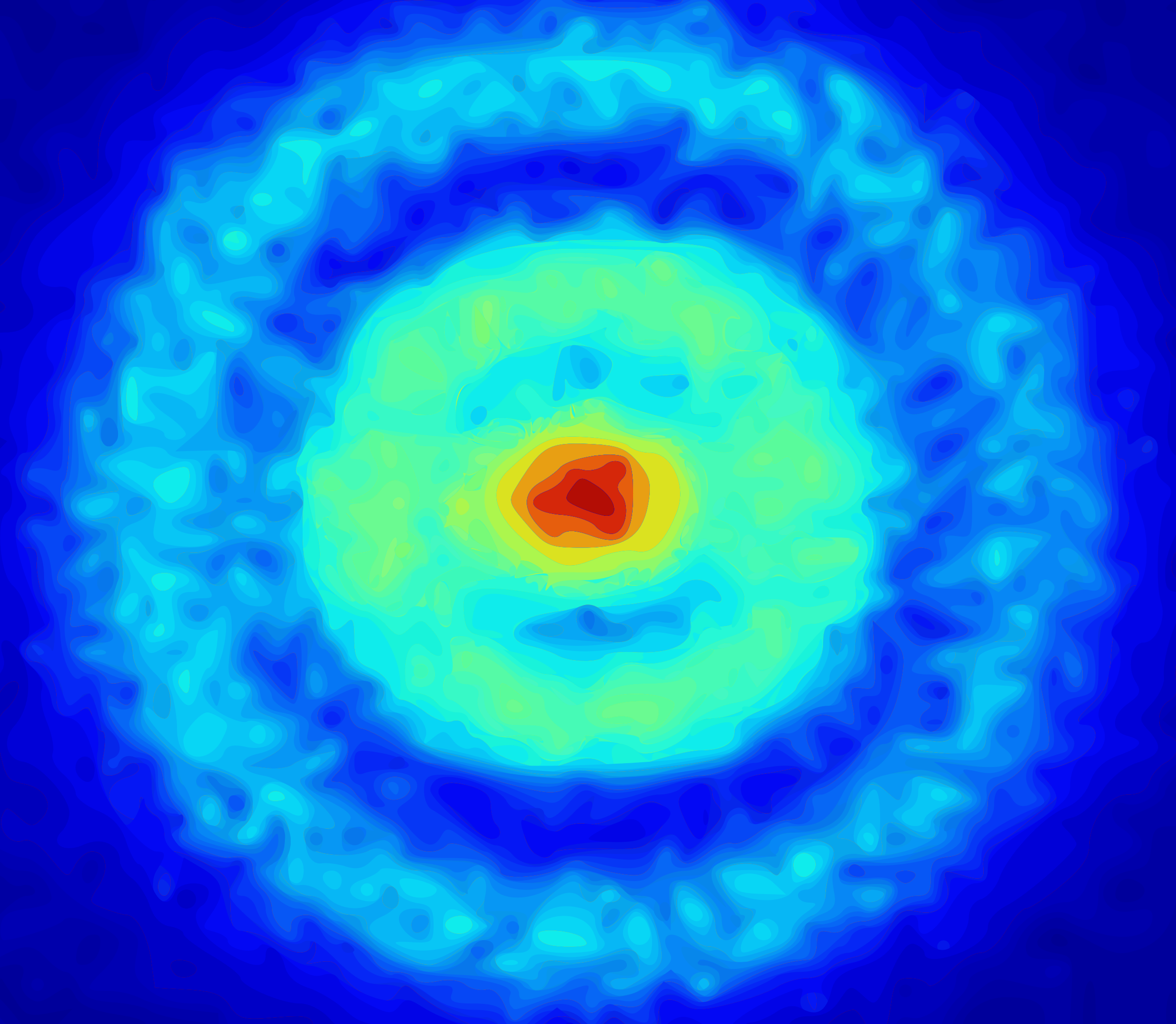
HYDROGEN
The once and future fuel?

John Constable



The Global Warming Policy Foundation

GWPF Report 44

Cover image

The cover shows a quantum camera image of a hydrogen atom.

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ISBN 978-1-9160700-4-2

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About the author

John Constable is a member of GWPF's Academic Advisory Council and the energy editor of the Global Warming Policy Foundation.

Acknowledgments

This study, almost a short book, has greatly benefitted from the advice and conversation of many colleagues, both in the Global Warming Policy Foundation and further afield. They have saved me from many misunderstandings and errors, and I thank them all. The literature around the hydrogen economy is not only vast, but littered with mistaken or confused information, even in reputable sources. Doubtless some errors still persist in my own text in spite of my efforts and those of the reviewers, and for these I accept full responsibility.

John Constable
29 October 2019

Summary and conclusion

Policy context

- International enthusiasm for a shift towards a hydrogen economy has never been stronger. However, this interest is not grounded in any recent technological breakthrough, but in the inexorable logic of current climate mitigation ambitions. Current policy sees in hydrogen a universal free parameter, offering the possibility of decarbonising otherwise extremely difficult sectors in line with the objectives of the Paris Agreement.
- Policy is thus dependent on the current state of hydrogen production, which is essentially a commodity production system, not an energy system, a fact with severely negative implications for round-trip energy efficiency and cost. It is a desperate measure, and critically dependent on the viability of carbon capture and sequestration (CCS) of the emissions arising from the production of hydrogen. The UK's proposals, as found in the work of the Committee on Climate Change (CCC)[1] typify the overall problem.

The proposals of the Committee on Climate Change

In order to meet the target of net zero emissions by 2050 and to address sectors otherwise all but impossible to decarbonise, such as shipping and HGVs, the CCC envisages the use of 270 TWh of hydrogen, a quantity of energy approximately equivalent to UK's current total annual consumption of electricity.

- The projected 270 TWh represents an increase of 220 TWh over the 50 TWh previously projected to meet the 80% emissions reductions commitment prior to the adoption of the net zero target.
- 225 TWh of the required hydrogen would be produced from 30 GW of steam methane reformers (SMRs) at between 30 and 60 sites, all equipped with CCS. The capital cost of these SMRs would be in the region of £30–40 billion, with an operating cost, aside from fuel cost, of about £1 billion per year.
- 44 TWh of the required hydrogen would be produced from 6–17 GW of electrolysers at 600–1700 sites. The capital cost of these electrolysers would be in the region of £4–12 billion. Expected plant life is short, at just over ten years, implying a rapid capital refreshment cycle. Operating costs would be between £60 million and £185 million per year at present, falling after 2030 to between £50 million and £140 million a year.
- To produce the required 270 TWh of hydrogen would require some 282 TWh of natural gas for the SMRs and about 60 TWh of electricity for the electrolysers, implying a conversion loss of about 20%, before further losses in transmission and distribution, and also due to leakage or boil-off in local storage tanks.
- CCS is essential if the net-zero ambition is to be realised, and the CCC very optimistically believes that a 95% capture rate is possible, leaving residual emissions of just 3 $MtCO_2e$.*
- The production of hydrogen from SMR and electrolysis requires significant quantities of water. The CCC does not provide estimates, but by using data from the scientific and engineering literature it is possible to calculate that the production of the projected

* Compared to total emissions of 460 $MtCO_2e$ in 2017.

270 TWh of hydrogen would require between 67 billion and 140 billion litres of water per year. This is equivalent to between 1 and 2% of current water use in the UK.

- While arguably manageable at a national level, water consumption of this order will necessarily be concentrated at local hydrogen production centres and would be likely to cause significant stress on regional water supplies in low-rainfall areas.

Safety

The dangers of widespread use of hydrogen as an energy carrier have been both under- and overstated. In common with other powerful energy sources and carriers, such as gasoline and electricity, hydrogen is intrinsically hazardous, more so in several respects, namely that it has a comparatively low ignition energy, a wide flammability range, and a strong tendency to proceed from deflagration (a simple fire) to detonation (an explosion with a flame frontier moving at speeds greater than sound and with an accompanying shock wave).

- While hydrogen has been used since the early 19th century as a fuel, in town gas for example, the comfort to be taken from that experience is limited, due to significant differences in the character of the town gas network, which was a local, low-pressure system delivering a blended gas of which only about 50% was hydrogen. The current proposals are for a national high-pressure network, delivering pure hydrogen.
- The now common misrepresentation of the *Hindenburg* disaster as unrelated to hydrogen is indicative of a lack of candour amongst academics and other enthusiasts. There can be no reasonable doubt that the hazardous physical properties of this 'lift gas'[†] lie at the root of the *Hindenburg* fire, and of other airship accidents.
- Nevertheless, the risks (hazard × probability) arising from society-wide use of hydrogen can probably be contained within reasonable limits, but only if (a) the hazards are acknowledged and addressed, and (b) sufficient time is allowed for technological and societal adaptation to its particular problems. Target-driven haste is a recipe for disasters.
- In the longer term, there must be some doubt over whether a renewables-fuelled hydrogen economy can generate the wealth required to support the technologies and practices require to contain the risks of hydrogen use. Neither gasoline nor electricity are cheap to use safely, but the great wealth created by fossil fuels makes the required safety measures easily affordable. It is not clear that the same can be true of a wind- or solar-powered system using hydrogen as its energy carrier.

Premature re-adoption of hydrogen will be counterproductive

From the early 19th century to the later 1970s, hydrogen was in widespread use as a component in town gas. However, it was expensive and it was eventually displaced by natural gas for sound economic reasons, bringing great increases in human welfare. These reasons still apply and should rule out both electrolysis and SMR as a means of hydrogen production.

- Input from an extremely productive energy source such as nuclear energy, which appears to be the long-term intention of the government of Japan, is probably the sole

† The technical term used to refer to the lighter-than-air gas that enables an airship to rise from the earth's surface.

means of generating hydrogen sufficiently cheaply to make the required safety precautions affordable, as well as delivering energy to satisfy human requirements.

1 Introduction

The return of hydrogen

Ten years ago, Professor David MacKay, later knighted for his services as the government's energy advisor, observed in his highly regarded and popular study, *Sustainable Energy Without the Hot Air*, that 'hydrogen is a hyped-up bandwagon'.[2] Justifying this dismissal, he went on to observe that it was 'just…a rather inefficient energy carrier, with a whole bunch of practical defects'.[3] Those practical defects can be quickly inferred from the physical properties of this gas, as summarised in Tables 1 and 2.[4]

Table 1: Physical properties of hydrogen.

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.8 kg/m^3 (−253°C, 1 bar)	1/6 of natural gas
Boiling point	−252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3 × that of gasoline
Energy density (ambient, LHV)	0.01 MJ/l	1/3 that of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/l	1/3 that of LNG
Flame velocity	346 cm/s	8 × that of methane
Ignition range (% volume)	4–77%	6 × wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 mJ	1/10 of methane

From IEA 2019, p. 35.

Table 2: Energy densities.

By weight	Hydrogen kWh/kg	Natural gas kWh/kg	Petrol kWh/kg
HHV†	39.4	14.5	13
LHV†	33.3	12.7	12.3
*By volume**	kWh/l	kWh/l	kWh/l
HHV	0.00354	0.0109	9.6
LHV	0.00300	0.0098	9.1

†HHV and LHV are defined on p. 15; *at 1 Nm^{-3} and 20°C. From ERP 2016, p. 8.

While the hydrogen has a high energy density per kilogram, the density per unit of volume at normally ambient temperatures and pressures compares unfavourably with natural gas and other fuels. However, its very low boiling point, near absolute zero, makes the liquid state energetically costly to achieve and difficult to maintain. Compression is also energetically costly and, being small, molecular hydrogen is likely to leak, which, combined with its

Hydrogen is a hyped-up bandwagon... a rather inefficient energy carrier, with a whole bunch of practical defects

Professor David MacKay

low ignition energy and wide range of concentrations at which it will ignite, raises questions about safety and ease of handling.

It should be no surprise, therefore, that MacKay's 'views were far from eccentric and in fact accurately represent the conclusions of many observers of the first big hydrogen push in the early 2000s. Even Joseph J. Romm, a former science advisor the President of the United States, and a strong proponent of hydrogen, felt obliged by what he regarded as counter-productive exaggeration to entitle his own book-length case for the fuel *The Hype About Hydrogen*. Academic and more or less neutral observers took the same view. For example, the papers collected in a standard and well-regarded general study, *Hydrogen Energy: Economic and Social Challenges* are in general restrained in their expectations. In summarising the volume, the editor, Paul Ekins, wrote:

> In respect of hydrogen technologies…the evidence suggests that their current market advantages over incumbent and developing technologies with which they are in competition are rather few…there is no literature that suggests the hydrogen economy will come to exist in the foreseeable future, if ever, without substantial and long-term public support.

Given the vocal enthusiasm for hydrogen in 2019, it might seem reasonable to assume that some significant – not to say dramatic – breakthrough had rendered irrelevant the tempered pessimism of MacKay and many others. However, this is not the case. There has, of course, been progress in the development of conversion devices, such as fuel cells, but that is not surprising since the most intractable difficulties of hydrogen have never been associated with its combustion; it burns readily and can easily be converted into energy by an end consumer, producing heat, light, rotary motion and, if desired, electricity. The deeper problems, the inefficiencies and the practical defects to which MacKay alluded, are all associated with its *production* and *delivery* to end consumers, and in relation to this almost nothing has changed since the publication of *Sustainable Energy* in 2009.

Hydrogen is like electricity in being an energy carrier, a variety of manufactured fuel. It is made either by electrolysis, which uses electricity generated by other sources to disassociate the hydrogen from the oxygen in water, or steam methane reforming (SMR), in which energy, usually natural gas, is used to raise steam. The steam is then brought into contact with a catalyst and an additional supply of natural gas to extract hydrogen from both, generating carbon dioxide in the process.

These processes are technically and commercially viable for manufacture of hydrogen for industrial use, but require significant energy input. Except in a limited number of niche applications, it will usually be possible to use electricity and natural gas directly, rather than manufactured hydrogen, which implies that hydrogen produced from electrolysis and SMR is always in competition with its own inputs, electricity and natural gas. Given the energy losses in hydrogen manufacture and even assuming optimally efficient use of the SMRs and electrolysers, it is impossible that hydrogen can win this competition. Indeed, hydrogen from electrolysis and SMR would only become attractive through the imposition of an artificial externality such as a carbon price, and probably a carbon price that exceeds the social cost of carbon (SCC). In other words, a penalty that exceeds the econometric estimate of the harms to human welfare from emitting a specified quantity of a greenhouse gas, a cure that is worse than the ailment it aims to treat.

That situation is unlikely to change, since the energetic inefficiencies in production are almost insusceptible to remedy, being determined directly by the physics and chemistry of hydrogen itself. Water is a tough molecule, and breaking its bonds requires much energy, with the result that the energy return on energy input is intrinsically poor. Steam methane reforming is similarly troubled. The separation of the hydrogen from the natural gas and the steam requires heat, a significant part of which is lost, and the sequestration of the resulting carbon dioxide puts a parasitic load on the process that renders the energy return still lower.

One can, on the other hand, be more optimistic about the prospects of addressing the *practical* difficulties of hydrogen: namely the low energy density, the propensity to leak, the high boil-off rate, the need to transport it at very low temperatures or high pressures, and the low ignition energy, not to mention the weight of conversion devices, such as fuel cells. Given time and resources these might be engineered around. The pace of this development could, with luck, be accelerated by coercive policy, though with the probability of corresponding inefficiencies and the increased risk of a major accident. Adoption should certainly not run ahead of the learning curve. That said, it must be granted even by the most cautious observer that the practical defects are not necessarily a *fatal* objection to the use of hydrogen as a mass-market energy carrier, though they are a very considerable obstacle today and are likely to be so for some time.

MacKay was and remains right. Hydrogen is an inefficient energy carrier with a host of practical defects, and its short-run future is still entirely dependent on mandates and coercions, as Ekins noted.

But hydrogen should not be hastily written off for the longer term. Marchetti's well known proposal of using thermochemical processes to split water using very high temperatures generated by large, dedicated nuclear reactors is plausible. This is because if the energy used is sufficiently cheap, the efficiency and fuel competition problems that currently inhibit hydrogen deployment are much less important. Cheap input energy also means that sufficient wealth is generated to deal with any practical difficulties involved in the use of hydrogen.

To deliver cheap input energy, Marchetti planned to create large production centres, much bigger than the current generation of nuclear electricity generators, which are limited in size by grid operation concerns, which arise because although a giant nuclear electricity generator is engineerable, it would almost certainly be the largest single generator on the network, and thus the single largest credible loss of generation. To insure against the possibility of it developing a fault, the system operator would have to ensure the rapid availability of equivalent reserve generators. This is costly and in practice limits the size of nuclear power stations. A nuclear thermal plant designed to break down water into hydrogen would not be restricted in this way because it would operate independently of the electricity network. Furthermore, such plants could also run at high load factors, storing hydrogen for later use or export, without reference to market demand at any moment. Large size and high utilisation means much cheaper hydrogen, and thus a possible road to viability. Indeed, only nuclear technology offers the prospect of the necessary productivity, whereas taking surplus, low-value electricity from unproductive sources such as wind and solar will only impose costs for which the collected energy cannot pay. Marchetti himself ruled out the renewable route with the remarks, telling from a physicist, that they 'do not scale' and were too 'thin and unreliable' to serve as the energy source for a society using hydrogen as its medium of energy transport. That is correct.

It remains perfectly true, of course, that the nuclear heat could be more efficiently converted into electricity, and this competition would in many areas make the adoption of hydrogen unattractive. But it would not do so in all cases. Aviation seems very unlikely to be able to employ electrically driven propulsion on the large scale, and sea freight and HGVs

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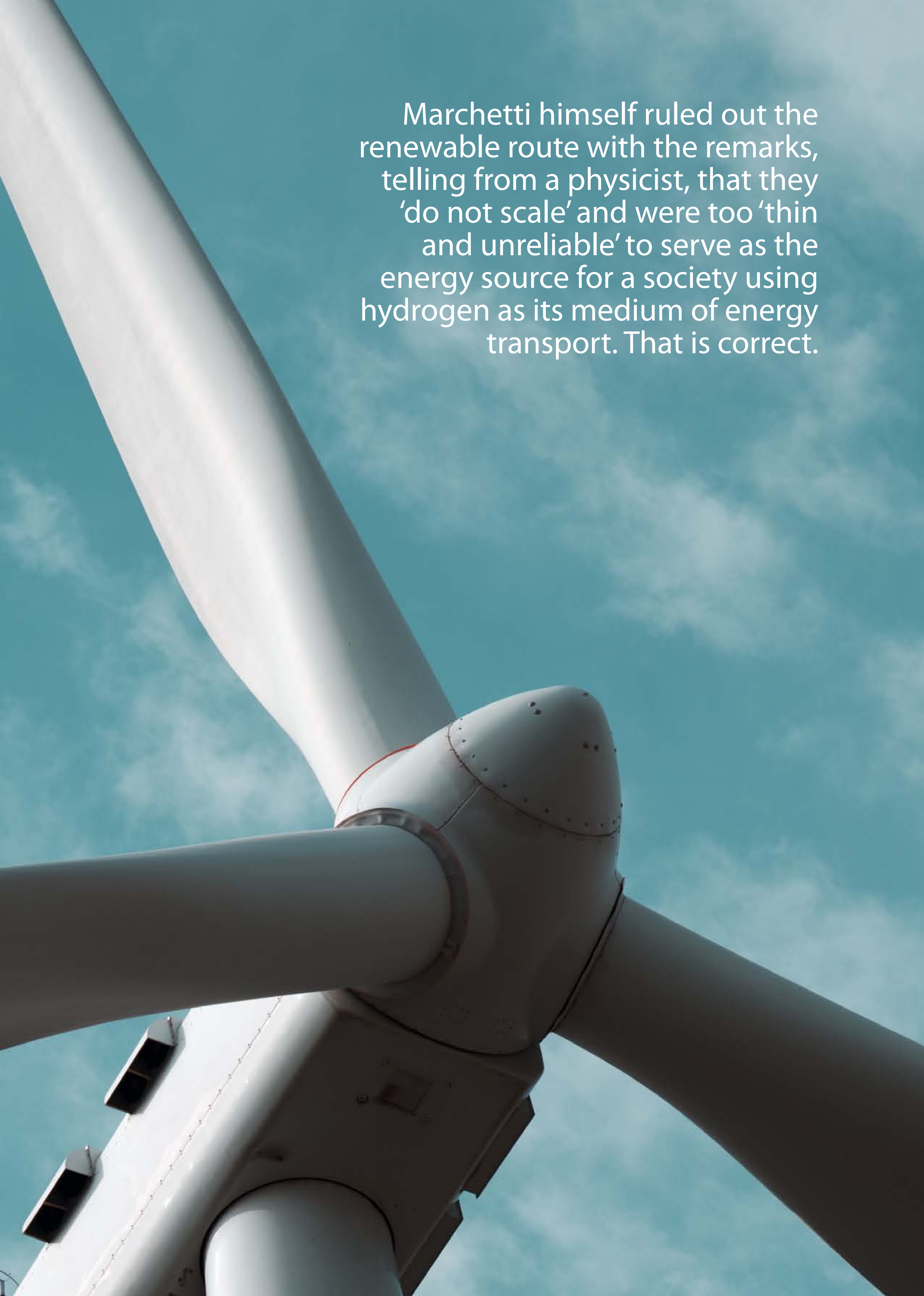


will also be resistant to electrification so long as batteries remain heavy and their energy capacity small, as at present.

These considerations form the background physical constraints and opportunities determining prospects for the development of a hydrogen economy, and are largely unchanged from the 1970s. What has changed, however, is the policy context, which has been transformed in the last five years. In the recent International Energy Agency (IEA) report backed by the government of Japan, a publication that is itself a symptom of increasing political enthusiasm, Fatih Birol, the agency's Executive Director, remarks that hydrogen is 'enjoying unprecedented momentum', and 'could finally be set on a path to fulfil its longstanding potential as a clean energy solution'. Dr Birol goes on to suggest that governments should 'seize this opportunity', clearly implying that the current momentum is independent of government action. That may be a pleasant thing for him to say, but it is clearly not the case. The current momentum is itself an outcome of policy pressure and circumstances. The new factor is not technological, or even internal to the proposed hydrogen economy; it is rather that international climate policy has run into severe obstacles, particularly because of the uncontrollable nature of renewables, and the difficulty of converting heavier transport and much industrial and even domestic heating to carbon-free energy. Hydrogen is seen as the remedy to those problems.

Furthermore, the short-term circumstances of Japan mean that the government is particularly interested in being able to import hydrogen rather than fossil fuels, making it low-carbon at the point of consumption. Of all the world's major economies it has the weakest renewable energy resources, and for the time being at least, public opinion is opposed to nuclear energy. This makes it extremely hard to address the very particular circumstances that face the Japanese economy in the short and medium term as the result of the Paris Agreement (discussed below in The Special Case of Japan). Hydrogen could address these problems, and at the same time, if hydrogen is adopted internationally, maintain Japan's industrial edge in key areas, by ensuring that its competitors were similarly disadvantaged. In addition, and as we shall see, Japan's interest is both deeper and more complicated. Since the 1970s, Japan has worked towards a long-term future in which thermonuclear routes to hydrogen deliver energy autarchy. Thus Japan's short-run interest, while entirely rational from their own perspective, may not be a transferrable endorsement.

Combining these considerations, we can see that if hydrogen is 'back', it is not because of a technological breakthrough but because of a climate policy deadlock. Whether hydrogen is capable of resolving this impasse is extremely uncertain, not least because international commitment to the hydrogen future is, Japan aside, weak.

Policy and the hydrogen research economy

As we have seen, the IEA describes the present as a time of 'unprecedented momentum for hydrogen',[5] but the data offered in their study provides only equivocal support for this claim. While it is true that an increasing number of countries now have policies supporting the use of hydrogen as an energy transport medium, with the present total being some fifty countries globally,[6] and that there have been numerous policy announcements since early 2018,[7] close examination shows many of these to be bureaucratic rather than industrial in character, and the associated funding to be modest. These appear to be tokens of interest, rather than fundamental commitments. For example, France has a 'Hydrogen Deployment Plan', but has allocated only €100 million to its support; Norway has funded an experimental hydrogen-powered ferry; the Netherlands has published a 'Hydrogen Roadmap'; the Kingdom of Saudi Arabia has announced the construction of their first hydrogen refuelling station; and the UK has announced two funds for innovation in low-carbon hydrogen supply, but has put only £40 million towards their support. More substantially, perhaps, China has designated Wuhan as a 'hydrogen city', and has promised 300 hydrogen filling stations by 2025, and 5,000 fuel cell electric vehicles (FCEVs) by 2020, as well as recommitting to an earlier target, announced in 2015, of 1 million FCEVs by 2030, with 1,000 fuelling stations. Japan has hosted the world's first hydrogen energy ministerial, and the Development Bank of Japan has launched 'Japan H2 Mobility', with the aim of building 80 fuelling stations by 2021. In the United States, meanwhile, substantive new developments are limited to California, where changes to the Low Carbon Fuel Standard require a still greater reduction in carbon intensity by 2030, and the California Fuel Cell Partnership has presented targets for a million FCEVs and 1,000 fuelling stations by 2030.

The statements of intent, however, are not supported by large-scale spending and actual deployment. The most telling information offered by the IEA relates to the RD&D‡ spending since 2005 (see Figure 1).

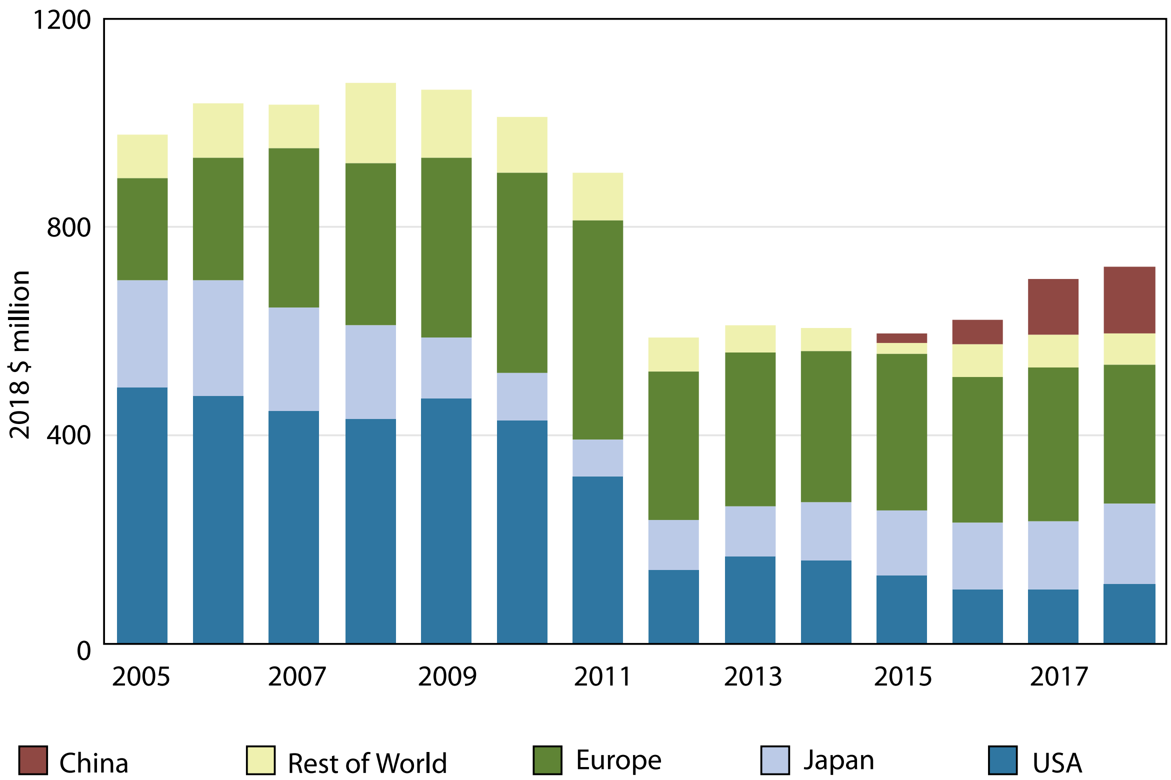


Figure 1: Government research into hydrogen and fuel cells.
Research, design and development budgets. 2018 figure is estimate. Source: IEA 2019, p. 20 and IEA 2018a, RD&D Statistics. IEA Note: 'Government spending includes European Commission funding, but does not include sub-national funding, which can be significant in some countries. RoW = rest of world.'

‡ Research, design and development.

Global spending was around \$1 billion a year from 2005 until 2010, with a peak in 2008, but spending fell sharply after 2010, to around \$600 million a year, and though global spending is now rising, topping \$700 million in 2018, this is due almost entirely to an increase in Chinese spending since 2015. The continuing attitude of the United States can be judged from the fact that while it was spending over \$400 million a year from 2005 to 2010, between half and one third of the global budget, this fell to about \$100m a year in 2012 and has never recovered. Even Japan cut its funding from 2008 onwards, and though it seems to be gradually increasing its disbursements, the total level of spending is only now, a decade later, approaching the earlier record spending of 2006. The European Union is distinguished in this context by having cut its spending less than any other governmental body.

The 'unprecedented momentum' that the IEA finds is fundamentally verbal, with the funds committed telling a much less bullish story. Perhaps that is entirely reasonable, and simply reflects the fact that total research spending over the period 2005–2018 has been significant, at about \$11.5 billion, and taxpayers in these various jurisdictions have a right to see a limit on support for what is, after all, not a completely new departure but only an inflection of an established industry. Hydrogen has been used as an energy carrier since the early 19th century, as an element in 'town gas' derived from coal and oil, and its industrial manufacture is well-established. Indeed, given the history, and the existence of a spontaneous commercial production system for hydrogen for various non-energy purposes, one might say that research spending at this level has been extremely generous, and the returns rather modest. From such a base, and with such encouragement over the last decade, it does not seem unreasonable to expect unsupported, organic growth. But in fact, there is no such thing. The current renaissance of interest is driven globally by the Paris Agreement and the consequent intense political pressure to reduce greenhouse gas emissions to a bare minimum by addressing all the most difficult remaining areas, particularly shipping, process heat, and non-passenger transport and traction. The example of the UK is representative and may be taken as typical. As discussed in detail below, the existing aspiration of an 80% reduction in emissions required only about 50 TWh of hydrogen, almost entirely for shipping and mostly for international shipping. The recent adoption of a 'net zero by 2050' target increases this to 270 TWh, and extends hydrogen use to industrial heat, HGVs, heat in buildings, and even agricultural vehicles. What is true of the UK is also true elsewhere. The global momentum detected by the IEA is policy momentum, not autocatalytic technological growth. Reaching for hydrogen is a desperate measure motivated by extreme climate policies that leave no other options.

But one does not spend \$10 billion without seeing some consequence, and the most striking result is to be found in academic research. There may only be trivial numbers of hydrogen vehicles on the roads, and very few places to refuel them, but the academic literature around the hydrogen economy is growing at a rate surely unequalled in any other field (Figure 2). *The International Journal of Hydrogen Energy*, the house publication of the International Association for Hydrogen Energy[8] and published by Elsevier, is a standard journal in the field. Counting the number of pages in the issues published is a simple but far from useless measure of the strength of academic interest, and the results speak for themselves. This journal commenced publication in 1976, emerging from the first hydrogen craze, and is now in its 44th annual volume. It began relatively modestly with a few hundred pages a year, but in 1990 reached 1,000 pages annually; by 2006 it was publishing 2,000 pages per year. In 2009/10 it published 10,000, and then 15,000 in 2011. This upward trend continued, with 2017 providing the current record of 31,000 pages. In 2018, it slumped back, but the journal was still adding another issue of about 500 double-columned pages *every week*, totalling some 23,586 pages annually. At a rough count this journal is currently publishing new hydrogen research at a rate of about 14 million words a year, not counting tables and charts. There are 19,452 pages published in 2019 so far (to the end of July), and there will be sixty issues this year. It could be a remarkable harvest, and arguably good value at £4,104 ($5,415) annually for the print edition.

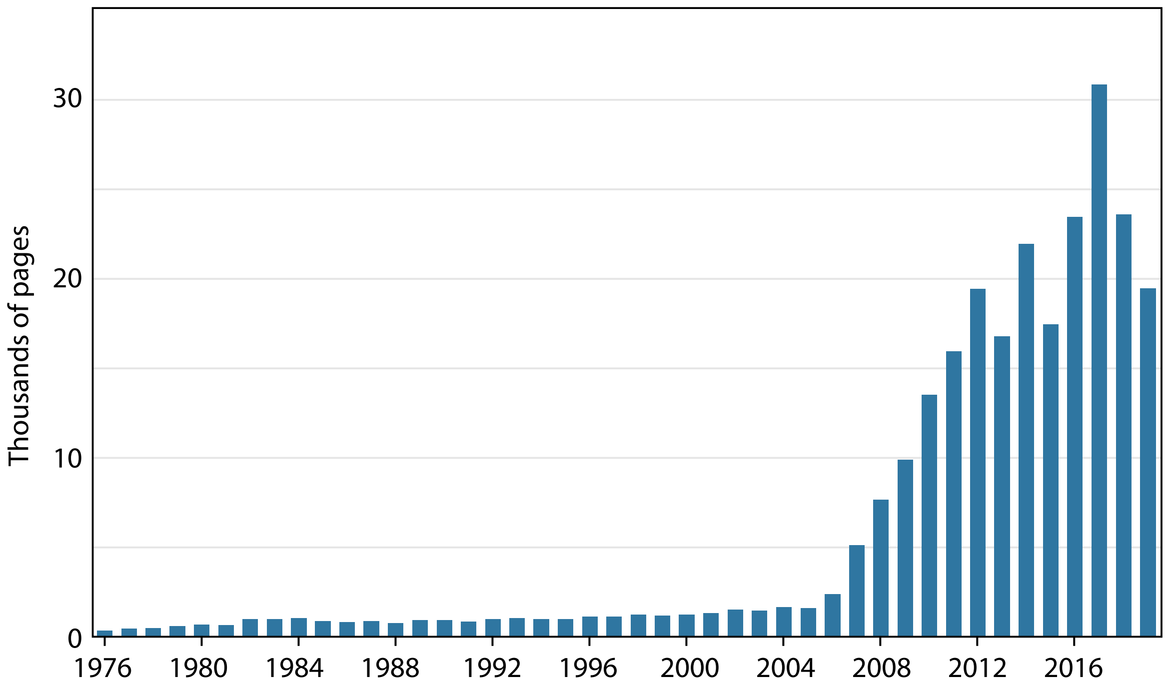


Figure 2: The growth of hydrogen energy research.
Pages per year published in the *International Journal of Hydrogen Energy* (1976 to 2019 (July)).
Source: Data collected by the author from volume listings at ScienceDirect
(https://www.sciencedirect.com/journal/international-journal-of-hydrogen-energy).

The volumes of material emerging are daunting, and it is no exaggeration to say that it would be a full-time job simply to read every article published in the *JHE*. Yet the problems this research addresses are as persistent and stubbornly unsolved as ever. Spontaneous growth is still elusive, and the vast bulk of academic writing is itself an indicator of that fact, for if hydrogen technologies were genuinely close to commercial application there would be less academic discussion and more concrete action. This is intellectual activity unconstrained by the discipline of real-world deployment.

Comparison with the growth of fossil fuels is instructive. In 1700, coal comprised 50% of Britain's total primary energy supply, rising to this level from almost nothing over a period of two hundred years. This astonishing augmentation, one of the most important events in world history, was not based on a research literature; indeed, it is doubtful if it was based on any kind of theoretical research at all. It happened because adopting coal generated wealth for those who did so. Good wine needs no bush, no advertisement, as the proverb says, and an authentically attractive technological development, in energy or anything else, needs no academic support. Indeed, the giantism of the *International Journal of Hydrogen*

Energy should be a cause of concern. If it is possible to say so much and at the same time do so little, it seems reasonable to infer that the hydrogen economy is a long way from practical reality.

To this observation it might plausibly be objected that Japan, the source of a great deal of hydrogen research, appears to be serious and is actually building a hydrogen infrastructure. There is some truth in this appearance, but in this matter, as in many others, Japan is a special case.

The special case of Japan

As observed above, hydrogen is the last resort, the only way to decarbonise the most awkward of sectors – shipping, trucks, and industrial process heat – as implied by the goals of the Paris Agreement and so insouciantly supported by the world's politicians. It is not accidental that the sole major economy to show only a residual and perhaps waning interest in hydrogen, the United States, is the only one to have turned its back on Paris. Supporters of the Paris Agreement are driven to adopt hydrogen. But not all national policies are the result of careless self-snookering. Some are deliberate and, though risky, entirely rational. The government of Japan is, for example, perhaps the most genuinely enthusiastic international proponent of the hydrogen economy. It funded the IEA's recent study,[9] published to coincide with the G20 in Osaka, and intends to use the 2020 Olympics to showcase Japanese hydrogen technologies. There are already 275,000 fuel-cell co-generation systems, albeit presently fuelled with natural gas, installed nationwide. Japan's 'Basic Hydrogen Strategy', announced in 2017, projects imports of hydrogen for energy rising from 0.2 TWh per year in 2020 to 12 TWh by 2030. Some, and the UK's CCC is an example,[10] might point to Japan's lead, and infer that if a first-rate technological society has approved hydrogen as an energy carrier, and is working towards a hydrogen economy, then we can take their endorsement as a certificate of feasibility. This would be naïve, not because Japan is likely to have blundered into error for ideological reasons – this is not Germany after all – but because the circumstances and national strategy of Japan is tailored for their needs alone, and what may make sense from their perspective could be a very ill fit for other states. Consider the situation: Japan is an extremely sophisticated societal structure, and its export economy relies on the manufacture of highly improbable objects. By quite a large margin it is the most complex economy on earth.[11] It has long been an energy importer and can be so because its trade in high value, high margin components and products enables it to pay the energy bill as well as supporting its own population. Since it is dependent on trade, and therefore wishes to maintain good relations with its customers, it is sensitive to international pressure requiring it to contribute to global efforts to reduce greenhouse gas emissions. Unfortunately, it has few options. Limited land area rules out biomass, mountainous terrain rules out onshore wind, its coastal waters deepen so rapidly that offshore wind is precluded except on experimental, hazardous and expensive floating platforms, and macroscopic adoption of solar has proved to be wildly costly but has done no more than scratch the surface of Japan's energy needs. Nuclear generation, controversial even before Fukushima, is now so tainted that even at best will take decades to recover in public esteem. Lastly, though perfectly capable of engineering carbon capture from gas and coal, it has no economic options for carbon sequestration within the national territory.

Energy imports must therefore continue, but if so, how can Japan be made clean? Interconnection of its electricity system with the Asian landmass is ruled out by military and political considerations and could in any case never be more than a minor element in total supply. How then to import fossil fuels in a clean way? The logic points inexorably towards hydrogen. Clean at the point of consumption, addressing urban pollution problems and global emissions targets, hydrogen gives Japan a perfect international profile while leaving its overseas hydrogen manufacturers to deal with the provision of the necessary and gigantic water supply, the tricky location and management of the industrial plant, and most of all with the sequestration of carbon dioxide and the not inconsiderable and fluctuating cost of any residual emissions that cannot be captured. Cleanliness becomes an upstream problem. While many of the additional costs would be pass-through costs, Japan would hope that long-term contracting, market power, and skilful hedging would ensure that the supplier was obliged to absorb a good deal of the downside risk.

This is not a strategy without its dangers, and the additional costs of hydrogen are certainly threatening, but from the Japanese perspective the hazards are to a degree offset by the potential for extensive engagement in the trading of manufactured items relating to the hydrogen economy – fuel cells, hydrogen vehicles, electrolysers, reformers, storage tanks, and control systems, for example – all areas in which Japan's industries have huge strengths that may be expected to increase as the domestic hydrogen sector expands and is tested on the domestic public. This has, after all, worked well with motorcycles, cars and televisions, to mention only the most obvious instances. Furthermore, the generally high value of the Japanese economy means that it can reasonably expect to pass through at least some of the additional energy cost to consumers of its exports, and in a world economy dominated by climate policy rather than fundamental economics, international rivals may be commercially disabled through carbon pricing. Overall, hydrogen seems from some perspectives to be a competitive option for Japan as well as providing medium-term alleviation of an acute diplomatic problem.

Moreover, though obviously motivated by short-term, tactical concerns, it would also act as a bridge to the long-contemplated future of energy autarchy, where hydrogen forms the universal societal energy carrier, and high-temperature nuclear reactors are its prime source. Short-term benefits aside, Japan's current enthusiasm for hydrogen is perhaps best understood as the first step towards the nuclear hydrogen future that has been on its bureaucratic and academic mind for so long. Tactics would become strategy.

It is certainly the case that Japan's interest in hydrogen is of long standing, preceding by many years any significant concern about greenhouse gas emissions. Marchetti's well-known vision of an economy supported by large high-temperature reactors on Pacific islands, all generating hydrogen for Japan, gathered supporters at the highest level in the early 1970s. As Marchetti himself recalled:

> At the beginning of the seventies the president of JAERI, the Japanese nuclear organization, did transit through [Euratom at] Ispra and I had the honor of lunching and chatting with him. The Japanese were developing a high-temperature reactor and had the intention of carrying out methane steam reforming with the high temperature reactor they were building as the Germans were doing with their pebble-bed reactor. He was instantly excited at the prospect of reforming the steam itself, and that was the beginning of a fruitful interaction with Japan. For them I wrote what I consider to be the manifesto of the hydrogen economy. As they have the sun in their flag and the emperor at the helm, they like to have a very long term objective with a clear roadmap. I gave them the dream of becoming a sort of Middle East, exporting energy to everybody on top of becoming energy-independent.[12]

This manifesto[13] was published in the *Chemical Economy & Engineering Review*, the house journal of the Chemical Economy Research Institute of Japan, and is still a classic in the field. The seeds sown by Marchetti immediately took root, and the Ministry for International Trade and Industry (MITI) initiated the 'Sunshine Project' in 1974, with funding of $2 billion and the intention of running the scheme until 2020 to develop hydrogen as a global energy carrier.[14] Although the spending never matched the promises, the commitment remained and in 1993 the Japanese government returned to the matter with a new initiative, the New Sunshine Project, embracing the WE-NET program for international trade in hydrogen renewable energy.[15] Interest has continued, quietly but unabated ever since, and is located under the aegis of the hugely influential and generously funded government agency, the New Energy and Industrial Technology Development Organization (NEDO).[16]

We can conclude, therefore, that current Japanese interest in hydrogen is simply the latest iteration of a consistent long-term national energy plan. Climate change policy may be the proximal cause, but the distal goal is autarchic prosperity and national security, and by developing the demand side – conversion devices, and the delivery system, filling stations and techniques, transportation networks and methods – Japan may be able to solve the chicken-and-egg problem notorious in the hydrogen debate. The demand for hydrogen and a means of delivering it will have been created. There can then be confidence in building large nuclear stations designed to crack water. In the meantime, they can stay on good terms with the international community by toeing the lines of the Paris Agreement. But in the short term the hydrogen has to come from other and highly problematic sources, effectively limited to the steam reforming of natural gas and electrolysis of water. These are the problems that Japan's approach hopes to keep safely distant in Australia and other hydrogen-exporting countries.

Production

Being highly reactive, elemental hydrogen, H_2, is found in only small quantities in nature on the earth's surface but is present in a very wide range of compounds. There are thus a substantial number of routes to hydrogen production, and many of these have been employed over the last two centuries in order to produce hydrogen for use as an industrial feedstock, or as war *materiel*. As we will have occasion to note again later in this study, much of the rhetoric around hydrogen relies on ignorance of history in order to generate an aura of spurious novelty and excitement, and thus of virgin territory and expanding possibilities. In fact, hydrogen research is well advanced, and in some respects the prospects are narrowing as scientific understanding improves. Teed, for example, provides a useful summary of the state of hydrogen production in 1919, a moment when the number of viable routes to the production of hydrogen seemed larger than it does now.[17] He lists, for example, the application of sulphuric acid to iron and to zinc, and also the application of alkalis, such as caustic soda, to zinc, aluminium and silicon. For production of very small laboratory quantities of hydrogen, he notes that metallic lithium, sodium, and potassium, and magnesium, calcium and strontium, and barium can all be placed in water. For larger volumes of very pure hydrogen at high pressure, he suggests the process then known as the Bergius process (a term now applied to the production of liquid hydrocarbons from brown coal), which involves the heating of iron and water to temperatures over 350°C at a pressure of 3,000 psi, or the iron contact process, responsible in 1919 for most of the global industrial production of hydrogen, where steam is passed over heated metallic iron. A variant of this process using barium sulphide to decompose the steam was also employed at this time. Teed also discusses, amongst others, catalytic processes for steam decomposition, the production of hydrogen from acetylene, hydrocarbon oils, and even from starch. The many varieties of electrolytic cell are also discussed, twenty-five patents being listed between 1890 and 1914.

This was clearly a period of strong interest in the production of hydrogen, much of the demand being anticipated to be for military purposes. Teed was himself a major in the recently formed Royal Air Force, and though he notes the growth of hydrogen markets for the hardening of oils and the synthetic production of ammonia, it was balloons and airships that seemed to him the principle future demand.[18] The nature of military demand, for which cost is no object, explains Teed's interest in such a broad range of production methods, many of which would be ruled out for commodity production by overall expense, the cost obviously meaning that there were other strong demands for the scarce resources required. In fact, even as Teed was writing, most of the methods he described were on the point of being rendered of marginal interest by the emergence of SMRs, which, and this is remarkably instructive, he does not describe. The German chemical company BASF had in fact placed its first patents for SMR in 1913, with IG Farben following in 1927. In 1930, Imperial Chemical Industries (ICI), Standard Oil, and IG Farben agreed to develop SMR jointly, and Standard Oil installed three reformers in Bayway in the United States in that year. ICI did not build a reformer until 1936.[19] SMR would quickly come to dominate the field, with only electrolysis providing competition in certain niche applications, which is broadly speaking where things stand today.

Several relevant points emerge from this history. Firstly, in spite of the fact that the Genevan doctor, Turquet de Mayerne first made hydrogen, or 'inflammable air' as he called it, in 1650 from sulphuric acid and iron filings,[20] the industrial production of pure hydrogen on a larger scale is comparatively new, with development of the currently dominant technique, SMR, being largely driven by military demand for the nitrates required for the manufacture of explosives and fertilisers during the Second World War.[21] Indeed, putting technology aside, much of the most advanced *science* of hydrogen is of 20th-century origin.[22] So hydrogen production is both mature, and, paradoxically, still promising. It would be pessimistic to rule out significant advances in the development of new methods of hydrogen production. Then again, the production of hydrogen is certainly not in its infancy, and we would be wise to reject as propaganda the claims to radical discontinuity or novelty. It would be rash to say that it is mature and exhausted of potential, but our expectations should be realistic.

This current state of the technologies is well covered in the IEA's study, and the interested reader is referred to that discussion for details.[23] While there are a variety of methods of production, the sources are few in number, being limited to either water, fossil hydrocarbons or biomass. We can rule out biomass, except as a niche contributor, on the grounds that the potential for large-scale production is inadequate to the global ambitions entertained, and because there are in any case competing demands for land and water for biomass production, including food, and the entirely understandable desire to limit human use of the wild land resource.

The remaining routes are thus permutations on the existing themes of water and fossil hydrocarbon transformation, currently focused on water electrolysis, natural gas reforming, and coal gasification. All, without exception, are ways of using an energy source to break an existing chemical bond between hydrogen and other elements, producing free molecular hydrogen, which can then be recombined with oxygen to release energy. This is straightforward chemistry, particularly so for SMR and coal gasification, and no dramatic surprises

The deeper problems with hydrogen are all associated with its production and delivery to end consumers

Part of an SMR plant

are to be expected. It would be unreasonable to expect anything other than incremental improvements.

Of the three electrolytic routes, alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolyser cells (SOECs), only the latter is novel and undeveloped, and the promise of SOECs is largely grounded in their high operating temperatures, and thus in the potential for attractive electrical efficiencies. But the temperatures currently under consideration, 650–1,000°C, are genuinely high,[24] which may have implications for equipment life and simplicity of operation. One area in which current and proven electrolysis methods have potential for improvement is in the use seawater. This is currently ruled out because it has a highly undesirable by-product, chlorine. Successful research in this area would avoid the current requirement for fresh water, for which there are other important uses, or for desalination, which adds cost and restricts the geographical location of the plant. Research on the use of seawater is still at an early stage.[25] PEM electrolysers are an established technology capable of producing high pressure (100–200 bar) hydrogen, and may be attractive as onsite generators, though they are expensive due to short lifetimes and the need for platinum and iridium catalysts.[26]

What strikes one in reviewing the production methods currently available, or likely to become so in the near term, is that they are all *commodity production processes* not energy generation systems. They are characterised by high capital expenditure, low productivity, and significant energy losses. The resulting hydrogen is valuable as a commodity, for non-energy purposes, but is an expensive energy carrier. The incremental improvements to which these processes are limited are worthwhile in a commodity production context, but are minor, verging on the insignificant for an energy process.

In summary, just as it is an error to focus our attention on the hydrogen conversion systems in the hope of finding the transformative technological breakthrough, for progress in that area is easy but irrelevant, so it is an error to look for this breakthrough in the chemical details of commodity production processes. For hydrogen to be viable as an energy carrier, the system must be radically altered in its fundamentals, that is to say in the *source of the energy that is to be carried*. It is this insight that lies behind Marchetti's proposal for high-temperature reactors and thermo-chemical routes, and which gives his work its enduring interest.[27]

Nevertheless, since the current adoption of hydrogen is being driven by short-term imperatives derived from climate policy, these long-term vistas are beside the point. It is to the currently available, commodity production processes that policymakers will be looking to generate the hydrogen required to reduce emissions in otherwise untreatable sectors. This will obviously be expensive, and it will be problematic in a number of ways. A case study of the consequences of haste is instructive, and in the following section we will examine in detail the contribution of hydrogen to the UK's net zero by 2050 target, as envisaged by the CCC.

2 Committee on Climate Change proposals for hydrogen and the net zero target

The UK government's independent advisor, the CCC, has projected that the ambition of net zero emissions by 2050 will require the UK to produce and use about 270 TWh of hydrogen per year in 2050, comprising 225 TWh from SMRs and 44 TWh from electrolysis.[28]

These quantities have apparently been calculated on a higher heating value (HHV or gross calorific value) basis, as employed in the CCC's earlier study, *Hydrogen in a Low Carbon Economy* (2018).[§] Indeed, the Committee's recent work on hydrogen as a component in the efforts to deliver the net zero target for 2050[29] must be read in conjunction with the earlier work to be fully intelligible.

270 TWh represents an increase of nearly 220 TWh over and above the hydrogen consumption projected in its Core Scenario (52 TWh for shipping and 2 TWh for buses). The Core Scenario represents what the CCC calls 'low-cost low-regret options that make sense under most strategies' required for an 80% reduction of emissions by 2050. This was the state of policy before the adoption of the net zero by 2050 target, which requires further policy actions. These are categorised under the headings of 'Further Ambition' and 'Speculative Options'. The CCC admits that the 'Further Ambition' measures are 'more challenging' and 'generally more expensive' while the Speculative Options 'currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability.'[30]

Before net zero, the extreme measures of the Further Ambition and Speculative Options scenarios were interesting but by no means indispensable possibilities. With a net zero target, many of them – and hydrogen is a good example – become indispensable. As the CCC itself writes: 'Low carbon hydrogen moves from being a useful option to a key enabler'.[31]

While it is fair to acknowledge that hydrogen is not the only extreme measure required, it is clear from the committee's summary that the Further Ambition scenario required to deliver net zero emissions by 2050 is in truth *critically* dependent on the use of hydrogen:

> A significant low-carbon hydrogen economy will be needed to help tackle the challenges of industry, peak power, peak heating, heavy goods vehicles, and shipping emissions. CCS will have a larger role, including in industry and at scale in combination with biomass. Major changes are needed to how we use and farm our land.[32]

As might be expected, this shift implies a significant increase in the marginal cost of emissions abatement, a point on which the committee is refreshingly candid:

> Some other changes have higher costs, such as switching from natural gas to hydrogen, applying CCS, installing heat pumps to replace gas boilers across the existing housing stock and GHG removals. Many of the options required to get from an 80% to a 100% target currently appear relatively expensive (e.g. with costs of around £200/tCO_2e).[33]

Such costs are well in excess of most estimates – even extreme ones – of the social cost of carbon, meaning that the policies required are more harmful to human welfare than the climate change they aim to prevent. The adoption of such policies is, of course, economically irrational. Nevertheless, the committee proposes precisely such measures.

Hydrogen, and the CCS necessarily associated with it, are a very large part of this striking increase in marginal cost, a point which is also granted by the committee:

> Many of the costs would involve increased investments, generally offset by reduced fuel costs. For example, wind and solar farms are costly to build, but avoid the need to pay for gas and coal; energy efficiency involves an upfront cost followed by reduced energy use.

§ The higher heating value (HHV), or gross calorific value, of a fuel is the heat released by its combustion and the return of the products of combustion to 25°C, which thus includes the heat released by the condensing of any water vapour. This is the preferred metric for almost all exact scientific or engineering analyses. The lower heating value (LHV), or net calorific value, is calculated by subtracting the latent heat of any water vapour produced during combustion. It is a useful rule of thumb for estimating the heat available under normal operating conditions in many though not all cases.

CCS and hydrogen are important exceptions requiring both increased upfront spend and higher fuel costs.[34]

Nevertheless, such measures are logically required, since the residual emissions from previous policies cannot be abated by further measures of the same kind. For example, the electrification of transport has already been taken to an extreme in previous scenarios, and cannot be extended further into commercial traffic, particularly HGVs. The adoption of hydrogen is therefore required, as the committee explains:

> By 2035 at the latest all new cars and vans should be electric (or use a low-carbon alternative such as hydrogen).[35]
>
> HGVs are harder to decarbonise. Our new research suggests that it is possible to get to very-low emissions by 2050 by switching most of these vehicles to hydrogen power or electrification. A hydrogen-based switchover would require 800 refuelling stations to be built by 2050 and electrification would need 90,000 depot-based chargers for overnight charging.[36]

A similar approach is taken towards the provision of heat in buildings. The committee explains that the Further Ambition scenario:

> …requires roll-out of technologies such as heat pumps, hybrid heat pumps and district heating in conjunction with hydrogen, and new smart storage heating, combined with high levels of energy efficiency. New homes should not be connected to the gas grid from 2025. By 2035 almost all replacement heating systems for existing homes must be low-carbon or ready for hydrogen, such that the share of low-carbon heating increases from 4.5% today to 90% in 2050[37]

In summary, the 270 TWh of hydrogen proposed is a universal aspirin, addressing headaches in a number of areas that are otherwise impossible to decarbonise within the specified timeframe. Put more technically, it is an arbitrary free parameter allowing the committee to produce a perfect fit between the policy proposals and the required emissions reduction curve over time. By any standard, curve fitting of this kind is poor policy analysis.

The breakdown of these areas of hydrogen deployment is as follows:

- 17.5 TWh of hydrogen would be used as ammonia in domestic shipping, and 52.5 TWh as ammonia in international shipping.
- 120 TWh would be used as a heat source for industry, replacing coal, oil and natural gas, and some 53 TWh is envisaged as supplying peak heat to buildings, providing a supplement to electrical heating via ground source heat pumps when they prove to be inadequate in cold weather. The aim here is to prevent households turning to resistive heating (electric bar heaters) and putting additional load on the electricity network. The CCC estimates that without hydrogen peaking the peak electrical heating load would require approximately 100 GW of additional electricity generation capacity, capacity that would of course be almost idle for the rest of the year, with obvious deleterious implications for cost.[38]
- HGVs would consume 22 TWh of hydrogen, agricultural vehicles 2 TWh, buses some 3 TWh, and trains about 0.3 TWh.
- A further 2 TWh is envisaged as being employed as either as hydrogen or ammonia in electricity generators to provide peak generation.[39]

While there is some doubt over the readiness and affordability of conversion devices – mostly fuel cells – for each of these uses, this is not the principal area of concern. As we have already noted, the end use of a highly combustible gas is unlikely to prove beyond the abilities of the global engineering profession, and indeed some real progress has been made in this area.[40] Further good news in the fuel cell sector is to be expected, but largely irrelevant, since the deepest and most intractable problems with hydrogen are all on the production side, with significant additional difficulties in its subsequent storage, transmission and distribution. The committee's own studies[41] are short on specific details of what is required to deliver its ambition for hydrogen, but by reference to its earlier study,[42] and other more recent studies such as that of the IEA,[43] it is possible to shed light on questions such as the capital and operating costs (excluding fuel) of the required hydrogen production plant, as well as the emissions sequestrations volumes, and energy and water requirements.

Energy and production capacity requirements

As noted above, the quantities of hydrogen specified are reported by the CCC on an HHV basis and assume an efficiency of 80% for an SMR plant fitted with carbon capture.[44] Since SMRs are considered to be about 90% efficient on an HHV basis,[45] a penalty of about 10 percentage points seems to have been applied to take account of the operation of the carbon capture system.

Assuming that the CCC's estimate of efficiency is correct, 225 TWh of hydrogen would require 282 TWh of natural gas as feedstock and process fuel source. This process is technologically mature, and there is no reason to expect any very significant improvement in process efficiency. Indeed, the IEA does not expect any technological progress in efficiency for systems, with or without carbon capture, up to 2030 or in the longer term.[46] We should not expect jam tomorrow, or at any future date, however distant.

With 20% losses in conversion, it is obvious the hydrogen output is unlikely to be able to compete with its own fuel stock, natural gas, where natural gas can be used directly, and this is true without accounting for the capital and operational costs of the SMR, or the cost of transportation and any hydrogen losses during transport.

The CCC projects that 30 GW of SMR capacity would be required, spread over 30–60 production sites.[47] Using the IEA's estimates of capital costs for SMR with carbon capture,[48] which are recent and plausible, we can calculate the capital expenditure required for the CCC's projected 30 GW of capacity as about £40 billion if built today, and about £30 billion if built after 2030.

The CCC has assumed an SMR load factor of 89%, which is high, given the presence of the carbon capture system and the consequent complexity, but perhaps not quite unrealistic. However, load factors of this level will require thorough maintenance and scrupulous operational procedures, leaving little leeway for cost shaving. The IEA suggests that annual operating expenditure for an SMR with carbon capture would be in the region of 3% of the capital cost,[49] so a capital cost for the SMR fleet of between £30 and £40 billion implies annual operating costs of between £0.9 and £1.2 billion.

The CCC further projects that 44 TWh of hydrogen will be delivered by electrolysis, from 6–17 GW of electrolytic capacity,[50] implying 600–1700 sites, and operating at load factors of between 30 and 90%.[51,‖]

‖ Readers should note that at other points in the CCC's text the required capacities are mistakenly reported as between 2 GW and 7 GW of capacity at 200 to 700 sites (CCC 2019b, 61). However, 2 GW of capacity cannot deliver 44 TWh of energy even with a load factor of 100%. This error would appear to be an unrevised trace of an earlier phase of the CCC's analysis.

Using the IEA's capital cost estimates,[52] we can calculate the capital expenditure required for these electrolysers as between £4 billion and £12 billion today, and between £3 billion and £10 billion beyond 2030. The IEA estimates that annual operating expenditure will be approximately 1.5% of the capital spend, so we can estimate annual operating costs of between £60 million and £185 million today, and £50 million and £140 million in 2030.

The IEA further suggests a lifetime of 95,000 operating hours for electrolysers, just over ten years, with very little likelihood of significant improvement even in the long term.[53] This indicates a relatively short capital refreshment cycle, and high cumulative capex over time – between £9 billion and £28 billion up to 2050 – giving a capital cost per megawatt little different from that for SMRs with carbon capture, which, in common with much industrial chemical plant, could be presumed to have a lifetime in the region of 30 years. It is difficult to see any economic justification for the use of electrolysers rather than SMRs, even with CCS, and it would appear that this method of hydrogen production is recommended partly as a route to diversity, which is understandable, but principally as a means to reduce the curtailment of uncontrollable renewables such as wind and solar. Operating in conjunction with wind and perhaps solar would explain the wide range of 30–90% load factor assumed by the CCC, and suggests that the lower load factors and the higher end of the capacity range are more likely than not. This matters because the cost of hydrogen produced by electrolysis from renewables is sensitive to both the electricity cost and the utilisation of the electrolyser, an expensive object as we have seen. The IEA notes that:

> Depending on local gas prices, electricity at USD 10–40/MWh and at full load hours of around 4,000 hours are needed for water electrolysis to become cost-competitive with natural gas with [carbon capture, utilisation and storage].[54]

Electricity from UK renewables is certainly more expensive than $10–40/MWh, and a full load of 4,000 hours per year is a 46% load factor, a level of productivity reached by only a small minority of wind farms in the UK, and by no solar sites. Electrolysers dedicated to specific wind or solar sites are therefore unlikely, and the optimising of utilisation of centralised electrolysers serving several renewable installations will be no mean feat. Since wind and solar output varies very considerably over all timescales, from minutes to years, it seems inevitable that the system will be faced with either underutilisation of the electrolyser or unavoidable curtailment of the wind and solar sites. Bearing this in mind, there would appear to be little chance that electrolysers in conjunction with renewables will ever be competitive with SMRs, with or without CCS, in the UK. The economic case for the production of hydrogen from electrolysers and renewable energy is extremely weak.

The CCC reports that the electrolytic component of its hydrogen scenario will require 60.1 TWh of electrical energy, implying a loss of 16 TWh or 27%.[55] As noted, 27% losses in conversion mean that the resulting hydrogen is very unlikely to be able to compete with its own feedstock where electricity can be used directly, and this is regardless of the cost of the electricity, and without accounting for cost of transportation and any hydrogen losses during transport.

The total capital expenditure required for the fleet of SMRs and electrolysers would be between £45 billion and £54 billion, if built today, and between £37 billion and £43 billion if construction is delayed beyond 2030 to take advantage of expected, though by no means certain, reductions in cost.

Overall, the 270 TWh of hydrogen would require energy input of 343 TWh, implying an energy loss of about 22% overall. This loss is prior to any further losses in transmission and

The total capital expenditure required for the fleet of SMRs and electrolysers would be between £45 billion and £54 billion distribution, and also to losses that may occur due to leakage or boil-off in local holding tanks, in fuelling stations and vehicles.

Emissions

The CCC reports that residual emissions from the 225 TWh of hydrogen produced by SMR will amount to 3.1 $MtCO_2$ per year, with a capture rate of 95%.[56] This implies total emissions of 62 $MtCO_2$ per year and sequestration of 58.9 $MtCO_2$. That further implies emissions of 11 $kgCO_2/kgH_2$, which is consistent with the 2018 report of the CCC.[¶] However, it is not consistent with the data in Figure 5.4 of the CCC report,[58,**] which implies a figure of 8.5 $kgCO_2/kgH_2$. It would appear that between its dedicated study on hydrogen of 2018[59] and the net zero reports of 2019,[60] the CCC has silently revised its estimate of emissions per kilogram of hydrogen from SMR from 11 kg to 8.5 kg. This may be a justifiable reduction, but it is unargued in the study. Furthermore, the inconsistency noted above suggests that this change happened recently and probably during the writing of the main study, not the Technical Report. In fact, the lower figure is close to the US Environmental Protection Agency[61] recommended emissions factor of 8.6 tCO_2/tH_2, and also the 8.9 tCO_2e/tH_2 suggested by the IEA.[62] However, there must be considerable doubt as to whether capture rates over 90% are remotely feasible, even if CCS is a practical undertaking, which is itself highly questionable. The IEA reports a 90% capture rate for the present time,[63] but does not envisage any improvement up to 2030 or even in the 'long term'. The CCC itself observes that 'If capture rates could only reach 85% emissions could be has high as 9.3 $MtCO_2$'.[64]

These doubts are crucial. CCS is, in the CCC's words, 'a necessity not an option' for the use of hydrogen, and the CCC regards hydrogen as a 'key enabler'.[65] Combining these observations, it becomes clear that the net zero 2050 target itself is a wager on the economic viability of CCS.

Given the uncertainties over the costs of the technology, the committee's position must be regarded as unjustified and unduly optimistic. One suspects that this position is not even reasoned but is an opportunistic response to the emergence of the net zero policy, and a further illustration of the invocation of an arbitrary free parameter. Indeed, as recently as November 2018, the CCC observed that 'If hydrogen from gas with CCS is deployed in large quantities, the emissions savings may be insufficient to meet stretching long-term emissions targets'.[66] 282 TWh of natural gas for hydrogen is clearly a large quantity, and the view of 2018 is plainly inconsistent with its present attitude. Yet nothing has changed technologically since those pessimistic words were written, except the political context.

Costs

As is obvious, hydrogen produced from SMR or electrolysis will be unavoidably more costly than its feedstocks, natural gas or electricity. The remaining question is by what margin it is more expensive when all relevant costs are taken into account. The CCC provides short-form analytic estimates of the levelised costs (i.e. without the costs of transmission, storage and

¶ The CCC's 2018 report[57] states the emissions intensity of SMR as 285 $gCO_2/kWhH_2$, which on an HHV basis (39.4 kWh/kgH_2) is 11 $kgCO_2/kgH_2$.

** In the Exhibits file to the CCC's 2019 net zero report (Figs. 5.4 and 5.5), the sequestered amount from SMR for hydrogen production is given as 46.2 $MtCO_2$. If this is 95% of total emissions, then the total is 48.6 $MtCO_2$ and the emissions factor is 8.5 $kgCO_2/kgH_2$.

distribution) of both SMR with CCS and electrolysis.[67] Table 3 is drawn from the supplementary data available behind the study.

Table 3: CCC central estimates for levelised costs of hydrogen production technologies.

	SMR with CCS £/MWh	Electrolysis £/MWh
Capex	4	4
Opex	3	7
Carbon and CCS costs	6	0
Fuel costs	25	63
Total	38	74
Lower bound	27	54
Upper bound	57	80

Source: Redrawn with additional calculations from CCC 2018, supporting charts and data.[68] CCC note: Cost of capital is assumed to be 10% across all technologies, and a 3.5% discount rate is applied to future costs. Load factors are assumed to be 90% across all technologies. Carbon prices rise to £227/tCO_2 by 2050. Gas prices: 39p/th [£13.31/MWh], 67p/th [£22.86/MWh], 83p/th [£28.32/MWh]. Electricity prices: £30/MWh, £46/MWh, £53/MWh.

Fuel accounts for the bulk of the costs of hydrogen in these estimates. The central gas cost of £25/MWhH_2 accounts for 66% of the estimated cost of the hydrogen. The central estimate of electricity cost of £63/MWhH_2 is 85% of the total cost of the resulting hydrogen. Variations in fuel cost are the dominant cause of variation between the upper and lower bounds, ranging from £13/MWh to £28/MWh for gas and from £30/MWh to £53/MWh for electricity.

On these estimates the 270 TWh of hydrogen required would cost approximately £12 billion per year to produce, exclusive of the systems costs of transport and storage required to deliver it to consumers. Of that £12 billion, the input fuels, well over 300 TWh of them, would account for approximately £8.5 billion. From the consumer's perspective it would obviously be much more attractive to use the natural gas and electricity directly, because they would get much more energy for much less cost, rather than converting it with losses and additional costs into hydrogen. The conversion efficiencies of hydrogen-burning devices, such as fuel cells, would have to be dramatically better than their fossil equivalents to even begin to offset the relative disadvantage implicit in these numbers, and in fact they are only slightly better, as in the case of wheeled transport, or largely unknown, as is the case with the real-world operation of the projected 'hybrid heat pump' system.[69] It seems best to assume, as the CCC itself does, that the use of hydrogen implies 'both increased upfront spend and higher fuel costs'.[70]

The costs of transmitting and distributing hydrogen to consumers are also likely to be very high. While it is true that the conversion of the gas network to the polyethylene necessary to convey hydrogen is already underway for other reasons,[71] the adoption of hydrogen is estimated by the CCC to add an additional cost of £500 million a year.[72] The CCC is optimistic that, away from the higher-pressure mains system, the local distribution pipes leading to individual consumers will be 'suitable for transporting hydrogen at all lower-pressure tiers',[73] perhaps taking comfort from the successful use of hydrogen as a component in the town gas system up to the late 1960s. However, as discussed below in relation to safety, it is quite possible that this confidence is misplaced, since the town gas system was very different from that currently proposed. The town gas network was local and of low pressure, being only 7 mbar at the gas holder and household level, a deliberate choice intended to reduce leaks. This compares to about 20 mbar in the current natural gas system. Furthermore, town gas was at most just over 50% hydrogen by volume. The much smaller molecular size of hydrogen gives reasonable grounds for concern that the higher pressure in the modern system may cause problems, particularly in older parts of the domestic supply network and with a 100% hydrogen gas stream. In the interests of public safety, it is clear that more work will have to be done in this area, and nothing would be less surprising than to find that further costs will be entailed. For the time being it is simply an unknown.

In other areas, there is more clarity about the costs of managing a hydrogen system. It is reasonably well understood, for example, that even the incomplete level of hydrogen deployment proposed by the committee in its net zero plan, would require considerable quantities of hydrogen storage, partly to ensure high load factors for the SMRs, reducing capital cost, and partly to meet peak demand in the winter.[74] This will be costly, even if the quantities of hydrogen stored are not large. The CCC itself admits that the 'costs of storing hydrogen in underground salt caverns are expected to be significantly higher than storage in existing gas networks'.[75] This is a striking understatement. The storage of natural gas has annuitised costs, according to the CCC, of about £34/GWh/annum, whereas the cost for hydrogen would be £200,000/GWh/annum, making the underground storage of hydrogen nearly 6,000 times more expensive per unit than natural gas. Lest this seem like a bad bargain, the CCC reports that the cost of medium pressure *overground* hydrogen storage is expected to be £1.2 million/GWh/annum, or 35,000 times more expensive per unit than natural gas.[76]

This means that even quite small storage requirements have significant costs. In work conducted for the CCC, a scenario is presented in which there is a requirement for hydrogen storage at the local network level of some 131–333 GWh, in quantities between 0.6 and 23 GWh at sites spread over the thirteen regions of the UK.[77] This modest level of storage would add about £350–600 million in cost.

The total level of storage required for the supply of 270 TWh of hydrogen, as projected in the net zero plan, is not clear from the published documents, but in its earlier study,[78] the Hybrid scenario, currently under consideration in a revised form, was estimated to require 20 TWh of storage at an annual cost of £6 billion.[79]

To these transmission and distribution considerations it will be necessary to add the cost of converting the UK's building stock. The CCC writes:

> Currently, use of natural gas for heating costs around £30 billion annually. That is largely the cost of buying and burning the gas, plus the cost of replacing gas boilers at the end of their lives (on average every 10–15 years).
>
> Decarbonising heat that is currently provided by natural gas is likely to incur additional costs of around £28 bn/year.[80]

In other words, the total cost of the Hybrid scenario for heating will be about £58 billion per year, an increase on the cost of the natural gas system of over 90%. To this already high figure must be added the possible additional annual cost of £6 billion per year for salt cavern storage.

It is necessary to note that there are differences in the heating scenarios considered in the committee's studies in 2019 and those undertaken in 2018, but the differences do not appear to be so great that the earlier costings are irrelevant. The 2018 figures are of the correct order of magnitude.

Even if these intimidating costs are regarded as tolerable, there is the lurking question of public acceptability. Will the public accept the underground storage of a gas with distinctly hazardous physical properties? Will they trust energy companies to handle it safely? It seems inevitable that in order to reassure a nervous public, government would be drawn into ultra-rigorous regulation and corresponding increases in cost.

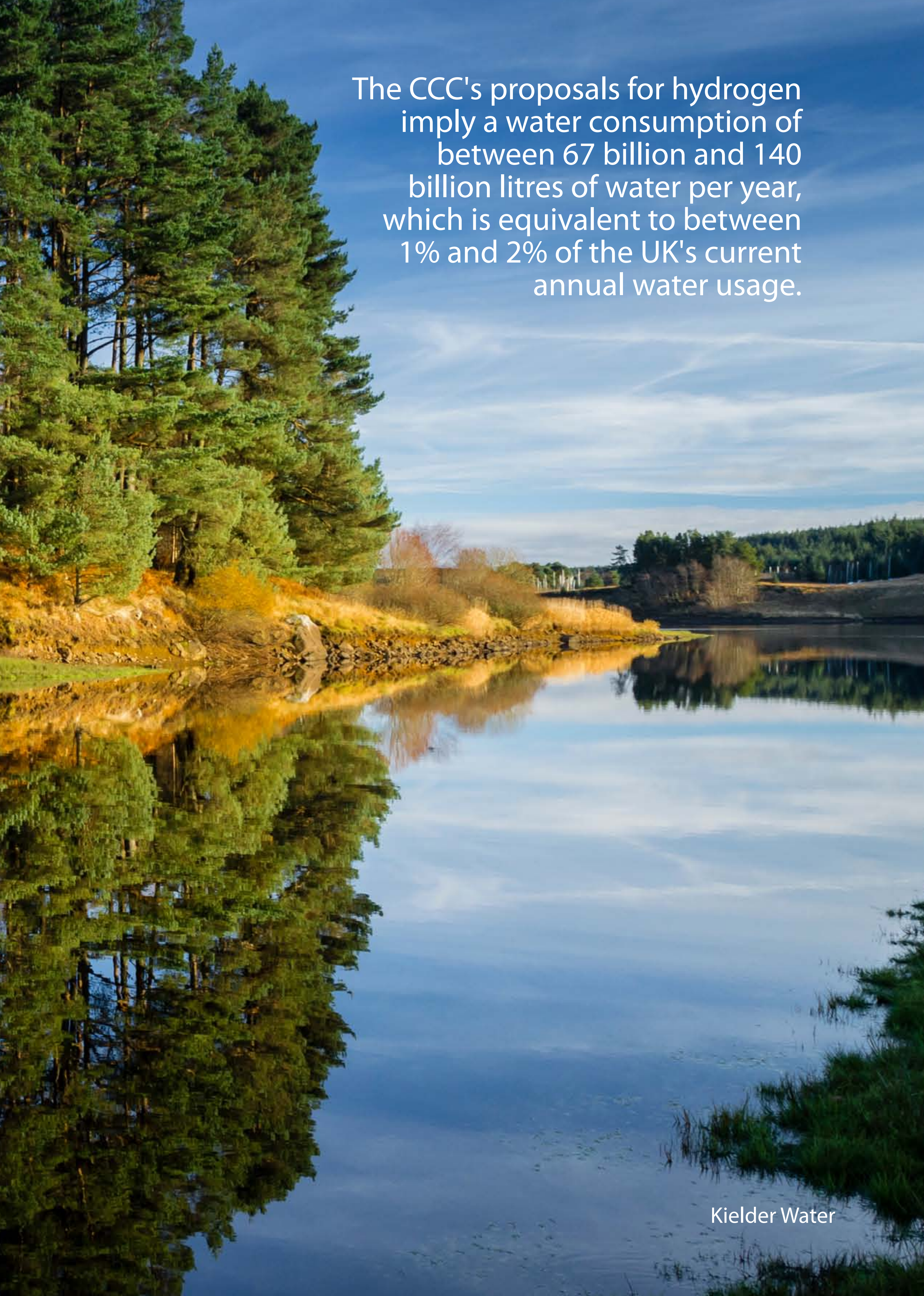
Water use

The CCC's projections for hydrogen generation entail a considerable water consumption. Chemically, in the conversion of methane to hydrogen some 4.5 litres of water are used per kilogram of hydrogen produced, but, due to excess steam, in the overall process the quantity is likely to be very much higher. The IEA reports that SMR *without carbon capture* requires 7 litres of water per kilogram of hydrogen,[81] and Lampert et al. of the Argonne National Laboratory in the United States report 11.7 litres per kilogram of hydrogen produced at centralised, larger-scale SMR, and 22 litres per kilogram at smaller, distributed plants.[82] The addition of carbon capture would increase water consumption, though discussions of this are scarce in the literature. Lampert et al.[83] suggest that CCS would require an additional 1.9 litres per kilogram of hydrogen, giving a figure of about 13.6 litres per kilogram of hydrogen overall.

Consultants to the CCC report a range of 3.9–11.8 litres of water per kilogram of hydrogen for the production process itself, and an additional quantity ranging from 3.9 litres to 30.0 litres per kilogram for cooling, the lower bound being for cooling towers (in themselves a salutary reminder of the energy losses involved), and the upper figure being applicable if sea water is employed.[84] Assuming cooling towers, since suitable coastal locations for the SMRs are likely to be few in number, this would give a total range for the SMR process of between 7.9 and 15.8 litres of water per kilogram of hydrogen. This seems approximately correct, but perhaps on the low side: the US National Renewable Energy Laboratory (NREL) reports that SMR would require 18.9 litres of water per kilogram of hydrogen.[85]

Taking the CCC's estimates, the projected 225 TWh of hydrogen from SMR would require between 45 billion and 90 billion litres of water per year. On the other hand, using Lampert et al.'s estimate for centralised SMR with CCS,[86] this figure would amount to between 78 billion and 128 billion litres of water per year, with the likelihood that it would be towards the lower end of this range because only large-scale SMRs would be employed with CCS, which would be consistent with the CCC estimates. On the estimate of NREL,[87] the 225 TWh would result in the use of 127 billion litres of water per year.

For electrolysis, the IEA reports that 9 litres of water are required per kilogram of hydrogen.[88] Thus, the CCC's projected 44 TWh of hydrogen from electrolysis would require about 10 billion litres of water per year. Consultants to the CCC have estimated the water requirement as 19.7 litres per kilogram of hydrogen,[89] which implies that 22 billion litres of water would be required. However, information provided by ITM Power, a manufacturer of electrolysers, to the Wood Consultancy (for their study of the production of hydrogen to fuel ferries between the Western Isles of Scotland) estimated the water cost on the basis of a consumption of 28 litres per kilogram of hydrogen.[90] On that basis, the CCC's 44 TWh would require 32 billion litres of water per year.



Kielder Water

On the CCC's estimates, total water use for the 270 TWh of hydrogen would be between 67 billion and 113 billion litres of water a year, or between 1% and 1.7% of current UK water use. On the estimates of Wood Group and NREL, water use would be approximately 140 billion litres per year, or about 2.1% of current water usage.

Combining these approaches, we can estimate the CCC's proposals for hydrogen imply consumption of between 67 billion and 140 billion litres of water per year, which is equivalent to between 1% and 2% of the UK's current annual water usage.

While arguably manageable in aggregate at national level, the fact that this additional water usage would be concentrated at 30–60 SMRs and 600–1700 electrolysers suggests that there is a clear potential for significant local problems, particularly in summer conditions in areas of low rainfall. For example, a medium-sized town such as Ipswich, with a population of about 133,000, has a domestic water usage of approximately 10 billion litres per year. Assuming one of the SMRs was located in the area, it would require, on the CCC's estimates, water equivalent to between 8 and 16% of current domestic usage in the town. Even at the lower end, an increase of this magnitude would obviously put a significant additional strain on the local water supply, and this would come at a time when the CCC itself projects increasing water stress even in the event of policies successfully limiting climate change. In a business-as-usual world, with 4°C of global warming by 2100, the committee writes that:

> Wetter winters and drier summers are expected, with around 40% less precipitation in an average summer across the UK (compared to the 1981-2000 average), leading to water deficits in around 25% of water resource zones.[91]

Should temperature change be limited to 2°C, the committee observes that water deficits would still occur in 15% of water resource zones. In this context, it is obvious that the potential for local water supply problems due to the presence of hydrogen production systems is real.

It should also be borne in mind that both SMRs and electrolysers *consume* water in a much stronger sense than that which applies to most other users. It is, of course, perfectly true that the combusted hydrogen will eventually fall as rain, but it would not necessarily do so in those areas where it is most needed. Water that is decomposed into its elements for energy use is lost to the local area in the short term, perhaps permanently, whereas water flowing through a building, its appliances and inhabitants, is returned to the system and is available for purification and reuse. Even a pipeline leak returns to the water table and can be re-abstracted. Hydrogen genuinely subtracts from the local water supply, reducing availability.

These problems are not necessarily insuperable, but, as with safety concerns (discussed below), candour is required if they are to be addressed successfully. Given this requirement, it is notable that while the CCC has previously admitted that in general hydrogen production 'requires the availability of large amounts of water',[92] and in the same document even provided estimates of the litres required per kilogram of hydrogen,[93] it has not applied this point in the more recent documents analysing the consequences of relying on hydrogen to deliver the ambition of net zero emissions by 2050. Indeed, neither the committee's principal discussion of the subject, *Net Zero: The UK's contribution to stopping global warming*[94] nor the supporting analysis in the *Net Zero Technical Report*[95] makes any mention of the water requirement for hydrogen, let alone attempting to quantify it. This is a very surprising omission, undermining confidence in the study's completeness, competence and integrity.

3 Hydrogen safety

The safety of hydrogen is so contentious that it seems wise to anticipate the conclusions reached in this discussion, which is that the intrinsic hazards of hydrogen are real and substantial, but do not constitute an insuperable obstacle to its widespread use as an energy carrier.

All fuels and carriers are hazardous, which is to be expected since something capable of bringing about *desired* changes in the world will also be capable of bringing about *undesired* changes; indeed, the more capable it is of satisfying human requirements, the more danger there is that it will cause unwanted outcomes. That is obvious and indeed should be axiomatic. A sharp knife is dangerous and requires careful handling. The dangers of hydrogen, like the dangers of gasoline and electricity, spring from its strengths, and the undoubted fact that hydrogen is hazardous is, in some sense, an indication of its promise. With sufficient technological and societal adaptation, which will be both costly and time-consuming, it should be possible to contain within acceptable limits the risks (hazard $\times$ probability) of widespread use of hydrogen as an energy carrier.

The appropriate and cautionary question to ask, therefore, is: 'Are policymakers and regulators approaching the deployment of hydrogen with all due care and attention?' If the answer is no, then it is clearly important though not particularly difficult to ensure that they do so, even if this means that the timetable has to be extended.

Alongside this practical, medium-run question stands the deeper issue of whether the economy currently envisaged, which sees hydrogen as an enabling technology for the long-term adoption of renewables, will be sufficiently rich to support the safe technologies and practices required. Gasoline, though hazardous, creates the wealth that enables acceptably safe use. Will that be true of renewables and the hydrogen economy? There are obvious reasons to doubt it, but this question will not be dealt with in depth since it is speculative. The immediate concern is with the short- and medium-term hazards, but even in regard to these there is a great deal of uncertainty, since the practical dangers of hydrogen have been both over- and understated.

Up to a point that confusion is to be expected. The hazards are obviously real, but the probabilities of accidents resulting from very widespread use are not well-understood. Uncertainty is the unavoidable outcome. One can present plausible arguments accentuating or minimising the problems, and those with vested interests will tend to downplay the difficulties, while others will tend to exaggerate them, either to protect an interest or simply, and quite understandably, as a reasonable precaution. As it happens, and for historical reasons, the safety considerations around a broadscale use of hydrogen are almost the first thing that occurs to the public mind. This is, firstly, because of a mistaken and irrelevant association with the thermonuclear hydrogen bomb; this connection is absurd and will not be discussed further here. Secondly, the hazards of hydrogen are salient to the public because of one particular class of genuinely pertinent accidents, namely those involving airships, and one incident in particular, that of the *Hindenburg* in 1937, which is notable for the dramatic rapidity of the fire, which destroyed the vessel in under a minute, and because LZ 129, to give its technical reference, was and remains, even in 2020, the largest aircraft ever to fly. This catastrophe, which will be discussed in some detail below, though involving fewer fatalities than many other air accidents, is obviously significant, and should be given some weight, but how much?

Furthermore, while it is true that hydrogen is used at scale industrially and has a good safety record, that record cannot be assumed to read across directly to a society-wide hydrogen economy, not least because many of the safety standards applied industrially would have to be revised in order to make broader consumer use possible. For example, the separation distances required industrially would have to be reduced for general deployment, and the limits placed on the quantities of hydrogen that can be transported through confined spaces such as tunnels[96] would have to be relaxed. Technological advances rendering these precautions needless might, perhaps, be applied, but their effectiveness is as yet unknown, and in some cases they remain to be fully developed.[97] This is potentially important since hydrogen is well known to be particularly prone to a transition from deflagration (a fire) to detonation (a supersonic combustion with an accompanying shockwave), and the circumstances favourable to detonation, namely confined spaces and turbulent airflow, are not uncommon in the built environment, for example in the tunnels already mentioned, and in car parks, particularly underground car parks, where boil-off from tanks in parked vehicles is to be expected.

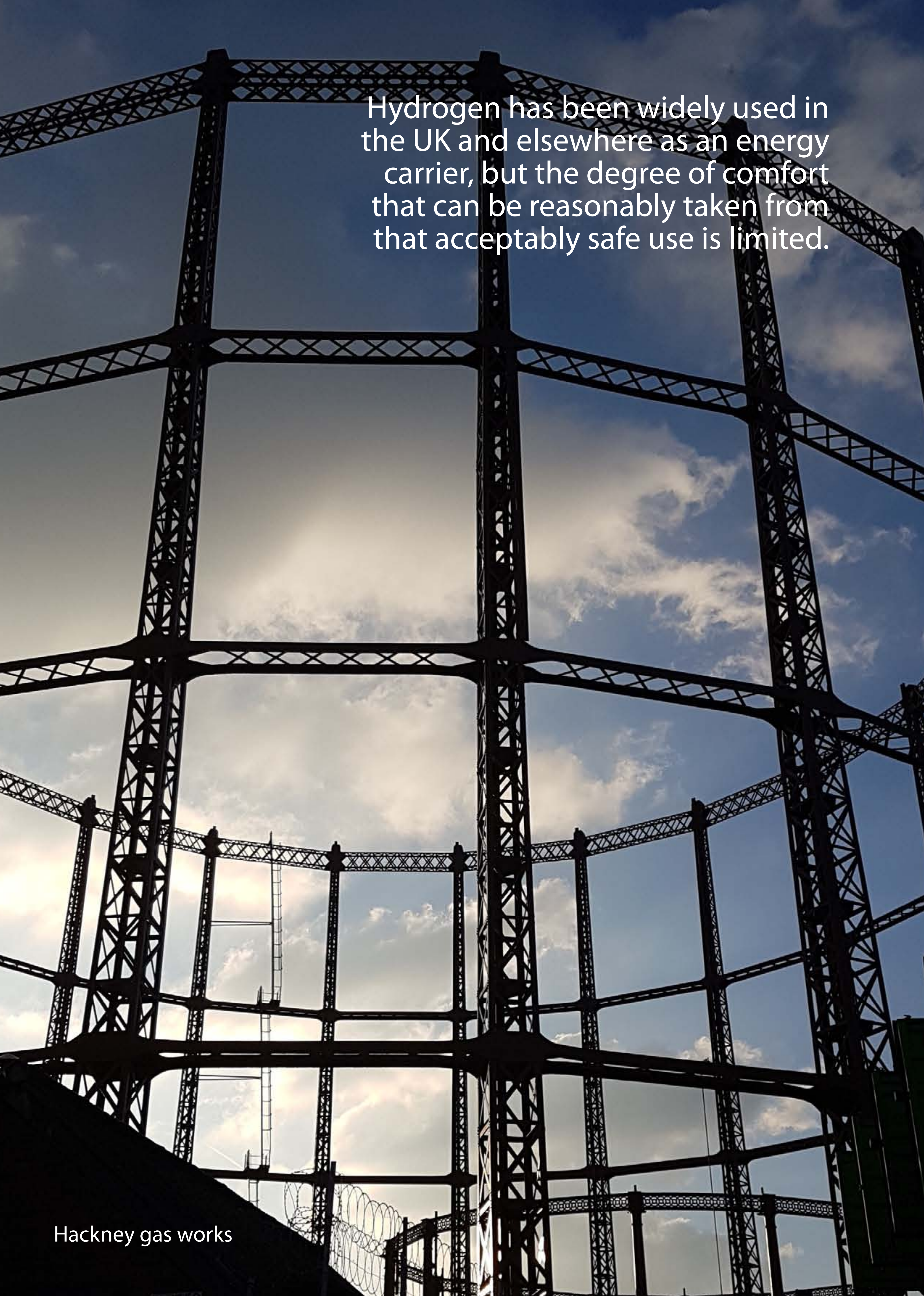
A cool-headed approach is obviously needed, and that entails a balanced consideration of the intrinsic properties of hydrogen, which have been touched on throughout this study, and also the historical record of hydrogen use, which offers some comfort and some warning.

Aspects of safety: the comfort of town gas?

It is widespread in general accounts of hydrogen to discuss its use as if it were a dramatic novelty, generating interest and excitement on that ground alone. By contrast, the more technically minded are inclined to point to the considerable record of experience, and to take comfort from that history. In approaching the case being made for hydrogen, which is rich in prophetic rhetoric,[98] it is useful to ask ourselves where precisely the novelty of the proposition is to be found. In a sense, we have a hydrogen economy already, and have done so for a while. We could identify its use as occurring from the moment that early humans started using fire, at the latest, for, as can be seen from the history and physics of hydrogen, organic life in general is dependent on the properties of this element, along with carbon, nitrogen, phosphorous and sulphur. A large part of biomass is hydrogen. Oil and gas are in large part hydrogen, and there is some substance to the claim that we already have a hydrogen economy in oil and gas, forms that have satisfactorily solved both conversion and storage problems. Indeed, with the growing predominance of natural gas over coal, the use of hydrogen has been increasing.[99] The novelty then, from this perspective, is not in the use of hydrogen, but in its use as a *pure* and *manufactured* fuel, a state in which the storage and transmission problems return. Some will infer, and with reason, that hydrogen is unlikely to be able to compete with fuels where these problems have been solved by evolution and the passage of time, with hydrogen encapsulated in complex organic molecules of dense, easily handled physical forms. The conversion and storage problems have to be solved before pure hydrogen can enter the market, and the solutions must be paid for from the rest of the system.

Subtract then the rhetoric around hydrogen, and we can see that it is a well-established energy carrier and that its use has actually been increasing, incrementally and viably, in some forms: those where David MacKay's points about inefficiency and practical problems do not apply because they are remedied by the characteristics of hydrogen in combination with another element, namely carbon, combinations that arise as the result of organic life. The

Hydrogen has been widely used in the UK and elsewhere as an energy carrier, but the degree of comfort that can be reasonably taken from that acceptably safe use is limited.



Hackney gas works

novelty of the proposition, then, lies in using hydrogen in a form that is not spontaneously occurrent on the earth through living forms. In other words, the proposition is for synthetic, humanly engineered, carbon-free hydrogen. The proposition is all about *production and delivery methods*, not about use. As has already been observed, using hydrogen is easy; it burns readily. We would prefer to use it in fuel cells, and these have been known since the 19th century. But even the presence of hugely improved fuel cells, while desirable and perhaps realisable, will not address the crux of the proposition, which is about the economic production and the safe handling of hydrogen as a manufactured fuel.

In point of fact, even as a manufactured fuel hydrogen is not a complete novelty, for it was an important component in the town gas used from the early 19th until the mid-20th century. Production techniques varied considerably, with eight out of ten town gas supplies in Britain being coal gas and the remainder derived from water gas. Production in the United States was somewhat different, with three quarters of all supply being carburetted water gas; that is enriched with hydrocarbons from oil.[100] However, overall and in general, town gas was about 50%, and sometimes as much as 57% hydrogen by volume.[101] Routledge reports that 'purefied coal gas' was nearly half hydrogen, 35% methane, and 7% carbon monoxide.[102] Clearly there was much variation, but for our purposes all that matters is that the proportions of hydrogen in town gas were high, making it relevant to the present case, though it must be emphasised that a 100% hydrogen gas stream will behave rather differently.

The town gas story begins very early, with Pall Mall being lit with gas on 28 January 1807. In the United States, Baltimore adopted gas lighting in 1816, and Paris in 1820. But as Routledge noted,[103] the combustion of coal gas provided much more heat than light, making it an unsatisfactory source of illumination; it was better than nothing but not overwhelmingly attractive. Indeed, hydrogen-rich gas (such as Mond gas) was of little use for lighting.[104]

Furthermore, there were concerns with the safety of gas holders,[105] but in 1814, Samuel Clegg, an early pioneer, dramatically demonstrated to Sir Joseph Banks, President of the Royal Society, and his colleagues, that this was not well founded. With the Royal Society committee at his side he theatrically took a workman's pick and punctured the gas holder's wall, then ignited the leaking gas, producing a long flame. There was, however, no explosion.

Nevertheless, the prudent Banks and his colleagues recommended the construction of an enclosure around early gas holders with the intention of improving safety. Instructively, this well-meaning precaution may actually have increased the likelihood of an explosion, since the brick building around the holder contained any leaking gas and allowed it to mix with air in a confined space.[106] Prudent intentions do not always lead to satisfactory outcomes.

However, within its niche, hydrogen-rich town gas was compelling, and there were even early employments of bottled gas for lighting in mobile transport. This had first been marketed in 1837, in a form derived from oil because the resulting fuel was low in hydrogen sulphide,[107] but was not initially successful. However, it returned to the German markets in 1871 as a means of lighting railway carriages. London's Metropolitan Railway adopted it in 1876, with the mix at this time being typically 48.6% hydrogen, 26.3% methane, 12.7% carbon monoxide and 3.8% illuminants.[108]

But it was not until the closing decades of the century, and the development of Auer von Welsbach's gas mantle, that gas became a prime candidate for lighting in urban areas. Welsbach discovered that if a non-combustible, refractory material was treated with a balanced mixture of lanthanum, zirconium, thorium and certain other earths, and then introduced into the gas flame, a very bright, white light could be produced, some seven times brighter than a simple coal gas flame. This innovation was commercially introduced in 1887, and became very widely used well into the early 1900s, largely, though not completely, superseding direct flame burners such as the bat's wing type familiar in the literature and memoirs of the period. For intense commercial lighting, in theatres for example, it was discovered that if the hydrogen flame were used to heat a piece of lime it would glow very brightly indeed.[109] The ghost of this practice survives even today in the term 'limelight', meaning the focus of public attention.

But town gas did not prevail in the lighting markets for long, and for most uses it was in turn superseded by electric lighting, which was cleaner, and by mineral oils, which were much cheaper,[110] both events that are highly instructive in the present context. Hydrogen has merits, but in direct competition with electricity and with fossil fuels it is unlikely to be successful.

This did not bring about the end of town gas. Although it had been almost entirely confined to lighting until the last third of the 19th century, town gas came to be very significant part of the provision of heat in buildings, retaining that position in Britain until the 1960s when it was replaced with natural gas. Use for cooking took a little longer. From the 1860s onwards, there were many patents and some exploratory devices, with some companies even renting gas cookers.[111] However, uptake was slow, and domestic cooking with gas was not firmly established until the 1870s.

It should also be remembered that town gas was used as a fuel for early internal combustion engines.[112] These stationary engines were used to supply mechanical energy to individual factory machines, enjoying an economic advantage over larger, centrally located coal-fired steam engines.[113] Stationary engines were also used to generate electricity for lighting in factories, shops and banks, all being institutions that had high peak demands and preferred to own their own generation, presumably for economic reasons.[114]

It is undeniable, then, that there is an historical record of pipeline and, on a small-scale, bottle-pressurised hydrogen-rich gas. That experience is obviously relevant, but how relevant? Consideration of the technical properties of the system as it existed from the 19th up to the middle 20th century sheds light on the matter. Cast iron mains pipes were used from the first in Britain, while in the United States wood was used until the 1870s.[115] Domestic connections were made from narrow-bore iron tubes, known as barrels because, at least initially, they were derived from reused muskets, of which there were very large numbers available after the end of the Napoleonic Wars. The number of joints in these systems made leakage a concern, with up to 20% of the gas being lost in transit even in the 1870s, so to reduce such leaks, pressure in the network was deliberately kept low. The pressure in late-19th and early-20th century gas holders was equivalent to that of a column of water two or three inches high.[116] That is equivalent to about 7 mbar at the holder, delivering about 4 mbar to the end user.[117] This is considerably lower than the current UK gas network pressures, as summarised in Table 4.

In total there are at present 542,600 km of gas pipes in the UK, of which 7,600 km are high-pressure transmission pipes, 47,000 km higher-pressure distribution, and 488,000 km low-pressure distribution or local consumer connections.

No estimates were found by this author of the size of the town gas pipeline network at the time of conversion to natural gas in the late 1960s, but by the early 1930s there were 40,000 miles (64,000 km) of gas mains in Great Britain, and 90,000 miles (145,000 km) in the United States, not counting the minor pipes linking the mains to domestic and industrial consumers.[119,120]

Table 4: Characteristics of UK natural gas networks.

Network type	Pressure bar	Material Pre-1970	Material Post-1970	Length km
Transmission	70–94	HSS	HSS	7,600
Distribution				
High pressure	7–30	HSS	HSS	12,000
Intermediate pressure	2–7	Steel	HDPE	5,000
Medium pressure	0.075–2	Iron	MDPE	30,000
Low pressure	< 0.075	Iron	MDPE	233,000
Service connections	< 0.075	Copper	MDPE	255,000

HSS, high-strength steel; MDPE, medium-density polyethylene; HDPE, high-density polyethylene. Source: Redrawn from Table 2 in Dodds and Demoullin 2013, p. 7191.[118]

Taking this estimate as comparable to all those pipes in Table 4 apart from the service connections, we arrive at a total of 287,000 km. On this estimate, the current natural gas 'mains', excluding service connections, is about four times larger than the comparable town gas network in the early 1930s.

All parts of the current network are at significantly higher pressures than were found anywhere in the town gas network. Current local supply is about 20 mbar,[121] so conservatively local supply is five times higher, and the modern distribution and transmission mains are anywhere between 300 times to 13,000 times higher in pressure than the 19th century and indeed the later town gas networks.

Thus, while it is perfectly true that the record of safety in the town gas network is encouraging with regard to the use of hydrogen, since it was not routinely and notoriously dangerous (except to suicides, because of its carbon monoxide content[122]), it was a hydrogen network of a very different kind than that currently proposed. Firstly, the proportion of hydrogen in the gas stream was at most just over 50% by volume. Secondly, the town gas system was significantly smaller, a quarter of the size, with many more production plants; there were perhaps 2,000 gasworks distributed throughout the country.[123] Thirdly, the low pressures in the town gas network – probably as a rule well under 10 mbar at the holder, and 4 mbar at the point of use – were a matter of deliberate choice, not technological limitation. Higher pressures could have been delivered, but the gas companies preferred lower pressures in order to reduce leaks.[124]

The town gas network was essentially a local and deliberately low-pressure system delivering a composite gas. By contrast, the hydrogen network currently being proposed will require a large, national, and thus high-pressure transmission network ultimately delivering pure hydrogen. Experience with town gas has almost no relevance to that proposal.

Furthermore, the network proposed will initially be a relatively high-pressure system at the point of use because it will inherit the pressures necessary to any transitional blend of natural gas and hydrogen. Natural gas and its appliances require higher pressures to operate safely. It may become possible to consider reducing pressure to end users should the system reach 100% hydrogen, but not before. The transitional phase, therefore, could be problematic, and while the relative safety of the low-pressure town gas network is to a degree encouraging, it is not completely reassuring. Leaks of hydrogen in the town gas network would have been from small pipes at low pressure, releasing only small volumes that could easily dissipate, reducing the hazard of combustion. Furthermore, the general public treated town gas with caution because, for almost the entire period of its use, it contained toxic levels of carbon monoxide, which made up between 10% and 20% of its volume.[††] This level only began to fall in some areas in the late 1950s and early 1960s, very close to the transition to natural gas, when the production basis changed from coal to oil and naptha, thus reducing the level of carbon monoxide.[125] Evidence for public caution in use of town gas and in reporting leaks can be found in the fact that, even at the peak for accidental deaths from gas, the rate was only 9 per 100,000 of population, and that many of these were suspected to be incorrectly classified suicides.[126]

In summary, the novelty of the current hydrogen proposition is subtle rather than obvious, for the use of hydrogen as a component in a pipeline fuel, and indeed as a bottled fuel, extends back for over a century. Even the use of hydrogen as a manufactured fuel for the sake of its local cleanliness, and in spite of its costs, has historical precedent, for town gas was for a period preferred to coal, even where coal could have been used in its original form for heat.

The true novelty of the current hydrogen proposition is found firstly in the scale and variety of the deployments intended, and secondly in character of the supply, with both liquid and high-pressure hydrogen being called for. It is perfectly true, as the Health and Safety Laboratory notes,[127] that there is industrial experience of hydrogen pipeline pressures up to 20 bar, and this is most certainly encouraging. However, these were purpose-built networks of limited extent, run by highly trained technicians; the use of high pressure or liquid hydrogen by the general public is a different proposition. It is both interesting and important that hydrogen has been widely used in the UK and elsewhere as an energy carrier, but the degree of comfort that can be reasonably taken from that acceptably safe use is limited.

Aspects of safety: the warning of the *Hindenburg*?

No discussion of the safety aspects of hydrogen would be complete without consideration of the *Hindenburg* disaster of 1937. It is almost the first thing to come up in any casual conversation about this gas and its use as an energy carrier. The prominence of the event is explained by three facts. The destruction of the ship was historically and politically significant in that the *Hindenburg* was emblazoned with swastikas and was being used as part of Germany's propaganda drive in the United States, as if to say 'When Germany reaches out its arm, it casts a shadow on New York'. Indeed, it had made some twenty successful Atlantic crossings before the accident, and the crash was a significant setback for the German government in its attempt to secure the tacit support and tolerance of the American people. Secondly, and partly as a result of the propaganda drive, there is a nearly complete film record of the event, allowing the viewer to appreciate in real time the strikingly acute nature of a fire that consumed a vessel 245 metres in length in 34 seconds.[128] The prominence of the disaster most certainly discouraged future development of the airship, and it plays a part in current public doubts about the use of hydrogen in the wider economy.

However, amongst hydrogen proponents,[129] the official interpretation of the accident is deprecated as a 'myth'. Instead, these authors accept the revisionist hypothesis of Addi-

†† With a modal value of 14.

Are policymakers and regulators approaching the deployment of hydrogen with all due care and attention?

The Hindenburg Disaster, 6 May 1937.

son Bain, which proposes that the cause of ignition, and of the severity of the fire, was not the hydrogen employed as the lift gas, but the substances used to paint (properly speaking 'dope') the outer skin of the vessel, a substance which Bain refers to as a 'rocket fuel'.[130] This revisionist view is now deeply embedded and appears even in the texts of authors either neutral or moderately sceptical about the potential of hydrogen.[131] In some circles it is on the point of becoming an orthodoxy.

The superficial attractions of Bain's view can be understood as a function of its contrarian novelty, reinforced by the apparent authority of Bain's former career working with hydrogen as a NASA employee. Furthermore, the argument has been widely disseminated as a result of Bain's prominence in the National Hydrogen Association and the International Association for Hydrogen Energy, in both of which he was a founding member. Senator Tom Harkin, speaking in Congress, can be taken as representing the standard hydrogen proponent's view of Bain's significance for their joint endeavour:

> Thanks to Addison Bain, we can continue down the path toward a renewable hydrogen future without the undue fear of a singular event from 60 years ago.[132]

However, contemporary and subsequent analyses have shown that Bain's attempt to excuse hydrogen from a significant role in both the cause and pace of the fire has very little merit and in several respects is obviously and fatally flawed.[133]

The academic physicist and former Space Science Director at NASA, A. J. Dessler, noted that doped cloth of this kind does not burn very rapidly in tests,[134] and furthermore, even if the *Hindenburg* had been painted with rocket fuel, which it was not, the speed of the resulting combustion would not have explained the extreme rapidity with which the fire proceeded to consume the entire ship. Rocket fuel does not burn in that way. On the other hand, the rapid development of the *Hindenburg* fire is entirely consistent with a rapid deflagration of hydrogen, the pace of which can be very fast indeed. The hydrogen fire at the Fukushima Daiichi Nuclear Power Station reached speeds of approximately 150 m/s,[135] which is slower than a detonation but nevertheless extremely rapid. Furthermore, independent empirical tests[136] not only confirm Dessler's position but show that, if anything, the dope acted as a fire *retardant*, slowing combustion as compared to undoped cotton fabric. Whatever started the fire, and that is still to a degree uncertain, it seems very unlikely that the rapidity of the destruction is explained by the dope applied to the skin of the airship, as claimed by Bain. It is explained by hydrogen.

In point of fact, Bain's own views seem to have undergone an evolution: his earlier statements[137] tended to suggest that the severity of the entire fire was the result of the dopant, while in his later and final account[138] he was more guarded, accepting that hydrogen combustion was significant from 1.5 seconds after ignition,[139] and highly significant after 5 seconds. He still maintained that the ignition itself was the result of the doping material, which he hypothesised was ignited by electrical activity facilitated by a plume of negatively charged carbon particulate emanating from a backfiring diesel engine. Whether that ignition hypothesis is plausible is also very doubtful. As his critics point out,[140] the doping substance used is not highly flammable, and was unlikely to have been ignited by such sparks, if any.

It seems reasonable to conclude at this point that, while it is true that the initial causes of the *Hindenburg* disaster are still open to some doubt, it is almost certain, as the original inquiries decided and most subsequent parties agree,[‡‡] that the fire was the result of an electrical discharge between the vessel's skin, which was not grounded, and the airframe, which

‡‡ Those suspecting sabotage being the most notable exception.

was earthed via a mooring cable, or possibly because of a corona discharge (St Elmo's Fire). These discharges are thought to have ignited hydrogen that had either leaked accidentally or been deliberately released to trim the ship during landing. It is unlikely that these electrical discharges caused ignition of the doped cloth covering.

In any case, the way in which the fire progressed and the rapidity with which it consumed the vessel strongly suggests that, however it began, it was *sustained* as a very rapid hydrogen fire, not a paint fire, a point that Bain himself implicitly conceded in his final statement.[141]

It is worth noting at this point that, while some witness accounts from onboard crew refer to 'muffled detonations',[142] there does not appear to have been a detonation in the technical sense of a supersonic combustion frontier with an accompanying shockwave. The *Hindenburg* was consumed by a rapid deflagration of hydrogen, not a detonation (*sensu stricto*).

Furthermore, the *Hindenburg* disaster is not an isolated instance of a hydrogen airship being destroyed by fire. The aviation historian Grossman refers to some dozens of examples, and lists twenty-one other incidents, involving the destruction of twenty-six airships between 1908 and 1937, not including those destroyed during combat.[143] In several of these cases the hydrogen was ignited by minor or otherwise unthreatening accidents, and in several by accidents that would have been serious but not necessarily disastrous if a non-inflammable lift gas such as helium had been employed. For example, the notorious case in 1930 of the experimental British airship the R101, which, probably because of design flaws, was unable to maintain altitude in difficult weather and suffered a low-speed crash into a French hillside. The hydrogen lift gas caught fire almost immediately, killing 48 of the 55 on board.[144] Had the lift gas been helium there would almost certainly been a lower loss of life.

The entire history of hydrogen airships shows that the hazards of this gas were difficult to control in practical applications, which is an enduring and important lesson. The *Hindenburg* was simply the most dramatic evidence of an underlying and general problem. And it is because of this crystallising, exemplary role that the *Hindenburg* continues to play so great a part in the public perception of the hazards of using hydrogen as a generally available energy carrier. For hydrogen apologists it is, consequently, a major obstacle to political acceptance. It is striking and informative that rather than addressing the obvious lessons of the full record of hydrogen airships by arguing for ways in which the hazards revealed can be mitigated or overcome in other applications – road transport for example – pro-hydrogen writers such as McAlister, Rifkin, Hoffmann, Lovins, and even the more generally prudent Romm, have preferred to defend and advance their position through focusing on the single case of the *Hindenburg*, while attempting to excuse hydrogen from blame by hastily and uncritically accepting the obviously tendentious and implausible hypothesis designed by a fellow advocate to be favourable to their case.

Indeed, Peter Hoffmann's[145] *Tomorrow's Energy*, a widely read book published by a reputable university press, suggests that it is irrational to be concerned about hydrogen on the basis of the *Hindenburg* accident, which killed 35 of its 95 passengers and wasn't, in his view, caused by hydrogen, but to neglect the hazards of kerosene, so amply demonstrated by the Tenerife airport catastrophe of 1977 (Figure 3), which killed 583 passengers of 644 on board the two planes concerned. Part of Hoffmann's point is not empty – kerosene is most certainly hazardous – but consideration and comparison of the nature of the two accidents suggests a different interpretation to that which he offers. The *Hindenburg* fire occurred as the result of an everyday event: an electric charge accumulated on the ship during a routine operation, namely low-speed landing and tethering of the airship. Furthermore, the hydrogen that burned may even have deliberately been released as a routine part of that landing process. The Tenerife disaster, in contrast, was a failure of air traffic control resulting in an exceptional collision between two aircraft, one nearly stationary on the runway, the other moving at high speed and at the point of becoming airborne, causing catastrophic structural disintegration of both airframes releasing kerosene that then ignited. The collision of the two aircraft would have caused great loss of life even if there had been no fire. The electric charge on the *Hindenburg* would have been harmless if there had been no hydrogen to ignite. Hoffmann's comparison is specious and misleading.

Contemporary accidents

The *Hindenburg* disaster, and the record of hydrogen as a lift gas in general, merely confirms what should be sufficiently obvious from examination of its physical properties. Hydrogen is without a doubt, and notwithstanding the remarks of the industry and its supporters, a *hazardous* gas, and indeed more hazardous in some respects, though not all, than either gasoline or natural gas. Hydrogen accidents are already occurring as attempts are made to disseminate hydrogen as a transport fuel. The UK government's Health and Safety Executive writes of such an event:

> On 26 August 2010 in Rochester New York State USA, a hydrogen tank exploded during a swap of hydrogen tanks at a hydrogen refueling station. The resulting fire caused a second hydrogen tank to explode and one person received 2nd degree burns from the fire. The area was used by a company supplying GM with hydrogen tanks for its fuel cell car fleet.[146]

It should be noted that these appear to be straightforward explosions – rapid deflagrations not detonations – but that they were triggered by an accident during a routine operation – swapping one tank for another – under highly controlled conditions at a hydrogen fuel station. Accidents of this nature continue today, with two being reported in June 2019

Figure 3: Tenerife airport disaster, 27 March 1977.

alone. One of these, in Santa Clara, California, occurred at a hydrogen reforming plant, causing shortages of hydrogen fuel in the Bay area, with nine out of ten fuelling stations still closed over a week later.[147] The fire in this case destroyed a number of hydrogen fuelling trucks, and took over an hour to extinguish, though whether this was because other fuels became involved is not clear. The second incident took place at a refuelling station in Kjørbo, Norway, and is particularly informative since the station was operated by Nel Hydrogen, a long-established company with many decades of experience in supplying the industrial hydrogen market, and the world's largest manufacturer of electrolysers.[148] Growth in the demand for hydrogen-fuelled transport encouraged Nel to diversify into the consumer market, but an industrial safety record does not read straightforwardly across into wider consumer deployment,[149] and Nel's extensive experience was not sufficient to save them from an accident, now identified as human error resulting in the mis-assembly of a plug fitting in a hydrogen storage tank.

The incident occurred at 17:30, and nearby roads were closed at 17:41. By 17:47 an exclusion zone of 500 m had been established around the site. At 19:28 a robot was used to enter and cool the site, and by 20:14 the fire department declared the fire under control and roads were reopened.[150] The only injuries reported were the result of airbags in nearby passenger vehicles being triggered by a shockwave, suggesting that this incident may have involved a deflagration-to-detonation transition. Witness accounts also describe a 'big bang',[151] which is consistent with this hypothesis, as is the generous 500-m exclusion zone established as a precaution. Nel Hydrogen's own Q&A webpage addresses the matter thus:

> Q: Was there an explosion?
>
> A: No unit exploded at the site. Based on our current information, hydrogen gas that had leaked caught fire in open air. This created a pressure wave.

It is clear therefore that no industrial unit, such as an electrolyser or a storage tank, exploded. However, the answer, while confirming the existence of a pressure wave, does not tell us whether there was an explosion in the open air, and whether this was a detonation in the strict sense. The author of this study corresponded with Nel Hydrogen in July 2019 but the company declined to confirm or deny the existence of a detonation.

While the character of the event remains a little unclear, the causes of the event are fairly well understood even at this early stage of investigation. Nel's summary statement reads:

> The preliminary Gexcon investigation shows that the incident started with a hydrogen leak from a plug in one of the tanks in the high-pressure storage unit. This leak created a mixture of hydrogen and air that ignited. The investigations will continue into the specific source of ignition.[152]

Within the more detailed analysis, we learn that the leak was caused by insufficient torque being applied to bolts securing a plug to the neck of a storage tank,[153] resulting in small leaks that degraded the inner seals, resulting in a pressure build-up behind the plug. The insufficient torque on the securing bolts meant that this pressure was able to lift the plug, causing complete failure of both the inner and outer seals and an 'uncontrolled' leak.[154]

This appears to be a case where, as Nel concludes, the materials and design were not at fault, but the assembly was, in their words, 'NOT OK'. Indeed, with the exception of their reticence regarding detonation, Nel's reaction to this event is commendably open. With only a hint of defensiveness, they correctly note that 'hydrogen has a high energy density and can be hazardous, just like gasoline, diesel, natural gas, and batteries', and go on to grant that this was a 'very serious incident'.[155] We might add that it was not only very serious, but also a deeply *prosaic* incident: there were no exceptional circumstances, no improbable concatenation of events, physics or chemistry. Some important bolts weren't tight enough, leading to a substantial leak of a highly flammable gas that happened to ignite. The precise causes of the ignition are as yet undetermined, but Nel has reported that 'the investigations by Gexcon have indicated that either auto-ignition and/or the movement of the gravel underneath the unit are the most likely sources'.[156] The leak was prosaic, the ignition was probably still more so.

We can infer from this incident that while technology and public practice adjust to use of hydrogen as an energy carrier there is a significant likelihood of accidents. Liquid hydrogen boils off easily, at $-252.76°$C, not much above absolute zero, and in its gaseous form it can escape through seals and indeed materials that are impermeable to larger molecules such as methane. When escaped, hydrogen has a low ignition energy, and ignites across a wide range of concentrations. It also has a relatively high probability of a deflagration-to-detonation transition, with a speed of detonation of 1,600–2,000 m/s, five to six times the speed of sound, producing a damaging shock wave. There is no real question that it is a hazardous substance. As noted several times in the preceding text, gasoline, kerosene and natural gas are also hazardous, and the nascent hydrogen industry has capitalised on this undeniable abstract similarity to claim that 'hydrogen is no more or less dangerous' than such fuels.[157] The UK's CCC even says 'None of these properties makes hydrogen inherently less safe than other fuels (e.g. natural gas [...]' But such remarks are thoroughly disingenuous. Gasoline and natural gas have several *inherently* less hazardous physical properties: they are less prone to leak, they have higher ignition energies, smaller ignition concentration ranges, and smaller detonation ranges, as can be seen in Tables 5 and 6.

Table 5: Ignition energies

Fuel	Ignition energy mJ
Hydrogen	0.02
Petrol	0.80
Diesel	20.00

Source: Follows 2015.

The potential for a hydrogen leak, and then for an ignition is intrinsically higher than for other fuels such as gasoline and natural gas. As the Kjørbo incident described above shows, as trivial a thing as an under-torqued bolt can lead to a serious incident. Furthermore, neither natural gas nor gasoline will *readily* move from deflagration to detonation with its devastating shockwave, something that is considerably more likely with hydrogen. It is true and fair to note that, even with hydrogen, the probability of a deflagration-to-detonation transition is dependent on quite specific circumstances – confined spaces with turbulent airflow being the most favourable – but generally speaking hydrogen is more likely to pass from burning to detonation than many other hazardous substances in use, and is susceptible to detonation across a very wide range of concentrations.

Even a simple deflagration is itself a very serious incident. The fire at the Buncefield oil storage depot in the UK on 11 December 2005, terrible and lethally destructive though it was, resulted from deflagration not detonation.[158] In other words, it could have been worse, There were no exceptional circumstances, no improbable concatenation of events, physics or chemistry. Some important bolts weren't tight enough, leading to a substantial leak of a highly flammable gas that happened to ignite.

The aftermath of the Kjørbo accident, 10 June 2019

Table 6: Detonation and flammability limits.

	Detonation				Flammability	
	Confined		Unconfined			
Limit	Lower Vol%	Upper Vol%	Lower Vol%	Upper Vol%	Lower Vol%	Upper Vol%
Hydrogen	18.3	58.9	—	—	4.0	75.0
Methane	5.7	14.0	—	—	5.3	15.0
Ethane	2.9	12.2	4.0	9.2	3.0	12.4
Propane	2.6	7.4	3.0	7.0	2.1	9.5
Butane	2.0	6.2	2.5	5.2	1.8	8.4
Methanol	—	—	—	—	6.7	36.0
Ethanol	5.1	9.8	—	—	3.3	19.0
Petrol	1.1	3.3	—	—	1.4	7.6

Selected and redrawn from Dahoe 2011.

as was an undoubted detonation such as that at the Flixborough chemicals plant, also in the UK, on 1 June 1974.

Fortunately, detonation is quite difficult to produce with most fuels, including hydrogen. It is clearly possible that measures can be taken to reduce the probability of such occurrences. It has been noted elsewhere in this study, for example, that leakage from vehicle tanks in underground car parks could deliver favourable conditions for detonation. An ingenious remedy is entirely conceivable, but it will be neither cheap, nor will it be rapid. In addition to technology, there must be the development of societal practice, and this will take time. In haste – and climate policy imperatives induce haste, with caution thrown to the winds – a major hydrogen accident is almost inevitable, somewhere, sooner or later. With care and caution, it need not be.

However, and this must be emphasised, *the risk of an accident does not constitute an insurmountable obstacle to the use of hydrogen as a generally available energy carrier*. If hydrogen is generated with a high-productivity energy source and has sufficient merits at the point of use, it will be both affordable and desirable to mitigate the hazard. That is to say, if the energy source itself is cheap, and thus creative of wealth, then it will be possible to spare some of that wealth to reduce the probability of a hydrogen accident, thus bringing the risk (hazard × probability) down to acceptable levels, as has been done with gasoline and natural gas and many other intrinsically hazardous substances. With care, expenditure and time, it should be possible to ensure that the public is not exposed to unreasonable dangers from the widespread use of hydrogen. But, as we have already noted, only a high-productivity input source can support such cost and expenditure. To make hydrogen safe, to overcome the 'practical defects', a wealthy economy is required, and that implies that the inefficiencies must be offset, with a productive source such as nuclear energy, rather than compounded with renewables or made comparatively absurd by the use of natural gas. It may well be possible to make hydrogen acceptably safe, but the society that does so will have to be candid in addressing the difficulties, patient in addressing them, and rich enough to afford the mitigating technologies.

To put this aphoristically, when considering hydrogen it is not the lesson of the *Hinden-*

burg to which we should attend, for that tells us only what we already knew, but instead the R101, a worthy and promising experimental vessel plainly unready for general or long-haul service that was hastily despatched to India by a government desperate to be seen to be doing something at the technological forefront.

Conscious of the news cycle, governments are very likely to be impatient, particularly when they are convinced that their policies are correcting a market failure. In the case of hydrogen, haste will be hazardous. Time must be allowed for technological and societal adaptation, to reduce the frequency and severity of accidents.

The difficulties should not be underestimated, and can be appreciated by focusing on a critical component: hydrogen storage tanks for use in light duty vehicles. Such tanks are important in themselves, highly relevant to safety, and also a useful general index of progress on cost reduction. In 2007 the IEA estimated that a storage tank for a fuel cell vehicle (FCV) capable of holding 4–5 kg of hydrogen (enough for a range of 400–500 km) would cost in the region of $3,000–4,000 per vehicle.[159] Consultants to the US Department of Energy have confirmed this approximate calculation (see Figure5).

The costs of 350-bar and 700-bar tanks are dependent on the volumes produced. Moreover, since a kilogram of hydrogen contains 33.3 kWh (LHV) of energy, the metric used in the DOE study, it is straightforward to calculate the costs of tanks in 2019 dollars (Table 7). To put such values in context, if a private individual were to replace the fuel tank in their current petroleum-fuelled vehicle they would – and anyone can verify this by internet searches for automobile parts – pay between $500 and $1,500 for the tank, depending on the size and type of vehicle, and it is likely that the original manufacturer of that vehicle would almost certainly have been able to obtain tanks for much less than that.

Even assuming very high production volumes for hydrogen storage tanks, these costs are alarmingly high; together with the cost of the fuel cell itself, they would be likely to ren-

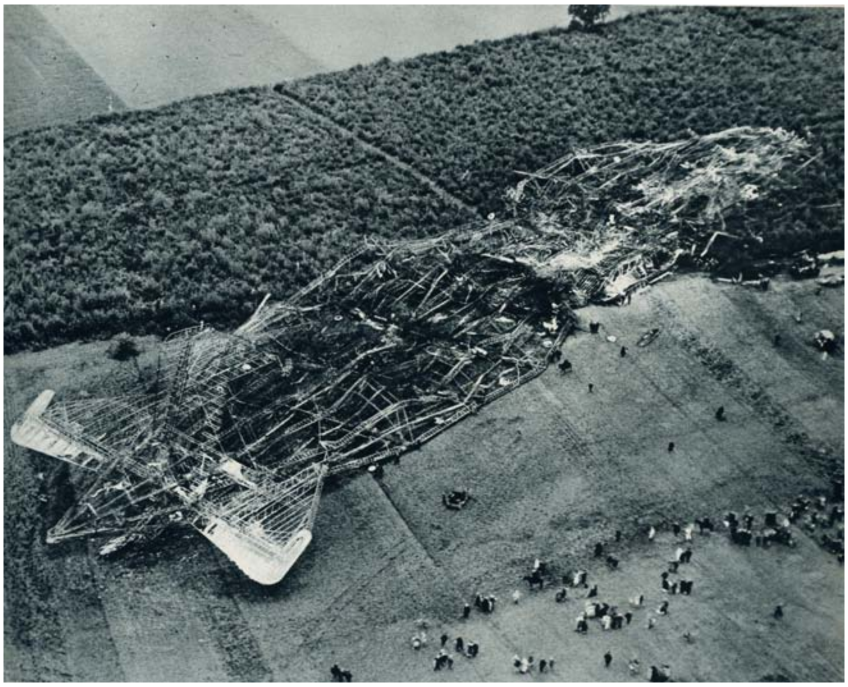


Figure 4: Wreckage of the R101.
Source: Airships.net (Grossman 2014)

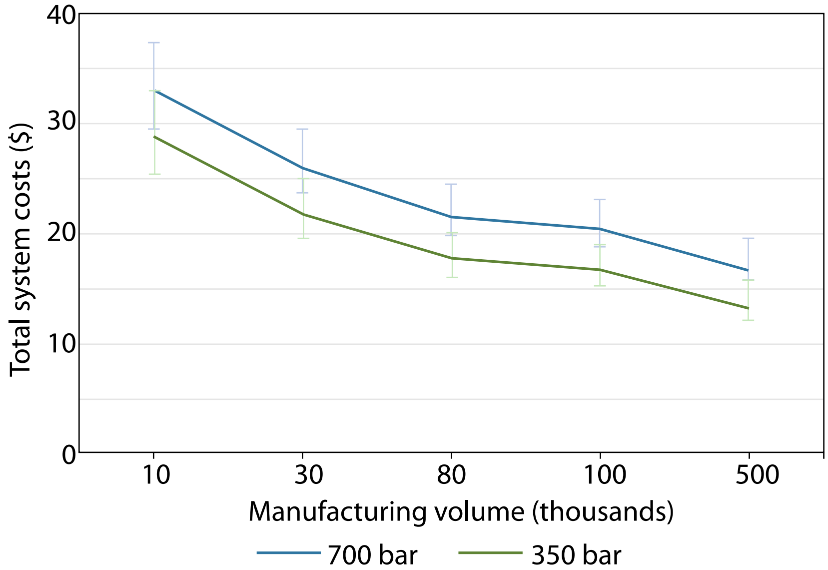


Figure 5: Hydrogen storage system costs
Projected costs in 2007$/kWh, at various annual manufacturing volumes, for (a) 350 bar and (b) 700 bar compressed hydrogen storage systems, sized to deliver 5.6 kg of hydrogen to the vehicle fuel cell powerplant. Cost analysis performed by Strategic Analysis for the DOE in 2013.
Source: DOE 2013.

Table 7: Approximate cost of hydrogen tanks.

	Systems per year	Cost of tank (2019 $) 350 bar	700 bar
Low volumes	10,000	6,500	7,500
High volumes	500,000	3,500	3,500

Source: Derived from DOE 2013.

der even the cheapest FCV very expensive indeed as compared to a gasoline-fuelled vehicle. Naturally enough, there has been hope that the costs would fall further at high volume, and there is some evidence to support that hope. Subsequent work for the US DOE by the same consultants reports that between 2013 and 2015 there was a 12% fall in expected manufacturing costs of a 700-bar Type IV pressure vessel system.[160] This is a useful reduction, but still results in tanks that cost $2,800.* That is cheaper but it is not cheap. Furthermore, it is crucial to note that the overall reduction is a net change, and that some elements in the manufacturing process resulted in *increases* in cost, notably a design change whereby internal reinforcements (doilies), reducing the need for carbon fibre and resin, were removed from the specification because they were found to increase the complexity of manufacture and also the risk of single-point failure. Details of this kind are a salutary reminder that in new and developing fields costs do not always go down, particularly when safety is involved.

* $3,500 at 2019 prices.

Safety: conclusions

Accidents with energy carriers are inevitable. An energy supply is simply a way of causing changes in the world, as required by users, but unwanted changes, fires, explosions, and electrocutions are also statistically certain over time. The frequency of such unwanted events can be reduced by careful engineering, and by training the users. The satire on male models, *Zoolander*, kills off a number of its characters in a grotesque scene where they playfully splash gasoline over each other at a highway service station, then strike impressive poses to light cigarettes, with the inevitable and far from cool result.

In his oration at the group funeral, their surviving friend, the eponymous Derek Zoolander, laments these deaths by describing them as the result of a 'freak gasoline fight accident', a phrase now notorious in popular culture. The remark is expected to induce laughter since ignorance of the very real dangers of gasoline is so unusual in the general public that these characters must be supposed to be preternaturally foolish. We all know, intuitively, that gasoline is dangerous. Indeed, if we were now discussing the *widespread* and *rapid* adoption of gasoline for the first time, the hazards of the substance would quite correctly be raised as a major concern. Contemporary gasoline use is only relatively safe because its gradual dissemination over a period of many decades has permitted the emergence of technological safeguards at reasonable cost, and societal and personal practices that contain its hazards and reduce the frequency with which accidents turn into disasters. The risk is kept relatively low, but the hazard remains real. If hydrogen is successfully adopted, the situation will be identical in character. The physical realities will remain unchanged. Societal practise and engineering will be required to ensure that these realities do not result in fatality and injury. That is not infeasible, but it will require a period of adaptation. Impatient deployment, driven by the largely arbitrary deadlines of climate change policies, is likely to result in more horrific learning experiences than is necessary.

If policymakers remain committed to an 'express service' in the adoption of hydrogen, then they need to realise that, firstly, special measures will be required to protect the public,

Figure 6: *Zoolander* (2001): the gasoline fight.

and secondly that the specious pleading of hydrogen proponents, who, as we have seen from the *Hindenburg* story, have a tendency to deliberately understate the hazards, must be ignored. It may be possible to use hydrogen safely, but absolute honesty about the nature of the problems is required; ubiquitous use in high-pressure long-distance networks will be very different in character from earlier deployments. Hasty and incautious adoption is likely to be dangerous, and thus counterproductive.

4 A premature return to hydrogen is a retrograde step

We have seen that hydrogen, as a component of town gas, has a long history of use as a gaseous energy carrier, and that, due to technical and societal adaptation, its safety record was by and large tolerable. Nevertheless, it was in most locations decisively and completely abandoned in favour of methane, natural gas. In the UK this process began in the late 1960s and was complete by the late 1970s. That was not an arbitrary decision, and it is worth reflecting on the reasons behind this transition.

In the 1870s, gas works in Britain were using 7 million tons of coal per year, about 7% of total coal consumption, greater than the global production of coal in 1700.[161] By 1887 this had risen to 10 million tons per year.[162] This rose further to about 18 million tons in 1938, roughly 10% of domestic coal production,[163] and by the early 1960s, just as coal use for gas had peaked, and oil and naptha were being adopted, the industry was using 22 million tons per year.[164] Town gas was an important fuel. Indeed, in 1968 when direct supplies of natural gas began, town gas and other manufactured gases were accounting for nearly 9% of British final energy consumption, almost as much as electricity.[165] Even making allowance for the presence of carbon monoxide, hydrogen was a significant part of British energy as recently as the mid-20th century. Yet by 1978 the contribution of town gas had fallen from 12 mtoe* per year to 1 mtoe, less than 1% of total final energy consumption, and in 1979 hydrogen and carbon monoxide production from coal ceased completely in Great Britain.[166] Encouraged by successful experimentation from the late 1950s onward with the injection of natural gas, obtained as liquefied natural gas from Algeria,[167] the decision to shift to natural gas was driven fundamentally by economics, an administrative decision that was vindicated by subsequent growth in consumption as the domestic and wider markets reacted to the relative cheapness of the new and plentifully available fuel. Hydrogen, as David MacKay said, is a rather inefficient energy carrier, with large conversion losses. Natural pipeline gas did not suffer these losses, and thus presented a significant increase in overall system productivity. As statisticians from the UK government's Department of Energy and Climate Change observed in their own historical account:

> When gas was made from other fossil fuels a large part of the energy content of these fuels was lost in the transformation process. Typically, in the 1930s the energy content of the gas was only a quarter of the energy content of the input fuels. As a result gas was a relatively expensive fuel.[168]

The first broadscale use of hydrogen, that in the UK, was inefficient and therefore expensive. The shift to natural gas, where there are only distribution losses amounting to about 6.4%,[169] may have been a bureaucratic mandate rather than market outcome, but it was a sound decision, and the effect on gas consumption was rapid and dramatic, as a remarkable chart from DECC shows (see Figure 7).

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* Millions of tons of oil equivalent.

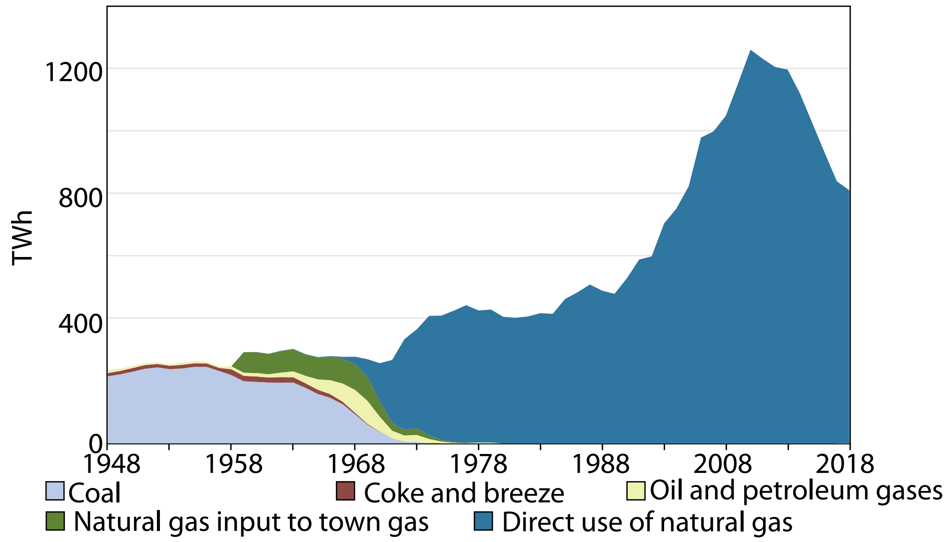

Figure 7: Fuel input to gas making, and direct use of natural gas, 1948–2018.
Source: DECC 2009, p. 29.

Cheaper natural gas easily satisfied existing consumers, and opened up opportunities for new demand. Consumption rose sharply through the 1970s, and then with perturbations still more sharply up to the early 2000s, as progressively more of this fuel was also used to generate electricity, a market in which hydrogen had only previously occupied a limited niche (see above). The early growth is particularly striking. Natural gas production amounted to 1.9 TWh in 1966 but was rising at the rate of 138% per year, and by 1971 totalled 202 TWh annually. The growth rate thereafter was more modest, but by 1976 production had doubled to 422 TWh per year, over two hundred times larger than production only a decade earlier. This remarkable increase occurred because the natural gas industry was immensely productive, delivering energy so cheap that it was spontaneously attractive, not only to the existing market for town gas – domestic and industrial customers seeking a source of heat – but also for the generation of electricity. No one, industrial nostalgics aside, for a moment regretted the disappearance of the coal-to-hydrogen economy that preceded it. Natural gas was a very much better fuel.

From this perspective, reversion to the manufacture of hydrogen from fossil fuels, this time natural gas itself, is in certain predominantly economic respects a retrograde step. And this is true in spite of the fact that SMRs are considerably more efficient than the gasification of coal. As noted above, and as logic confirms, hydrogen cannot win a competition with its own fuel stock where that fuel stock can be used directly for the same end purpose. Hydrogen was forced from the UK energy supply by overwhelming economics; reintroduction will for many uses be counter-economic, as consideration above of the costs implicit in the CCC proposals richly demonstrates.

Furthermore the coal gas industry, the first hydrogen gas energy system, was adopted in part for environmental reasons: it was relatively clean at the point of use, but had highly significant negative environmental effects at the sites where the gas was produced, typically poorer urban areas.[170] Indeed, it is a classic instance of low-income citizens being exposed to the undesirable effects of a production process without being able to afford to purchase its benefits. Local pollution from the gasification of coal was serious and long lasting. Indeed, these effects persist even today. The clean-up at the site of the Greenwich Peninsula gasworks, preparatory to the construction of the Millennium Dome in the late 1990s, cost £185 million (over £300 million at 2018 prices), and of course only moved the contamination from the building site itself to a landfill at distance. Many towns in Britain have areas otherwise attractive for development where building is strongly discouraged because they were formerly used as gasworks.

As already noted, those enthusiastic about the use of hydrogen as an energy carrier take comfort from the fact that it was used, fairly successfully, as the major component in town gas. In spite of the differences between the two networks, this is not entirely unreasonable. But one cannot take comfort from an historical precedent without also taking warning where it is due. The historical record reminds us that it is very hard to do just one thing; hydrogen in town gas was relatively clean at the point of use, and welcomed for that reason, but it created an enduring pollution problem at the centralised production works, a downside cruelly visited in fact upon those economically excluded from its upside. Contemporary enthusiasm for hydrogen should be tempered by an awareness of the potential for something similar even today. Hydrogen may be clean at the point of use, but its very numerous production centres will have significant local environmental impacts, water usage amongst them, as well as serious disadvantages of cost. Methane replaced town gas for very good reasons, and a carelessly premature return to hydrogen could easily be a step into the past rather than the future.

Notes

1. CCC 2019.
2. MacKay 2009.
3. MacKay 2009 p. 129.
4. Some small variations will be observed between certain data points in these tables, and in subsequent tables drawn from other sources. These discrepancies are not material.
5. IEA 2019, p. 18.
6. p. 20.
7. See the list in IEA 2019, pp. 21–22.
8. http://www.iahe.org.
9. IEA 2019.
10. CCC 2018, p. 91.
11. Hausmann et al. 2013, p. 74.
12. Marchetti 2007.
13. Marchetti 1973.
14. Hoffmann 2012, 12.
15. IEA 2019a, p. 19.
16. https://www.nedo.go.jp/english/introducing_index.html.
17. Teed 1919.
18. Teed 1919, p. 1.
19. For this history, and the subsequent development at ICI's Billing site, see Murkin and Brightling 2016.
20. Teed 1919, p. 9,
21. Murkin and Brightling 2016, p. 264.
22. See Rigden 2002.
23. IEA 2019, 37ff.
24. IEA 2019, p. 44.
25. IEA 2019, p. 43.
26. IEA 2019, p. 44.
27. Marchetti 1973, 1998, 2005.
28. CCC 2019b, p. 61.
29. CCC 2019a, 2019b.
30. CCC 2019a, p. 141.
31. CCC 2019b, p. 64.
32. CCC 2019a, p. 137.
33. CCC 2019a, p. 27.
34. CCC 2019a, p. 29.
35. CCC 2019a, p. 34.
36. CCC 2019a, p. 145.
37. CCC 2019a, p. 145.
38. CCC 2018, pp. 32–33.
39. All estimates from CCC 2019b, p. 61.
40. IEA 2019, pp 89–165 is an up-to-date summary.
41. CCC 2019a, 2019b.
42. CCC 2018.
43. IEA 2019.
44. CCC 2018, p. 69.
45. Bossel et al. 2004, p. 91.
46. IEA 2019, Assumptions Annex, p. 3.

47. CCC 2019a.
48. IEA 2019, Assumptions Annex, p. 3.
49. IEA 2019, Assumptions Annex, p. 3.
50. CCC 2019b, p. 21.
51. CCC 2019b, p. 60.
52. IEA 2019, Assumptions Annex, p. 3.
53. IEA 2019, Assumptions Annex, p. 3.
54. IEA 2019, p. 54.
55. CCC 2019b, Figure 2.3.
56. CCC 2019b, p. 61.
57. CCC 2018.
58. CCC 2019a.
59. CCC 2018.
60. CCC 2019a, CCC 2019b.
61. EPA 2008.
62. IEA 2019, Assumptions Annex, p. 3.
63. IEA 2019, Assumptions Annex p. 3.
64. CCC 2019b, p. 61.
65. CCC 2009b, p. 64.
66. CCC 2018, p. 7.
67. CCC 2018, p. 80.
68. https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/.
69. CCC 2018, passim.
70. CCC 2019a, p. 29.
71. CCC 2018, pp. 28–29.
72. CCC 2018, p. 82.
73. CCC 2018, p. 82.
74. Gammer 2015, CCC 2018, Strbac et al. 2018.
75. 2018, p. 85.
76. CCC 2018, p. 87; See also Strbac et al. 2018, Supporting Data.
77. Strbac et al. 2018, p. 71.
78. CCC 2018.
79. CCC 2018, pp. 86, 108.
80. CCC 2018, p. 107.
81. IEA 2019a, p. 43.
82. Lampert et al. 2015, p. 32.
83. Lampert et al. 2015, p. 32.
84. CCC 2018, p. 79.
85. NREL 2001, p. 15.
86. Lampert et al. 2015 p. 32.
87. NREL 2001.
88. IEA 2019, p. 43
89. CCC 2018, p. 79.
90. Wood Group 2019, p. I20, p. J29.
91. CCC 2019a, p. 64; see also p. 233.
92. CCC 2018, p. 62; see also p. 67.
93. CCC 2018, p. 79.
94. CCC 2019a.
95. CCC 2019b.
96. Ricci et al. 2010, p. 230.

97. Ricci et al. 2010, p. 235.
98. Rifkin 2002.
99. Ausubel 2007.
100. Vowles 1931, p. 258.
101. Thomas 2014c, p. C19; Hodges 2015, p. 19.
102. Routledge 1899.
103. Routledge 1899, p. 777.
104. Thomas 2014a, p. A9.
105. Williams 1981, p. 19.
106. Thomas 2014b, p. B8.
107. Williams 1981, p. 29–30.
108. Thomas 2014a, p. A41.
109. Routledge 1899, p. 777.
110. Routledge 1899, p. 776.
111. Williams 1981, p. 35–36.
112. Manufactured by Otto and Langen from 1878 onward.
113. Williams 1981, pp. 37–38.
114. Williams 1981, p. 38.
115. Williams 1981, p. 19.
116. Routledge 1899, p. 766; Williams 1981, p. 182.
117. Frazer-Nash 2018, p. 2.
118. As reported by Dodds and Demoullin 2013.
119. Vowles and Vowles 1931, p. 256.
120. Thorsheim (2002, p. 383) reports that London had 2,000 miles of mains, presumably defined in the same maner as Vowles and Vowles 1931.
121. Frazer-Nash 2019, p. 20.
122. See Kreitman 1976.
123. Thorsheim 2002, p. 382.
124. Williams 1981, p. 19.
125. Kreitman 1976, p. 87.
126. Kreitman 1976, p. 90, p. 92.
127. HSL 2015 p. 17.
128. https://www.youtube.com/watch?v=gXJjtMbfniY.
129. Harkin 1998; Lovins and Williams 1999, p. 7; Lovins 2003/2005; Rifkin 2002, p. 212; Hoffmann 2002, pp. 233ff; Hoffmann 2012, 281–284; McAlister 2003, pp. 85–87; Romm 2004, p. 104, and many minor echoic sorces discussed in Grossman 2009.
130. Bain 1999, Bain 2001, Bain 2004.
131. For example Crane et al. 2010, p. 67.
132. Harkin 1998.
133. Dessler 2004, Dessler et al. 2005, DiLisi 2017; Grossman 2009; Grossman 2018; Grossman et al. 2019.
134. See Dessler 2004, Dessler et al. 2005, and DiLisi 2017.
135. Tsuruda 2013.
136. DiLisi 2017.
137. Bain 1999, 2001. See also the statements by his collaborator, R. G. van Treuren 2001.
138. Bain 2004.
139. See the timeline on pp 214–218.
140. See Dessler 2004, Dessler et al. 2005 and DiLisi 2017.
141. Bain 2004.
142. Quoted, for example, in DiLisi 2017, p. 270.

143. Grossman 2011.
144. Grossman 2011.
145. Hoffmann 2002, 2012.
146. HSE 2011, p. 4.
147. Geuss 2019.
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149. As predicted by Ricci (2010).
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