Review

Decarbonising energy: The developing international activity in hydrogen technologies and fuel cells

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Abstract

Hydrogen technologies and fuel cells offer an alternative and improved solution for a decarbonised energy future. Fuel cells are electrochemical converters; transforming hydrogen (or energy sources containing hydrogen) and oxygen directly into electricity. The hydrogen fuel cell, invented in 1839, permits the generation of electrical energy with high efficiency through a non-combustion, electrochemical process and, importantly, without the emission of CO₂ at its point of use. Hitherto, despite numerous efforts to exploit the obvious attractions of hydrogen technologies and hydrogen fuel cells, various challenges have been encountered, some of which are reviewed here. Now, however, given the exigent need to urgently seek low-carbon paths for humankind’s energy future, numerous countries are advancing the deployment of hydrogen technologies and hydrogen fuel cells not only for transport, but also as a means of the storage of excess renewable energy from, for example, wind and solar farms. Furthermore, hydrogen is also being blended into the natural gas supplies used in domestic heating and targeted in the decarbonisation of critical, large-scale industrial processes such as steel making. We briefly review specific examples in countries such as Japan, South Korea and the People’s Republic of China, as well as selected examples from Europe and North America in the utilization of hydrogen technologies and hydrogen fuel cells.

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A Tribute to Professor Dang Sheng Su

I first met Professor Dang Sheng Su in Berlin in 2010 when he and one of his mentors, Professor Robert Schlögl, organised a highly successful symposium devoted to the applications of electron microscopy to the frontier science area concerned with catalysis, energy conversion and cognitive topics. They had succeeded in assembling many of the world leaders that were working in this area. All those who attended were very pleased with the success of the event; and they expressed the hope that similar symposia would be held in future years, which, indeed they were (in 2012 and 2014).

My first impression of Professor Su was also the lasting one that he left with me: a resourceful, highly intelligent and dispatchful scientist, brimming with energy. Every personal encounter I had with him was pleasant and rewarding. We met, by chance, on one occasion, when I was staying in a hotel in Vienna, where I had been invited to give two short talks there in the University. It was such a pleasure meeting him on that occasion. Realising that we had not planned our meeting, he was full of enthusiasm about our encounter.

Others in this special issue can write more extensively about his vibrant personality and achievements. I simply wish to put on record my memories of him as a vitally interesting and able scientist; and the fact that it was a privilege for me to know him. His passing is mourned by a large circle of scientists and others who worked with him and who admired his scientific and personal qualities.

I have a feeling that he would be very interested in the paper that my colleagues and I have herewith submitted, especially since we devote quite a fraction of our discussion to the lead given by China, Japan and S. Korea in the drive towards the hydrogen economy.

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Cambridge, UK
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1. Introduction

Numerous countries across the world are now urgently engaged in advancing a low-carbon or decarbonised energy future for humankind. In particular, the merits of moving away from vehicles powered by fossil fuel internal combustion engines towards battery-operated vehicles are being strongly advocated and enthusiastically implemented [1].

In a major study, the US National Academy of Sciences has recently addressed many of the challenges of achieving a future dominated by carbon-free energy [2].

In this article we highlight several vignettes that reflect a complementary approach; namely, the implementation across the globe of hydrogen energy technologies and hydrogen fuel cells as a route to the effective decarbonisation of transport, energy and manufacturing. Our aim is to demonstrate that commendable technological solutions in this area are currently being implemented, worldwide, to help redress the adverse environmental effects of our carbon-based energy sector. We are convinced that the prospects of hydrogen as an energy carrier or vector will, if appropriately implemented, ultimately help humankind towards a goal of a low- or zero-carbon energy future.

In addition to discussing the adoption of hydrogen fuel cells for transport, we also discuss their uptake as stationary power sources and domestic systems, and the conversion of natural gas networks to a hydrogen mixture as a means of significantly reducing the emission of CO₂. We also outline increasing efforts to utilise hydrogen in critical, difficult-to-decarbonise, high-CO₂ emission manufacturing industries, e.g. steel-making. There also exist many applications that are inherently technically challenging for conventional battery sources, but not for hydrogen fuel cell power applications, particularly heavy transport including buses, trucks, rail and maritime applications such as ferries. The increasing large-scale use of fuel cell powered fork lift trucks and their proposed use of drones are examples of an unfolding revolution in the application of hydrogen fuel cell technology in logistics, see Box 1. The superiority of hydrogen fuel cells in these instances is not in doubt.

Box 1. HYDROGEN TECHNOLOGY: THE NEW LOGISTICS

Over recent years there has been a trend for an increasing amount of on-line shopping with major debates about the social implications of this on communities. Intuitively, this leads to fewer private car journeys although discussion with transport officials reveals that this is a more complex situation than it appears in view of increased deliveries. Nevertheless, there is an increase in distribution centres and this provides a real world example of a use case for a fuel cell powered vehicles – the fork lift truck for moving goods within the distribution centre and the use of uncrewed air vehicles (UAVs) for “last mile” home deliveries.

Already, there are 25,000 fuel cell powered fork lift trucks in use in the US [3]. Amazon is investing in this technology [4,5]. Amazon Prime Air is expected to start a drone delivery service in selected cities by the end of 2019 [6]. There are proposals [7] by several suppliers for hydrogen fuel cell powered drones for this purpose on the argument that these UAVs typically have 3 times the radius (9 times the area coverage) of an equivalent battery operated vehicle.

This is an example of how a change in societal behaviour leads to the adoption of technology for both technical and commercial reasons in unforeseen way.
Fig. 1. Copy of Grove’s letter to Faraday\(^1\) (a) in which he describes his “curious voltaic pile” (Copyright © Royal Institution of Great Britain). After John Meurig Thomas, W.R. Grove and the fuel cell. Philosophical Magazine 92 (2012): 3757–3765 and (b) Grove's 1839 fuel cell (Wikipedia).

2. Historical background

Fuel cells are electrochemical devices, transforming hydrogen (or hydrogen-containing fuel feedstocks) and oxygen directly, with high efficiency, into electricity and heat with only water as the emission product at their point-of-use. The electrochemical cell is one in which the free energy of combustion of a chemical fuel is directly converted into electrical energy – remarkably, without the aerial combustion process and the concomitant emission of CO\(_2\). The notion of a fuel cell goes back to the invention by William R. Grove, a lawyer and amateur electrochemist [8,9]. Grove used two platinum electrodes dipping into an electrolyte, at one of which hydrogen underwent the following catalytic reaction: \(2\text{H}_2 \rightarrow 4\text{H}^+ (\text{ads}) \rightarrow 4\text{H}^+ + 4\text{e}^-\); and at the other, the reaction: \(\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}\). The overall electrochemical–note; not combustion–process is then simply: \(2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}\) with a generated electric current now flowing into an external circuit. Grove himself regarded his invention as a “gas cell”. And in a famous letter that he wrote to Michael Faraday in 1842, he described it as a “curious voltaic pile” (see Fig. 1).

A useful summary of the different types of fuel cells has been produced by the US Department of Energy [10], and a typical, widely-used fuel cell is the so-called proton exchange membrane fuel cell, depicted in Fig. 2.

The term “fuel cell” was coined by the industrialist Ludwig Mond who in 1889 advanced the critical finding that this electrochemical oxidation of hydrogen [11], rather than the oxidation of hydrogen in an aerial combustion process, was the thermodynamically more efficient process for releasing energy (see later). Since hydrogen can be continually fed to the cell, Mond regarded it as a “fuel” and Grove’s electrochemical cell was no longer described as a battery, but rather as a “fuel cell”.

The Nobel Prize winning chemist, Wilhelm Ostwald [12] also realised that, in principle, the electrochemical generation of power in a fuel cell was much more efficient than the conventional combustion of fossil fuels. Ostwald, therefore, speculated that it might be possible to electrochemically “burn” coal and he further speculated whether this would be the 20th century method of choice for generating power.

2.1. Francis Bacon and fuel cells

A century after the pioneering demonstration by Grove, the first practical hydrogen-oxygen fuel cell was developed by Francis Thomas Bacon (a direct descendent of the Francis Bacon of Novum Organum fame), who began his influential studies in fuel cells in the mid-1930s [13].

Notably, his patents for the fuel cell were licensed by the US Company, Pratt & Whitney, to provide electrical power for the Apollo moon mission in 1969. Remarkably, it was largely Bacon’s work that enabled the Apollo 11 crew to partly power their craft and also to produce clean, drinking water for them during their epic voyage, a combination deeply appreciated by the astronauts (see Fig. 3) Indeed, President Richard M. Nixon told Bacon, “Without you Tom, we wouldn’t have gotten to the moon.”

That period marked a significant and highly successful advance in the precisely targeted application of hydrogen fuel cells in the US.

Bacon gave a memorable Friday Evening Discourse at the Royal Institution of Great Britain on 12 February, 1960 [14]. During the course of his presentation he said:

“The efficiency of all heat engines, that is to say, engines in which heat is converted into mechanical work, is governed by Carnot’s cycle: this means that the efficiency is limited in practice by the difference in temperature at which the heat is taken in by the working fluid and the temperature at which it is rejected. It is the possibility of avoiding the Carnot limitation which constitutes the main, but not the only, reason for interest in fuel cells”.

Apart from the merits described extensively elsewhere [15], Bacon (who used an alkaline electrolyte in his cell) emphasized that fuel cells operated silently, and that they were independent of the prevailing conditions of the wind or the sun. Interestingly, he also advocated using nuclear reactors to electrolyse water so as to build up adequate storage of hydrogen for future use in fuel cells, an idea put forward again recently (2019) by Rolls Royce plc [16].

\(^1\) London Institution
Saturday Oct 22 1842
My dear Sir

I have just completed a curious voltaic pile which I think you would like to see, it is composed of alternate tubes of oxygen & hydrogen through each of which passes platina foil so as to dip into separate vessels of water acidulated with sulphuric acid the liquid just touching the extremities of the foil as in the rough figure below.
2.2. President George W. Bush and the hydrogen fuel cell

In his State of the Union address on January 28, 2003 [17], President George W. Bush made the following statement:

"With a new national commitment, our scientists and engineers will overcome obstacles to taking these (hydrogen fuel cell cars) from laboratory to showroom, so that the first car driven by a child born today will be powered by hydrogen and pollution free".

Whilst, in retrospect, President Bush’s remarks may now appear overly optimistic, it must not be forgotten that as early as 1966, General Motors (GM) in the US developed the first fuel cell road vehicle, the Chevrolet Electrovan [18]. The Electrovan was considered the most advanced electric vehicle ever built at the time. As the first fuel cell powered automotive vehicles, it was rated as a major technical achievement in 1966. In 2007, GM launched “Project Driveway,” a 119-vehicle fleet of hydrogen fuel cell-equipped Chevrolet Equinoxes that were driven in daily use for more than 3 million miles by more than 5,000 consumers. It was the world’s largest fuel cell vehicle fleet ever assembled at the time. It eloquently demonstrated the viability of a hydrogen based transportation system.

3. International strategies towards hydrogen technologies and hydrogen fuel cells

We present here a brief overview of several international efforts centred on:

(i) Using hydrogen as a secondary energy vector. Excess electrical power generated from renewable energy sources – such as wind and solar – then being used for the production of hydrogen by electrolysis. This hydrogen, acting as a storage vector for renewable energy, can be used for (ii) and (iii) below, in addition to large-scale industrial processes such as ammonia and steel production.

(ii) Harnessing hydrogen fuel cells as key energy providers, not only for transport (land, air and maritime), but also in stationary power sources.

(iii) Developing the putative conversion of domestic natural gas networks to ones operating solely, or partially, with hydrogen, a conversion that would massively reduce the emission of CO2 into the atmosphere.

In so far as defining what, precisely, is meant by a hydrogen society or a hydrogen economy, one of us (Peter P. Edwards), with colleagues, has previously outlined a possible working definition [19].

A future “hydrogen energy economy” is one in which the dominant role currently played by fossil fuels as an energy vector, especially in personal transportation, would instead be fulfilled by hydrogen, almost invariably associated with the extensive use of fuel cells. The term is often associated with a cleaner future energy economy, which increasingly relies more heavily on renewable or sustainable rather than fossil energy sources, and in which hydrogen, as a secondary energy carrier, will be the principal currency for the transfer of chemical potential energy. One can therefore distinguish between a sustainable hydrogen economy, in which fossil fuels can play no part, hydrogen production is achieved without them, and a transitional hydrogen economy, in which hydrogen will almost certainly be generated using fossil fuels (for example, by the steam reforming of methane) while an infrastructure for hydrogen production, distribution, and end utilization, for vehicular transportation especially, is established.

A 2008 representation of the essential ingredients of a possible hydrogen energy society or economy is shown in Fig. 4.

4. Activities and developments in a global context

4.1. In Japan

Several years ago the government of Japan expressed their strong intention to implement a Hydrogen Society (Fig. 5). Indeed, this concept of a hydrogen and fuel cell based society or economy has been under continuous and active consideration in Japan since 1993 [20].
For more than 30 years in downtown Tokyo and many other Japanese cities, shopping malls, schools, hospitals and other centres of population have been successfully powered by hydrogen fuel cells.

In March 2019, the Fuel Cell and Hydrogen Energy Association (FCHEA) published [21] several key facts that reflect the impressive extent of activities being pursued in Japan concerning hydrogen fuel cell development. The view expressed in that report is that hydrogen fuel cells, as a power source for several modes of transportation as well as stationary and other mobile applications, will allow Japan to significantly diversify and strengthen its national energy infrastructure. In addition, the resulting independence from the fossil-fuel driven electric grid that distributed electrical power from hydrogen fuel cells would achieve a route to enable Japan to move towards a more self-sustaining, clean and secure energy future. Encouraged by their Prime Minister, Shinzō Abe, the country’s aim is to reduce the price of hydrogen fuel to as little as a fifth of the 2018 price. In this way, Japan aims to reach a target of 40,000 fuel cell electric vehicles (FCEVs) on its roads by 2020 and 800,000 by 2030. To support such a large-scale increase, the Japanese Government also plans to enact new regulatory reforms to accelerate the construction of hydrogen fuelling stations, up to 320 Nationwide by 2025.

Advanced uses have also been made of stationary power sources that use fuel cells. These operate quietly and have extremely low undesirable emissions, so that they can be installed more or less anywhere and can be part of a distributed, micro-grid configuration and, notably, useful at times of natural disasters for use in off-grid regions. Importantly, fuel cells provide power on-site directly to customers without the efficiency losses of long-range grid electricity transmission.

The Tokyo Metropolitan Government (TMG) aimed to develop a CO₂-free hydrogen power source for extensive use during the Tokyo Olympic/Paralympic Games. All official vehicles to be used during the Games were to be fuel cell powered. Moreover hydrogen as a source of energy was to be used throughout the event; and hydrogen pipelines installed in the Olympic Village, the ultimate aim being that an Olympic “Hydrogen Society” would have been one of the enduring legacies of the Games.²

² As the iconic Bullet Train remains for the 1964 Games [22]. The Games, originally scheduled for 2020 have now been postponed until 2021 as a consequence of the COVID-19 pandemic.

The plan by TMG is to use some hydrogen produced by electrolysis using at least some renewable energy generated at a new facility in Fukushima Prefecture [23]. It was intended that hydrogen refuelling stations during the Games would be installed in industrial areas and districts, so that these may be harnessed to supply domestic electricity and to heat municipal buildings. The overall aim is to facilitate new business models for using hydrogen in residential areas. An excellent review of hydrogen technologies and developments in Japan has recently been published and includes (Fig. 8 ibid) specifications of fuel cells for business and industry use [24].

In December 2019, Japan launched the world’s first liquefied hydrogen transport ship – the Suiso Frontier – expected to be fully seaworthy in late 2020. This will be used for shipping hydrogen from Australia and demonstrates a commitment to the hydrogen society in Japan [25]. However, this raises several significant environmental issues. A think tank (the Australia Institute) claimed in November 2019 that the projections for Australia’s hydrogen roadmap inflates the market requirement for hydrogen by Japan and South Korea by a factor of 11. Initially, the hydrogen would be produced in Australia from lignite – brown coal – and a fossil fuel-based hydrogen export industry will almost certainly result in increased Australian emissions. Japan’s main incentives are energy security and lower domestic emissions. However, this can be seen as simply exporting Japan’s CO₂ emissions to Australia [26].

Coal-based, so-called “Brown hydrogen” production could make it possible to capture and sequester the CO₂ in bulk as the by-product of the production process Nevertheless, this does not appear to be a priority in the pilot project. If so-called “Green hydrogen” production from water electrolysis using renewable energy is developed, the obvious dilemma is thereby raised; namely, “...whether a drought-stricken country like Australia would be keen on sending fresh water overseas in the form of hydrogen” [27].

4.2. In China

In December 2016, China’s 13th Five-Year Plan included a National Fuel Cell Technology Roadmap, which laid out ambitious targets for hydrogen fuel cell and hydrogen energy development, primarily for transport. The Roadmap called for over 1,000 hydrogen-refuelling stations to be in operation by 2030, with hydrogen production mainly coming from renewable energy resources. In addition, the Roadmap set a target for over 1 million fuel cell electric vehicles in service by 2030 (See Fig. 6). A series of detailed technology road maps for fuel cell vehicles for China may also be found elsewhere [28].

In 2018, to overcome the current gaps in the country’s knowledge and fuel cell infrastructure, China began to invest heavily in foreign hydrogen fuel cell technology. Weichai Power, China’s largest state-owned diesel engine manufacturer purchased a 20 percent stake in fuel cell manufacturers Ballard Power Systems (Canada) and Ceres Power (UK). Air Liquide signed an agreement with Sichuan Houpu Excellent Hydrogen Energy Technology to build and market hydrogen-refuelling stations in China. Ceres
Power are leaders in solid oxide fuel cell technology. This particular type of fuel cell is highly efficient and stable, but, unfortunately, requires a high operating temperature. However, these solid oxide fuel cells are particularly well suited for a variety of hydrogen-containing fuels for decentralised power generation for homes, offices and other facilities such as data centres [29].

China initially moved its Government subsidies from battery electric vehicles to hydrogen fuel cell vehicles, but then announced all subsidies will be withdrawn to eliminate a “subsidy culture” in an attempt to promote competition. However, the decision to eliminate subsidies on New Energy Vehicles (to include battery electric and fuel cell vehicles) was reversed on 10 January 2020 [30].

There is a partnership with Toyota, which will supply key fuel cell technology to China’s First Automobile Works (FAW Group), and Higer Bus. Both are major players in the truck and bus segment. Toyota is also setting up a research institute in Beijing in partnership with Tsinghua University to study car technology using hydrogen power and other green technologies.

It only took a decade for China to build the world’s largest battery electric vehicle market. Now the architect behind that success, Wan Gang (Minister of Science and Technology, 2007–2018), wants to do the same for hydrogen-powered fuel cell electric vehicles. The strategy is captured in a perceptive and strong statement [31] made by Huang Libin, a spokesman for the Ministry of Industry and Information Technology (MIIT):

“Hydrogen fuel cell vehicles and pure electric vehicles with lithium batteries are important technical routes for new energy vehicles. Pure electric vehicles are more suitable for urban and short-distance passenger travel, while hydrogen fuel cells are more suitable for long-distance and large commercial vehicles. We believe that hydrogen fuel cell vehicles and pure electric vehicles will coexist and complement each other for a long time to meet the needs of transportation and people’s travel.”

It is noteworthy that an unmanned aircraft powered by hydrogen fuel completed 10 test flights, significant progress by its developer, the Commercial Aircraft Corporation of China, in exploring new propulsion methods for aircraft [32]. Fuel cells are more suited as a means of power for aircraft flying at low altitudes since the water exhaust has a potential deleterious effect at higher altitudes [33].

According to a city development plan, Wuhan, capital city of central China’s Hubei Province, will build itself into a “Hydrogen City” through developing hydrogen energy industry [34]. It is reported that the city is to advance research and development of core technology of hydrogen production, storage and transport, and improve hydrogen infrastructure in the coming years. Grove Hydrogen Automotive, named in honour of the fuel cell pioneer, is an upmarket automobile producer located in Wuhan.

4.3. In South Korea

In an announcement in January 2019, the Government of South Korea laid out an ambitious roadmap for a hydrogen society. Its stated goals are the production of 6.2 million fuel cell electric vehicles and also the construction of 1,200 refuelling stations across the country by 2040 (Fig. 7). Another projection is 630,000 hydrogen fuel cell vehicles on the road by 2030. The plan is for hydrogen to drive a new economic growth engine and turn South Korea into a society fuelled by eco-friendly energy [35].

Sales of the Hyundai Nexo fuel cell vehicle (FCV) passed the 1,000 mark in 2019 [36] and the company is also opening a series of hydrogen-refuelling stations. Hyundai is also producing a heavy fuel cell powered truck for possible entry into the US market [37]. Daesang Green Energy is constructing one of the largest hydrogen fuel cell power plants in the world, and is expected to be operational in June 2020 [38]. More than $200 million has been committed to the 50 MW plant, which will generate electricity for 80,000 homes [39,40].

It is interesting to note that despite energy independence being a stated goal of the Government roadmap, that document also pronounces that it seeks to “Establish overseas production base” [41]. This appears to be linked with the policy of the Australian government, which has a programme aimed at becoming as a global supplier of hydrogen in the near future [42,43].

4.4. In the USA

Throughout this paper, there are references to US activities in many contexts such as the pioneering application of hydrogen fuel cells to space travel, recent societal changes (Box 1) to novel methods of hydrogen production (Section 5). Even though the George W. Bush initiative stalled when many experts believed that a broader-based, nearer-term energy policy would mark a surer route to the same goals of a low carbon energy future [44], there are now many ongoing activities, a selection of which are described below.

As an example of fuel cell development for heavy haulage, the Nikola Motor Company is reinventing its trucking fleet by replacing diesel heavy-duty trucks with hydrogen fuel cell trucks. It is reported that Anheuser-Busch has ordered hundreds of hydrogen trucks from Nikola. The deal, for “up to 800” trucks, is 20 times as big as the one the beer distributor struck with the Tesla company [45].

In another example [46], a Toyota and Kenworth venture is deploying 10 hydrogen fuel-cell semi-trucks at the Ports of Los Angeles and Long Beach in California. The project is being funded in part by the California Air Resources Board.

Refuelling infrastructure is obviously a key issue for the uptake of fuel cell vehicles (FCVs). The Fuel Cell Technologies Office (FCTO) of the United States Department of Energy (DOE) reports that as of January 25, 2018, there are 39 publicly available hydrogen stations for fuelling (FCV) in the United States – 35 in California, 2 in South Carolina, and 2 in the Northeast. Another 29 public stations in California and 5 in the Northeast are planned [47].

Selected examples of advanced projects include the following. In May 2019, NASA announced [48] support for a University of Illinois (Urbana-Champaign) examination of the use of liquid hydrogen as fuel cells that generate electricity to propel an aircraft. The supercooled liquid would be used to enable the highly efficient superconducting electrical systems.

Washington State University’s School of Mechanical and Materials Engineering has received a grant from the U.S. Army to demonstrate a liquid hydrogen-powered UAV and refuelling system. The $7.2 million total grant includes researchers from Mississippi State University, Insitu Inc., and Navmar Applied Sciences Corporation. Insitu, a subsidiary of Boeing, will provide their ScanEagle® UAV, equipped with a fuel cell-powered electric engine [49].

It is apparent that these activities are clearly not part of a coordinated national programme as in the earlier George W. Bush initia-
tive, but rather dispersed and initiated by regional and industry-led programmes. A coalition of 19 companies including auto, truck, energy, information systems and analytical support have an ambitious roadmap on how the US could lead in hydrogen technologies [50].

The roadmap suggests nine actions, including decarbonisation goals, infrastructure development and reviewing energy sector regulations to ensure they account for hydrogen.

Despite laudable activities within the US Department of Energy [51], such as the injection of $40 million in August 2019 for a range of hydrogen-related projects [52], it is unclear if a co-ordinated national strategy will be forthcoming to compete on the same scale as Japan and China. Furthermore, the crisis drivers of the past decades are not immediately apparent. In December 2018, the U.S. became a net oil exporter for first time in 75 years [53] and in August 2017, withdrew from the Paris Climate Accord [54]. Therefore, there might not be the same incentive to develop a "Hydrogen City" like Wuhan [34].

4.5. In Germany

Germany approved its National Innovation Programme for Hydrogen and Fuel Cell Technologies for a further ten years with EUR 1.4 billion of funding, including subsidies for publicly accessible hydrogen refuelling stations and fuel cell vehicles, to be complemented by EUR 2 billion of private investment. Germany operates the first commercial hydrogen-powered train and there is a large annual increase in the number of refuelling stations, with an estimated 100 by the end of 2019 [55].

The German automobile industry is embracing hydrogen technology through the development of fuel cell vehicles with the Audi company leading this effort. Chairman Bram Schot has stated that the reasons behind the move include continuing environmental and humanitarian concerns over the necessary natural resources for battery production (particularly lithium and cobalt) and doubts over electric cars being able to deliver on ever-more demanding customer requirements [56].

German companies are actively developing Green hydrogen technology and are collaborating with companies such as Royal Dutch Shell plc to bring production to commercial scale to develop a national hydrogen infrastructure. There is also consideration of use of hydrogen mixtures in the gas grid and for large-scale industrial processes such as steel making [57]. For the last 200 years, the incumbent, worldwide technology of steel production leads to the continuous emission of copious amounts of CO2. Germany has made significant strides in converting steel production units that normally liberate CO2 to those that liberate only water by using hydrogen instead of carbon to reduce iron oxide [58-60]. We note also that the related Swedish project ‘Hybrit’ (Hydrogen Breakthrough Ironmaking Technology) is set to produce the ambitious target of so-called “zero-carbon steel” from 2020 onwards also by using hydrogen instead of carbon as the reactant in the reduction of iron ore to elemental iron [61]. Steel making is a forefront, excellent example where the use of hydrogen can lead to truly significant decarbonisation in an otherwise highly carbon-intensive industrial process.

Up to 1500 radio tower (cellular telephone) sites in Germany could receive their emergency back-up power from hydrogen fuel cells. Operators have to ensure a minimum of 72 hours power autonomy and fuel cells provide a reliable alternative to diesel generators to provide power to critical infrastructure [62].

4.6. In the UK: a prediction is realised!

There have been successful trials of hydrogen fuel cell buses in London since 2003 [63]. These early Mercedes buses only had a range of 125 miles but the trials appeared to be successful so it is surprising that there has not been more activity in the area. There was an announcement in May 2019 that 20 double decker fuel cell buses would be introduced to London although the company concerned, Wrightbus, went into receivership but has now (November 2019) been partially rescued. Since the transport sector is responsible for the highest source of CO2 emissions (33%) in the UK [64], the introduction of hydrogen fuel cell powered buses would make a valuable contribution in reducing levels of emissions as well as reducing the (recognised) toxicity of the city’s atmosphere. There are examples of emergency service interest in fuel cell vehicles in London with the Metropolitan Police Service in London launching a zero-emissions programme and has already started trialling 21 hydrogen-powered cars [65].

There are also plans in the UK to create local regions where there will be a strong emphasis on the use of hydrogen [66] and also, intriguingly, to create methods of turning waste plastic into hydrogen [67]. From December 2020, over 600 homes and businesses in Gateshead will receive gas blended with 20% hydrogen in a demonstration lasting 10 months, as part of the UK HyDeploy hydrogen blending programme [68].

As far back as 2006, the Hydrogen Energy Group, part of The Forum for Renewable Energy Development in Scotland published an ambitious vision for hydrogen [69]. There have been considerable advances and it has indeed been suggested that “Scotland could have the first 100% hydrogen network in the world”. One major achievement is HYSEAS III, a hydrogen fuel cell-powered ferry due for delivery in 2020 for use around the Orkney archipelago [70]. The hydrogen will be produced locally by electrolysis using tidal and wind power generation. It could indeed be argued that hydrogen production in Orkney, now self-sufficient in renewable electrical power, is 300 years ahead of Haldane’s more general prediction from 1923 about a future UK hydrogen economy based on renewable energy [71].

5. The grand challenge of the large-scale production of clean hydrogen

By far the largest current source of hydrogen, worldwide, originates from the steam reforming of natural gas and the partial oxidation of heavy hydrocarbons. Although highly effective and efficient, the current steam-reforming industrial process nevertheless entails a significant liberation of CO2.

Producing cost-competitive, low-carbon emission-clean, Green hydrogen in large volumes is without question the greatest barrier to developing a truly sustainable or renewable hydrogen energy society. It is recognized, worldwide, that the large-scale incorporation of hydrogen in numerous technologies and hydrogen fuel cells will not reach fruition until it becomes possible – routinely – to generate large quantities of high purity clean Green hydrogen through renewable energy routes with zero (or low) associated CO2 emissions from the production process. Once Green hydrogen can be routinely produced in massive quantities, it will undoubtedly replace the hydrogen now produced by steam reforming of methane [72].

Fuel cell electric vehicles running on hydrogen currently use filling stations, which deliver hydrogen at 70 MPa pressure. Very few stations, worldwide, currently have hydrogen produced from renewable sources like solar energy. It is, however, encouraging that photovoltaic installations during the past decade have seen a significant increase and as pointed out by Eisenberg et al. [2] that price points per kWh have become competitive with electrical energy obtained from fossil fuels. It is important to note that this situation has arisen because of the present day ability to produce photovoltaic grade silicon in large quantities – cheaply – in China as a historical consequence of extensive subsidies. Further advances in the general area of clean Green hydrogen are eagerly anticipated and surely imminent. Dubai Electricity and Water
Authority, Expo 2020 Dubai and Siemens are co-operating on a joint project that will become the Middle East and North Africa’s first solar-based hydrogen electrolysis facility [73].

In March 2019, an important agreement was signed between New Zealand and Japan [74]. This entailed the involvement of the company Halcyon Power which engaged with the Canadian Hydrogenics Corporation to install a 1.5 MW hydrogen production facility at the Mokai geothermal power plant in New Zealand. This plant will start operating in 2020, and it enables geothermal power to be used to produce hydrogen by electrolysis of water. When this initiative reaches steady state, there will be a hydrogen supply chain from New Zealand to Japan. New Zealand has also issued a consultation paper to use hydrogen as a means of storing some of its renewable energy [75].

Even though electrolyzers have in the past been considered to be rather inefficient, rapid progress is being made to make them more efficient and hence competitive with other hydrogen generation technologies [76]. It is predicted that the cost to produce hydrogen by electrolysis using renewable sources could fall by up to 80% by 2030 [77]. It is also estimated that if by 2030 the cost of hydrogen generated from renewable energy falls below $2.20 per Kg, it will be competitive to be used in steel making assuming a coking coal price of $310 per ton [78].

It should also be noted that unless renewable energy, rather than electricity generation by burning coal is used for electrolysis, steam methane reforming, which emits CO2 would still have a considerably lower environmental impact, being only about 3% that of electrolysis [79]. New catalysts are continually being developed in an attempt to replace the use of scarce and expensive platinum in the hydrogen production processes [80].

Many years prior to current climate change concerns, it is particularly interesting to note as mentioned earlier, that George W. Bush in his State of the Union address, highlighted not only the use of nuclear (fission) generated electricity for electrolysis of water, but also fusion power [17] as a means of generating clean (i.e. CO2-free) hydrogen.

As is the case for New Zealand, Norway is rich in renewable sources of energy thanks to its extensive network of hydroelectric schemes. In June 2019, the South Korean President Moon Jae-in signed a Memorandum of Understanding with Norway to co-operate in the field of hydrogen energy so as to capitalise on South Korea’s strength in hydrogen-powered vehicles and Norway’s ability to produce and supply carbon-free hydrogen [81]. Norway has a long history and experience of the use of electrolysis to produce hydrogen for industrial purposes and recent work describes the development of an electrolyzer for high-pressure steam using novel catalysts [82].

Nel Hydrogen (Oslo) is in collaboration with Nikola Motor Company (US) in the development of refuelling stations supplying hydrogen generated locally by electrolysis using renewable sources. We note also a truly ambitious programme of 700 hydrogen filling stations is planned for the US and Canada by 2028 [83]. As in New Zealand, it is also interesting to note that geothermal power is used for hydrogen production by electrolysis in Iceland (Hellsheidi Fig. 8).

Other routes to carbon-free, Green hydrogen production include pyrolysis and microwave-initiated catalytic dehydrogenation or “hydrogen stripping” of hydrocarbons. A preliminary cost estimate of thermal catalytic pyrolysis – the decomposition of methane to hydrogen and solid carbon (thus, importantly - without CO2 liberation) – shows that the cost of producing hydrogen by this process is approximately the same as that for steam reforming of methane before the cost of sequestration of either CO2 or carbon is incorporated [84]. Since the cost (both in financial and energy terms) of capturing and sequestering (gaseous) CO2 is inevitably greater than that for solid, elemental carbon, the thermal decomposition process should be less expensive and energy intensive than the steam-reforming process. Thus, it is much easier to sequester elemental carbon as a stable solid than CO2 as a dilute gas or low temperature liquid. The resulting solid carbon produced is also viewed as a marketable product for application such as fillers [84] or carbon nanotube materials. Of course, there will also be a carbon tax saving, as noted, when the product is sequestered as solid, rather than aerial carbon (CO2) through this interesting process.

A novel pyrolysis technique under investigation, yet to be scaled up, centres on the high temperature pyrolysis of methane, then bubbling through a liquid metal (or liquid metal alloy) to allow the release of the hydrogen and collection of the solid carbon [85]. The Russian company, Gazprom, have realised that their substantial European market share is likely to decline without the promise of a near zero-emissions fuel. The company has reported a low-temperature plasma thermal methane pyrolysis process, currently being trialled in Tomsk [86]. It should also be noted that considerable variations exist between European countries as to the maximum allowable blend-level of hydrogen in the natural gas grid e.g. 4% for Switzerland and 12% for the Netherlands, as a consequence of national regulatory processes. A more consistent regulatory framework would be required for a supranational gas grid. This has considerable infrastructure implications and it could be more viable to generate hydrogen at a more local level, perhaps by electrolysis using renewable energy.

Another route to carbon-free, Green hydrogen is the liberation of hydrogen, intriguingly, directly from fossil hydrocarbons themselves, including wax and even petroleum and diesel, using microwave-initiated catalytic dehydrogenation or hydrogen-stripping [87]. This provides a capability of the on-demand, distributed generation of hydrogen thus reducing the taxing requirements for storage and transportation of hydrogen either as high-pressure gas or liquid. This technique might also be applicable to generate hydrogen from other sources, such as biomass and lignite, and might be another greener route to exploit large lignite deposits such as those found in Australia. There are several claims that aluminium-based powders, which react with water or any water-based liquid produce on-demand hydrogen for power generation without a catalyst [88,89]. Similar claims are made of silicon [90] and other materials. General Atomics have been awarded a two year contract from the US Army to demonstrate a hydrogen on-demand system using the company’s aluminium alloy hydrogen generation technology [91]. Russian workers have demonstrated similar devices for application, such as chargers for mobile
devices [92]. If this technology is demonstrated to be viable, this could be transformative, since it vastly reduces infrastructure requirements for the storage and transport of hydrogen.

Hydrogen may be considered as an “indirect” greenhouse gas since it reacts with the hydroxyl (OH) radical, normally a sink for methane – a potent greenhouse gas [33]. The effect of the loss of hydrogen through leaks and its potential deleterious environmental effects by reacting with other gases in the atmosphere therefore need to be minimised. The Japanese Agency New Energy and Industrial Development Organization (NEDO) is pursuing the development of polymer materials for gas seals and dispensing hoses and improved steels, including stainless steel for hydrogen containment.

The recent discovery of natural hydrogen, for instance in Mali [93], provides another potential source of hydrogen in the longer term. This fascinating natural phenomenon has been little explored and considerable research and development would require for exploration and exploitation of these hydrogen reserves, in much the same way as it took a century for a similar development process for petroleum.

6. Concluding remarks

The perceived role of hydrogen technologies and hydrogen fuel cells in the global energy system has undergone many vicissitudes. Excessive early expectations, followed by (perhaps anticipated) disillusion, the lack of both policy stability and a long term government view have all had their roles in influencing opinions about the viability of hydrogen technologies and hydrogen fuel cells, as have been cogently described by Stafell et al. [94].

What is indisputable is that the general public is now urgently demanding replacement – even abandonment – of fossil fuels and introduction of renewable non-threatening alternative fuels that can secure the much desired low and ultimately zero-carbon scenario worldwide. Indeed “zero-carbon” has become a shibboleth by certain groups as a ready identifier of a socio-political stance.

In summary, it is our view that hydrogen obtained from renewable energy sources must surely be considered as the progenitor of the ultimate clean and climate-neutral energy systems.

We have endeavoured to demonstrate, by specific examples, that hydrogen technologies and hydrogen fuel cells, in various manifestations across the world, are now beginning to play a key role in the path towards a low-carbon future. Hydrogen technology is a key to a sustainable and renewable energy future and one of the world’s growth markets: it is also providing a breeding ground for new science and technology, new innovations, new companies, products and employment.

Declaration of Competing Interest

The Authors declare that there is no conflict of interest.

Appendix I

Recent Advances – Post submission

Since there are continuing developments, we add below a few examples since the paper was originally submitted.

An infographic has recently been published since submission of this paper illustrating the dynamic landscape of hydrogen technologies to include activities in countries not discussed in this paper [95].

The availability of low-carbon Green hydrogen produced economically, sustainably at scale is key to the utilisation of hydrogen. Recent examples include:

EDF are planning to generate hydrogen as part of the UK nuclear power update programme [96].

Recent work from the US describes research on a novel electrolysis method using an alkaline anion exchange membrane (AEM) and low cost catalysts such as nickel and iron [97]. Other studies have investigated the electrolysis of low-grade and saline surface water, an important considerations in area where water is a scarce resource [98]. Hydrogen storage is an important support technology. Liquid organic hydrogen carrier (LOHC) technology is being developed in South Korea as an alternative to compression storage [99].

In our earlier discussion on activities in China, it was mentioned that Wuhan would be a “Hydrogen City”. More recently, Zangjiaok in Hebei Province aims to become the hydrogen capital of China. Many projects are planned including a hydrogen metallurgy steel demonstration project with Tenova Group from Italy. Similar to Japan’s aspirations to have a Hydrogen Olympics (now 2021), the 2022 Winter Olympics with some events to be held in Hebei Province will also drive hydrogen developments [100]. The COVID-19 pandemic crisis will influence decisions about hydrogen production with many corporations required to make decisions about maintaining their current mainstream business rather than future investments. One example is a decision concerning the world’s largest offshore wind farm in the Dutch North Sea to produce green hydrogen where it is suggested that it is likely that this will proceed in view of the timescales involved [101].

The Energy Observer (Fig. 9), a converted ocean-racing catamaran recently completed its first 5,000-nautical mile transatlantic voyage from Brittany, France, to the Cape Verde Islands in Africa to...

Fig. 9. London, October 12, 2019: The world’s first hydrogen powered boat, the Energy Observer, sails on the Thames as part of a European tour (Loren’s London/Shutterstock).

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Martineau in the Caribbean [102]. The yacht's energy management system co-ordinates energy production and transmission from its solar panels, wind turbines and hydrogen fuel cell. This is a good example of the synergy between a hydrogen fuel cell and other electrical power generation technologies.

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