey & Company provided analytical support, based on data from BNEF, IRENA, Energy Insights

Appendix 5. A Nobel approach



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4	Former Chairs of the Federal Reserve (All)
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Economists' Statement on Carbon Dividends

Global climate change is a serious problem calling for immediate national action. Guided by sound economic principles, we are united in the following policy recommendations.

I. A carbon tax offers the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary. By correcting a well-known market failure, a carbon tax will send a powerful price signal that harnesses the invisible hand of the marketplace to steer economic actors towards a low-carbon future.

II. A carbon tax should increase every year until emissions reductions goals are met and be revenue neutral to avoid debates over the size of government. A consistently rising carbon price will encourage technological innovation and large-scale infrastructure development. It will also accelerate the diffusion of carbon-efficient goods and services.

III. A sufficiently robust and gradually rising carbon tax will replace the need for various carbon regulations that are less efficient. Substituting a price signal for cumbersome regulations will promote economic growth and provide the regulatory certainty companies need for long- term investment in clean-energy alternatives.

IV. To prevent carbon leakage and to protect U.S. competitiveness, a border carbon adjustment system should be established. This system would enhance the competitiveness of American firms that are more energy-efficient than their global competitors. It would also create an incentive for other nations to adopt similar carbon pricing.

V. To maximize the fairness and political viability of a rising carbon tax, all the revenue should be returned directly to U.S. citizens through equal lump-sum rebates. The majority of American families, including the most vulnerable, will benefit financially by receiving more in "carbon dividends" than they pay in increased energy prices.

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