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Guest Editorial

Johnson Matthey Technology Review Special Edition on Clean Mobility

The world is at the start of an energy revolution: the biggest energy transformation since the Industrial Revolution, during which the use of fossil fuels drove growth and prosperity, with global temperature increase implications that we have only started to understand relatively recently. This energy revolution will drive the world towards a lower carbon, more sustainable future, with major implications for energy and electricity generation, heating, industrial power and transportation. Governments, states and regions are proposing, and in some cases (such as the UK) committing to, net zero greenhouse gas (GHG) or carbon dioxide emission targets over the coming years. To date, 15 countries have set defined targets to become net zero economies by 2050 or earlier, with over 50 others, including Germany and Canada, discussing when to implement such a target. Perhaps most significantly, the European Union (EU) intends to be net zero by 2050: this objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement.

Interestingly, at the time of writing, around 49% of global gross domestic product (GDP) derives from nations and regions discussing, or with legislated, net zero emissions targets to be achieved by 2050 at the latest (1). Significantly, eight months previously this figure was only 16%, demonstrating the rapid rate at which such commitments are being made. Companies are also making net zero commitments, and this pace is accelerating too: in 2017, 87 companies made such commitments, in 2018 this rose to 174, and in 2019 398 companies announced net zero targets.

Figure 1 summarises the proportion of global fossil-derived CO_2 from each of the major sectors. While electricity generation is the largest contributor, the transportation sector comes second, accounting for around 23% of global CO_2 emissions.

Figure 2 looks into the transport sector in a little more detail, revealing that passenger road vehicles contribute almost half (45%) of transport CO_2, with freight vehicles accounting for another 30%, so road transport accounts for almost 75% of the emissions. The aviation and shipping industries also release large levels of CO_2, each at around 11% of global transport-derived emissions, with rail being a relatively minor contributor, at 1%. But to add a little context, these rail CO_2 emissions are around 0.1 billion tonnes per year, the same level as those of Belgium or Austria. Therefore, it is clear that transport has a critical role to play in the global decarbonisation agenda.

Decarbonisation of Transport

This special edition of the *Johnson Matthey Technology Review* looks at the challenges faced in the decarbonisation of the transport sector, and highlights the likely solutions that will be implemented to enable this transition. The articles consider the regulatory frameworks already in place, and those likely to come in the near future, to accelerate the moves to net zero across the transport ecosystem. The current status of the technologies that will play a key role in this transition is discussed, along with expected future developments and performance targets. It is clear that both battery-based and hydrogen fuel cell-based electric vehicles will make major contributions to the decarbonisation of ground transportation, across cars, vans, buses and trucks, and these technologies are discussed in detail. Challenges with the roll-out

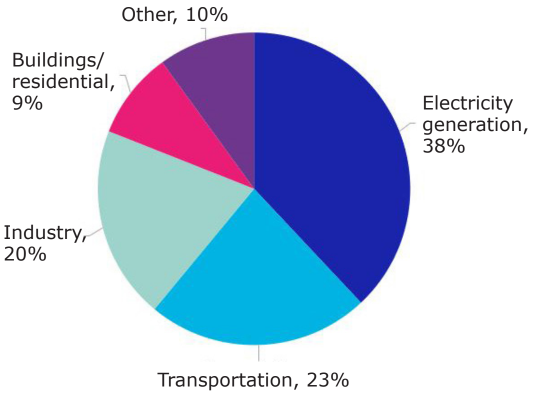

Fig. 1. Proportion of global fossil-derived CO_2 emissions by sector (2)

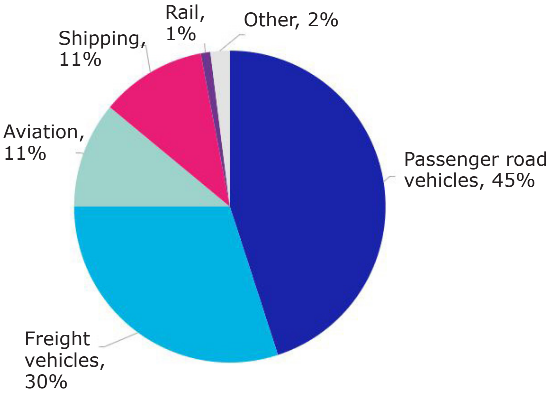

Fig. 2. Global transport CO_2 emissions by segment (3)

of the infrastructure for these new vehicles are also assessed, and the likely paths forward are presented.

Battery and fuel cell technologies are unlikely to see large scale uptake in the marine and aviation sectors in the foreseeable future, so here the focus is on the development and deployment of alternative, sustainable, lower carbon fuels which will replace the existing heavy fuel oil and aviation fuels, to mitigate carbon emissions from these two very large sectors.

Meeting net zero GHG emission targets within the transportation sector can only be achieved alongside clean generation of electricity and hydrogen, since these will be the fuels for the highest volume future transport modes (cars and trucks). Therefore, articles in this special edition also look at the changes required in electricity and hydrogen generation to enable the move to clean transport. Recall that electricity generation currently accounts for around 38% of global CO_2 emissions, so increasing the use of renewables and nuclear power are an essential piece of the net zero jigsaw puzzle.

This brings me to the final message: reducing transport CO_2 or GHG emissions to zero is not in itself enough to stabilise earth's climate. It is a critical step, but needs to take place alongside the decarbonisation of the other major sectors: power generation, industry and building heating and cooling. There is a need for a cross-sector, systems-based approach, rather than looking at individual large emitters in isolation. The article on hydrogen looks at the role that it can play as an energy vector, enabling cross-sector coupling to facilitate the decarbonisation of transport, as well as other key areas such as domestic heating, industrial processes, and as a feedstock for low or zero carbon chemicals and fuels. It also discusses hydrogen's use as a source of low carbon dispatchable power, as well as how it is a key enabler of significant increases in renewable energy or electricity generation. To reach net zero GHG emissions all the key sectors need to work together, and this special edition, though focused on transport, considers the other changes in the future energy ecosystem that link to, and in some cases enable, clean mobility.

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Powering the Future through Hydrogen and Polymer Electrolyte Membrane Fuel Cells

Current commercialisation and key challenges with focus on work at Hyundai

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To date, the world has been making a massive shift away from fossil fuels towards cleaner energy sources. For the past decade, polymer electrolyte membrane fuel cells (PEMFCs) powered by hydrogen have attracted much attention as a promising candidate for eco-friendly vehicles, i.e. fuel cell electric vehicles (FCEVs), owing to their high power density, high efficiency and zero emission features. Since the world's first mass production of Tucson ix35 FCEV by Hyundai in 2013, global automotive original equipment manufacturers (OEMs) have focused on commercialising FCEVs. In 2018, Hyundai also unveiled the second generation of the mass-produced FCEV (i.e. Nexo) with improved performances and durability compared with its predecessor. Since then, the global market for PEMFCs for a variety of FCEV applications has been growing very rapidly in terms of both passenger vehicles and medium- and heavy-duty vehicles such as buses and trucks, which require much higher durability than passenger vehicles, i.e. 5000 h for passenger vehicles *vs.* 25,000 h for heavy-duty vehicles. In addition, PEMFCs are also in demand for other applications including fuel cell electric trains, trams, forklifts, power generators and vessels. We herein present recent advances in how hydrogen and PEMFCs will power the future in a wide range of applications and address key challenges to be resolved in the future.

Introduction

For the past few decades, energy demand in the world has been rising considerably due to an increase in global population and demands for industrial production. The world has been undergoing a massive shift away from fossil fuels towards cleaner energy sources and hydrogen could be an excellent alternative for this purpose (1–3). PEMFCs powered by hydrogen have attracted much attention as a promising candidate for eco-friendly vehicles, i.e. FCEVs, owing to their high power density, high efficiency and zero emission features (4–10).

Since the world's first mass production of Tucson ix35 FCEV by Hyundai Motor Company (hereinafter abbreviated as Hyundai) in February 2013, global automotive OEMs have also focused on commercialising FCEVs (11–15), including the latest manufacturing of the second generation FCEV (i.e. Nexo) by Hyundai in March 2018 (2). Specifically, Toyota Motor Corporation, Japan, unveiled a mass-produced FCEV, i.e. Mirai, in December 2014 (11, 12). The Mirai FCEV with a seating capacity of four persons employed two hydrogen storage tanks and hydrogen compression pressure of 70 MPa. To reduce contact resistance and improve water management in fuel cells, Mirai adopted three-dimensional fine mesh flow fields which were different from conventional flow fields composed of ribs and channels. In 2016, Honda Motor Company, Japan, also deployed a mass-produced FCEV, i.e. Clarity (13). The Clarity FCEV offered a seating capacity of five persons, two hydrogen storage tanks and hydrogen compression pressure of 70 MPa. In 2017, Daimler, Germany, launched a new generation of FCEV, i.e. Mercedes-Benz GLC F-CELL, with a hydrogen storage system similar to that of other automotive OEMs (14). In June 2018, Audi, Germany, teamed up with Hyundai to share intellectual property and components of fuel cells, with the aim of accelerating the commercialisation of FCEVs and expanding the global market (15). Accordingly, the global market for PEMFCs has been expanding to a broad range of applications including not only for vehicles such as passenger (i.e. sport utility vehicles (SUVs) and sedans) and commercial vehicles (i.e. buses and trucks) but also for trains, trams, forklifts, power generators and vessels. To meet the needs and requirements for these various applications, it is essential to develop more durable and cost-effective materials, components and systems for PEMFCs. Here we present the recent advances in hydrogen and PEMFCs technologies and address remaining technical challenges and barriers to be resolved, which are critical to commercialise next-generation PEMFCs and thus power the future society.

Hydrogen

Hydrogen has been regarded as a promising candidate for alternative energy to fossil fuels because it is versatile and can be used in a broad range of applications such as transportation, chemicals, synthetic fuels and metals processing (16–30). **Figure 1** shows the concept of wide-scale hydrogen production and utilisation suggested by the US Department of Energy (DOE) (21).

In addition, hydrogen is abundant in that approximately 70 million tonne-H_2 year^{-1} is used today in pure form, mostly for oil refining and ammonia manufacture for fertilisers. A further 45 million tonne-H_2 year^{-1} is used in industry without prior separation from other gases (22). One of the key features of hydrogen production is its diversity. Hydrogen can be produced by a variety of resources including fossil fuels such as natural gas and coal (with carbon capture and storage (CCS)), nuclear energy and renewable energy sources such as wind, solar, biomass, geothermal and hydroelectric power (16–30). **Figure 2** shows an illustration of hydrogen production technologies suggested by the US DOE (25, 26). Most hydrogen is currently being produced by conventional ways based on fossil fuels (i.e. steam methane reforming (SMR) or natural gas reforming) which generate a significant amount of carbon dioxide emissions, resulting in 'brown' or 'grey' hydrogen. However, if the carbon dioxide emitted from the conventional SMR process can be captured and stored, or reused, the hydrogen produced is cleaner than grey hydrogen, which is often referred to as 'blue' hydrogen. The cleanest version of all is 'green' hydrogen which is produced

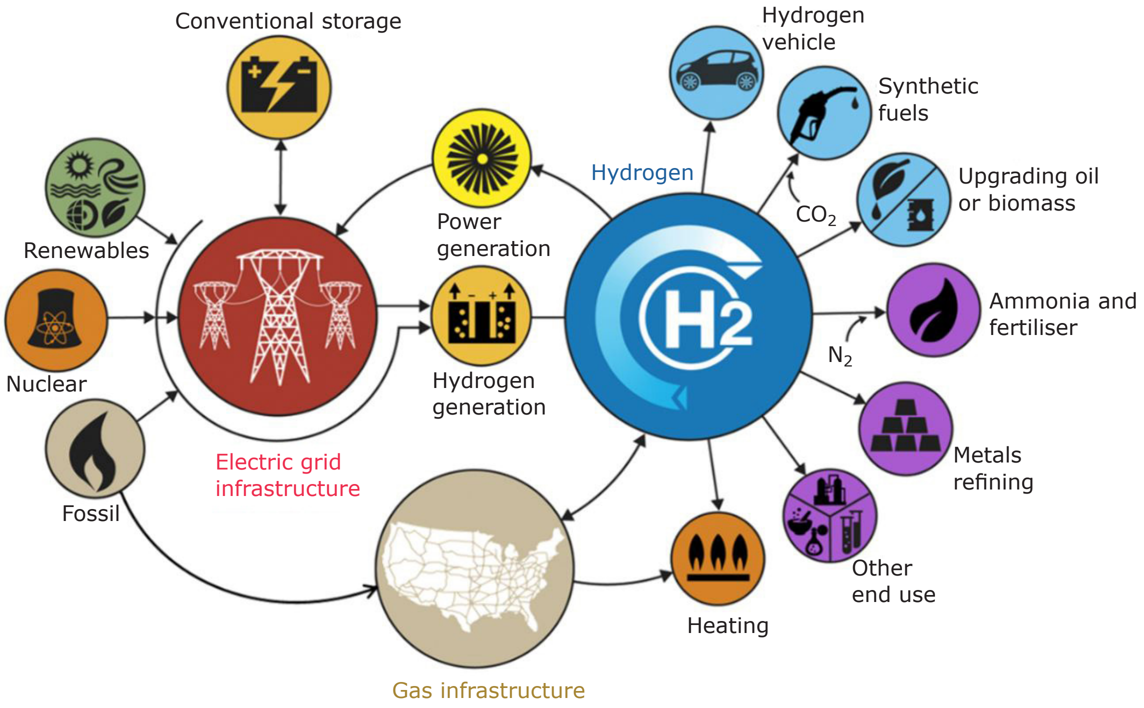

Fig. 1. An illustration of wide-scale hydrogen production and utilisation suggested by the US Department of Energy (21)

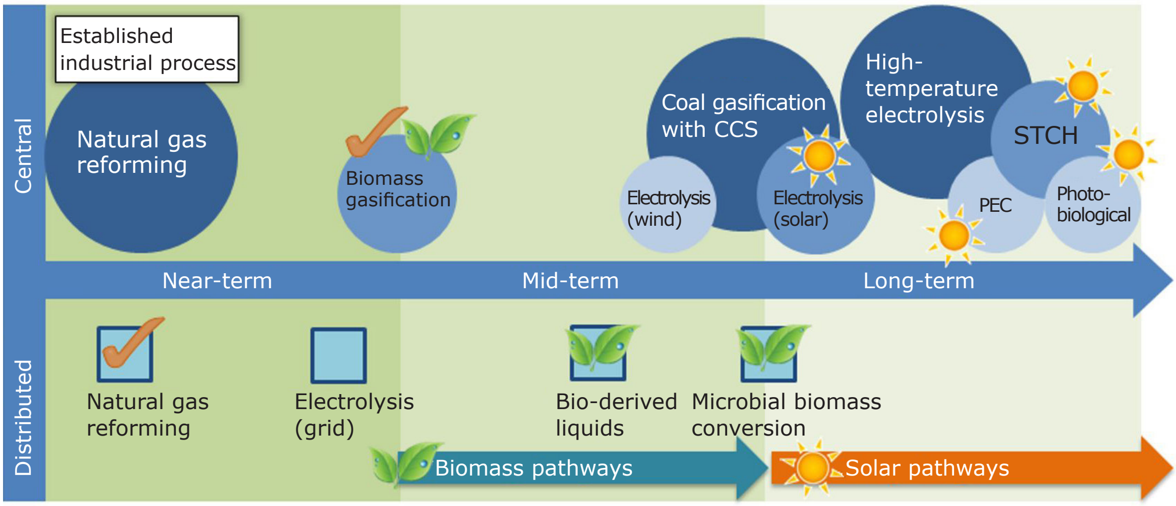

Fig. 2. An illustration of hydrogen production technologies suggested by the US Department of Energy (25, 26) (PEC = photoelectrochemical; STCH = solar thermochemical hydrogen)

by renewable energy sources such as wind or solar power, without generating carbon dioxide emissions (23–26). Although the share of green hydrogen produced by clean technologies is now relatively low, the production amount of green hydrogen is expected to increase considerably through water electrolysis powered by renewable energies, photoelectrochemical (PEC) and solar thermochemical hydrogen (STCH) techniques in the future as the hydrogen economy grows (3, 16–20, 23–26).

Hydrogen can serve as a versatile energy carrier and plays an essential role in decarbonising major sectors of the economy (27–29). In the power sector, the timing of variable electricity supply and demand is not well matched over the day nor between seasons, which increases the need for operational flexibility. For instance, the production amounts of renewables vary considerably between seasons. Solar generation in Europe is approximately 60% lower in winter than in summer, which coincides with higher electricity demand of about 40% as days become shorter and colder in winter than in summer (27, 28). Therefore long-term energy storage is necessary for large-scale renewable power integration and in this context hydrogen enables large-scale and efficient renewable energy integration through cost-effective long-term storage capability. **Figure 3** shows the electricity supply and demand simulation results for Germany in 2050 (27). In this scenario of 90% renewables in Germany, curtailment of more than 170 TWh year^{-1} is predicted for 2050, which is equivalent to approximately half the energy needed to fuel the German passenger vehicles with hydrogen. As shown in **Figure 3**, summer has curtailed periods of electricity oversupply, whereas winter has periods of electricity deficits, indicating strong mismatch between supply and demand of electricity produced by renewable energy sources (RES). Therefore, if we use water electrolysis to convert excess renewable electricity into hydrogen during times of power oversupply, the produced hydrogen can be used to provide back-up power during power deficits or can be used in other sectors such as transport based on fuel cells, industry or residential applications (21, 22, 27–29). In this way, hydrogen can bridge gaps in supply and demand of power and thus can serve as a long-term carbon-free seasonable energy storage medium (27, 28).

Hydrogen enables international energy distribution, linking renewable energy-abundant regions (for example, Australia or Norway) with those being deficient in renewable energies and thus requiring energy imports (for example, Japan or South Korea) since hydrogen can store and transport renewable electricity efficiently over long periods of time (27–33). For instance, Japan plans to launch the first technical demonstration of a liquefied hydrogen carrier ship to enter international trade in the near future (27–33). To date, hydrogen pipelines and gaseous or liquefied tube trailers are the most common ways of transport. As the distribution of hydrogen increases, the costs for liquefaction and transport are expected to drop by 30–40% by 2032 (27).

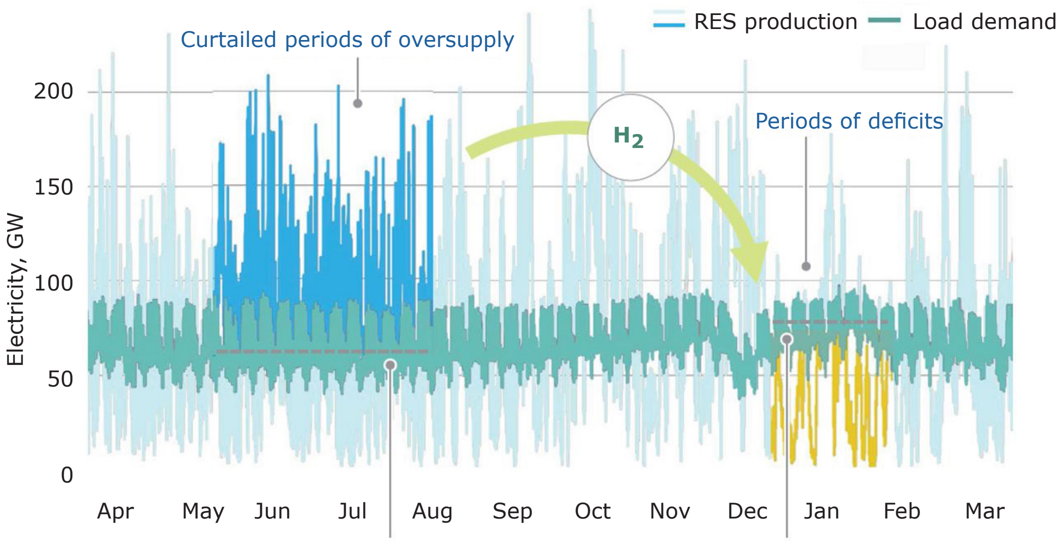

Fig. 3. Electricity supply and demand simulation results for Germany in 2050 by Hydrogen Council (27). RES indicates Renewable Energy Sources. Load demand is higher in winter while RES production is lower

Paradigm Shift in Global Automotive Industry

Here we address the recent paradigm shift of global automotive industry before going deep into the details of FCEVs powered by PEMFCs. Recently, while hydrogen has been receiving great attention worldwide and facilitating the energy transition from fossil fuels to renewable energies, the global automotive industry has been experiencing a paradigm shift from traditional internal combustion engine vehicles (i.e. gasoline- and diesel-powered vehicles) to next-generation vehicles based on future mobility concepts such as connected, autonomous, shared and electric (CASE) vehicles (also called autonomous, connected, electric and shared (ACES) vehicles) (34–36). **Figure 4** represents an illustration of future mobility concept of Hyundai which is intended to provide 'connected mobility', 'clean mobility' and 'freedom in mobility' for customers.

The CASE technologies are closely interlinked with each other and to implement the future mobility concept, in particular, the combination of both autonomous and electric vehicles should be inevitable. The level of autonomy ranges from level-0 (i.e. no automation) to level-5 (i.e. full automation) (37–39). The electric vehicles powered by either batteries or fuel cells are generally well suited to autonomous vehicles. However, as the autonomous vehicles encounter the need for a higher level of autonomous driving technologies which normally require a rapid energy consumption of electric vehicles, the vehicles need more frequent electricity-charging for battery electric vehicles (BEVs) or hydrogen-refueling for FCEVs. In this case, FCEVs could be a better candidate for the platform of autonomous vehicles owing to their longer driving range: over 600 km (i.e. Nexo FCEV) and shorter refueling time, usually less than 5 min (40, 41).

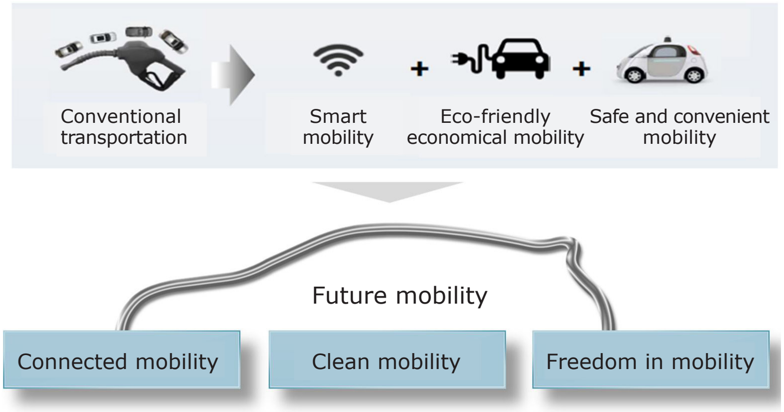

Fig. 4. Future mobility concept of Hyundai

To meet various demands and requirements for customers in the world, as shown in **Figure 5**, Hyundai has been developing a variety of clean and eco-friendly vehicles over the last decade, i.e. gasoline- and diesel-powered vehicles with improved fuel economy, hybrid electric vehicles (HEVs), plug-in HEVs and pure electric vehicles such as BEVs and FCEVs. And Hyundai has been increasing the share of electrification of the vehicles. In general, BEVs and FCEVs have different strengths that complement each other in that BEVs are more adequate to shorter driving range applications, while FCEVs have a more competitive edge in heavier and longer driving range applications such as buses and trucks.

Recently, Hyundai has been actively increasing its commitment to commercialising FCEVs due to their versatile potential in the future power systems, which will be discussed in detail in the following section.

PEMFCs for FCEVs and Beyond

Figure 6 shows the history of FCEV development of Hyundai since 1998. Hyundai developed a proprietary in-house 80 kW stack system in 2004 and since then Hyundai has achieved significant advancements in FCEV commercialisation technologies, finally launching the world's first mass-produced FCEV (i.e. Tucson ix35: the first generation FCEV) in February 2013, followed by the manufacturing of the second generation FCEV (i.e. Nexo) in March 2018, whose features will be discussed later in more detail.

Figure 7 shows a photo and a package layout of the world's first mass-produced Tucson FCEV of Hyundai. The Tucson FCEV employed an existing internal combustion engine vehicle's platform. A 100 kW fuel cell stack was located in the engine bay. The vehicle adopted a battery system with 24 kW and two hydrogen storage tanks with a capacity of

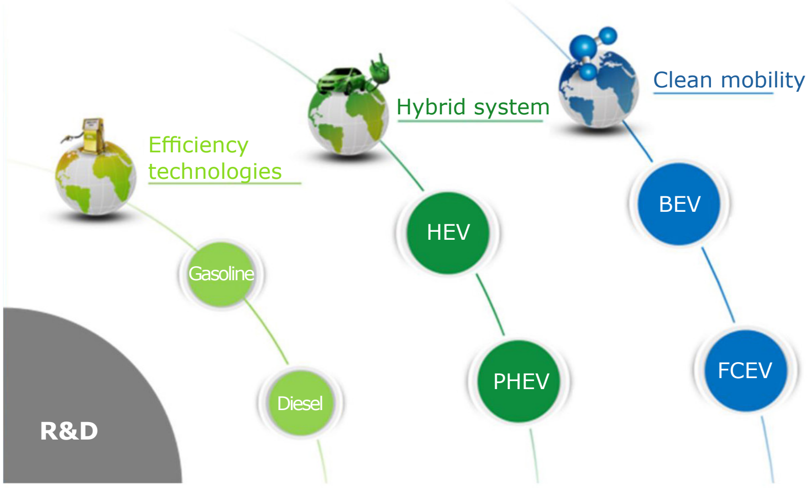

Fig. 5. Clean and eco-friendly vehicles of Hyundai

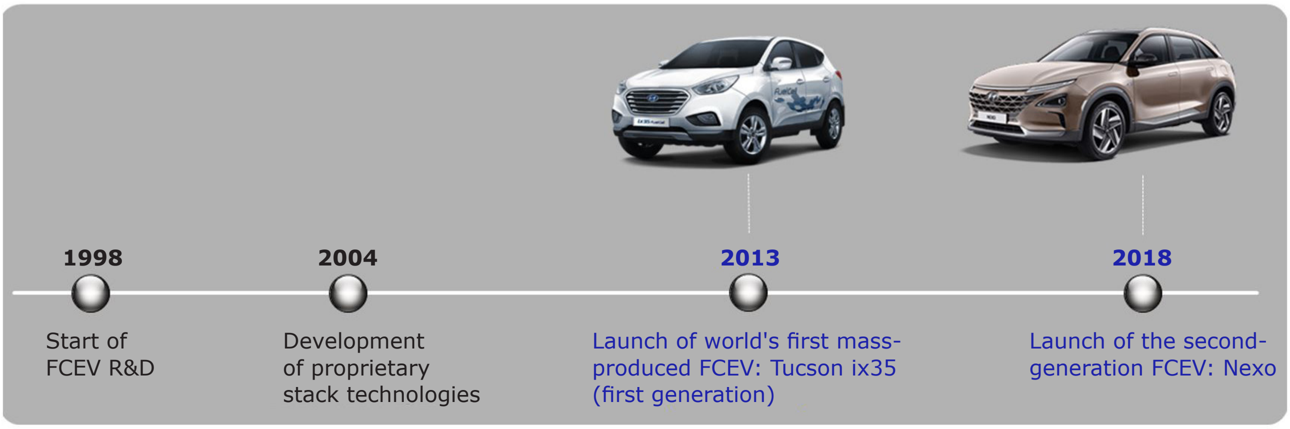

Fig. 6. History of FCEV development of Hyundai

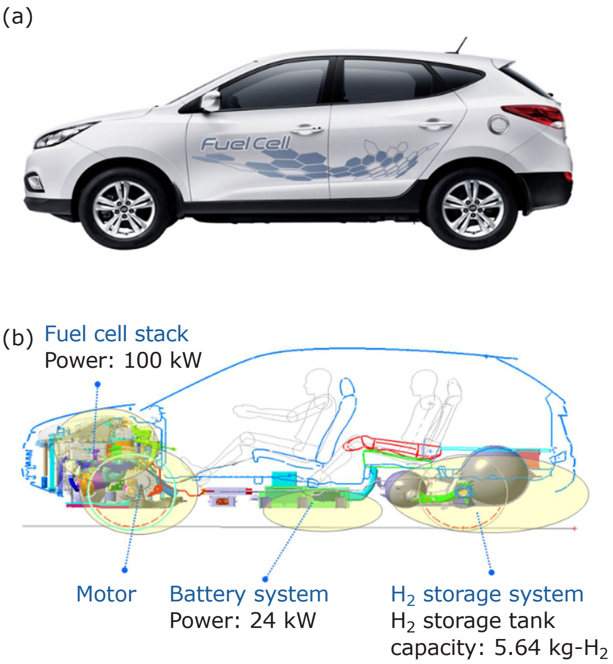

Fig. 7. (a) Photo; and (b) package layout of the world's first mass-produced Tucson ix35 FCEV of Hyundai

5.64 kg-H_2, leading to a driving range of 415 km according to fuel economy tests in Korea. The Tucson FCEVs were deployed in 18 countries worldwide.

Through the technical expertise for manufacturing Tucson FCEV since 2013, Hyundai had improved significantly the PEMFC technologies and finally commercialised the second generation of the mass-produced Nexo FCEV in March 2018, with improved performances and durability compared with its predecessor. **Figure 8** shows an overview and general features of the Nexo FCEV. In contrast to the Tucson FCEV which had to use an existing internal combustion engine vehicle's platform, the Nexo FCEV was built on a newly developed and fully dedicated vehicle platform, which renders it higher power and improved driving dynamics than the Tucson FCEV. **Figure 8(a)** shows the new design of Nexo which was optimised to reduce the drag coefficient from 0.35 (Tucson) to 0.33 (Nexo). Multiple aerodynamic features were discreetly integrated into the front, side and rear areas of the Nexo. As shown in **Figure 8(b)**, the Nexo also performs a remote smart parking assist function which allows the vehicle to autonomously park or retrieve itself from a parking lot.

On top of that, a variety of advanced driver assistance system technologies such as the blind-spot view monitor, the lane-following assist and the highway driving assist systems were implemented into the Nexo FCEV to facilitate safe driving. As shown in **Figures 8(c)** and **8(d)**, the interior of Nexo features the wide black dashboard that houses two large liquid-crystal displays to hold the digital instrument cluster (left) and the navigation system (right). **Figure 8(e)** shows the overall package layout of the Nexo FCEV. It primarily consists of an integrated power module with a fuel cell stack and a balance of plant (BOP) system, a motor with maximum torque of 395 N m, three hydrogen storage tanks with a capacity of 156.6 l and 6.33 kg-H_2 and a battery system with a power of 40 kW and an energy capacity of 1.56 kWh.

Figure 9 shows an enlarged view of the integrated power module of the Nexo FCEV. The integrated power module is mainly composed of a 95 kW fuel cell stack and a BOP system consisting of fuel (hydrogen) processing, thermal management and air processing systems. The fuel cells in the Nexo's stack employ advanced membrane-electrode assemblies (MEAs) with perfluorinated sulfonic acid ionomer-based reinforced membranes and platinum-based electrodes, carbon fibre paper-based gas diffusion layers (GDLs) with microporous layers, metallic bipolar plates and elastomeric sealing gaskets. The BOP system is also of great importance to achieve improved performances, enhanced durability and reduced cost of the Nexo FCEV. The fuel processing system mainly consists of hydrogen supply lines and hydrogen-related sensors, and the air processing system is primarily composed of air humidifier, air compressor and other components. The thermal management system includes cooling-related valves and sensors.

Table I summarises key features between Tucson and Nexo FCEVs of Hyundai. Both FCEVs placed their stacks in the front engine bay instead of under the floor and employed hydrogen compression pressure of 70 MPa, hydrogen refuelling time of less than 5 min and a seating capacity of five persons. The Nexo FCEV adopts a variety of proprietary fuel cell components and systems as well as advanced vehicle operation technologies as summarised in **Table I**. In comparison with its predecessor Tucson FCEV, as listed in **Table I**, the motor power of the Nexo FCEV increased significantly from 100 kW to 120 kW. Most importantly, the durability of the Nexo FCEV approximately doubled from 4 years/80,000 km to 10 years/160,000 km and the driving range on a single charge increased considerably from 415 km to 609 km, to the authors' best knowledge, which should be unprecedented among all mass-produced electric vehicles commercially available to date. The cold start-up capability in wintertime

Fig. 8. An overview of the Nexo FCEV of Hyundai: (a) and (b) exterior; (c) and (d) interior; (e) overall package layout

had been limited due to the freezing of water produced intrinsically during the oxygen reduction reaction (ORR) at the cathode of PEMFCs and thus challenging to a wide adoption of FCEVs on the real road worldwide. As for the Nexo FCEV, however, the cold start-up capability was greatly improved from −20°C to −30°C, facilitating the vehicle's market penetration in the world. The system efficiency of the Nexo improved from 55% to 60% as a result of enhanced performances of fuel cell components and systems. The acceleration time from 0 to 100 km h^{-1} of the Nexo decreased by 3.3 s, i.e. from 12.5 s to 9.2 s and the maximum vehicle speed increased from 160 km h^{-1} to 177 km h^{-1}. Thanks to the newly developed and fully dedicated vehicle platform, the Nexo FCEV can adopt three hydrogen storage tanks, which enable a larger internal volume of hydrogen tanks from 140 l to

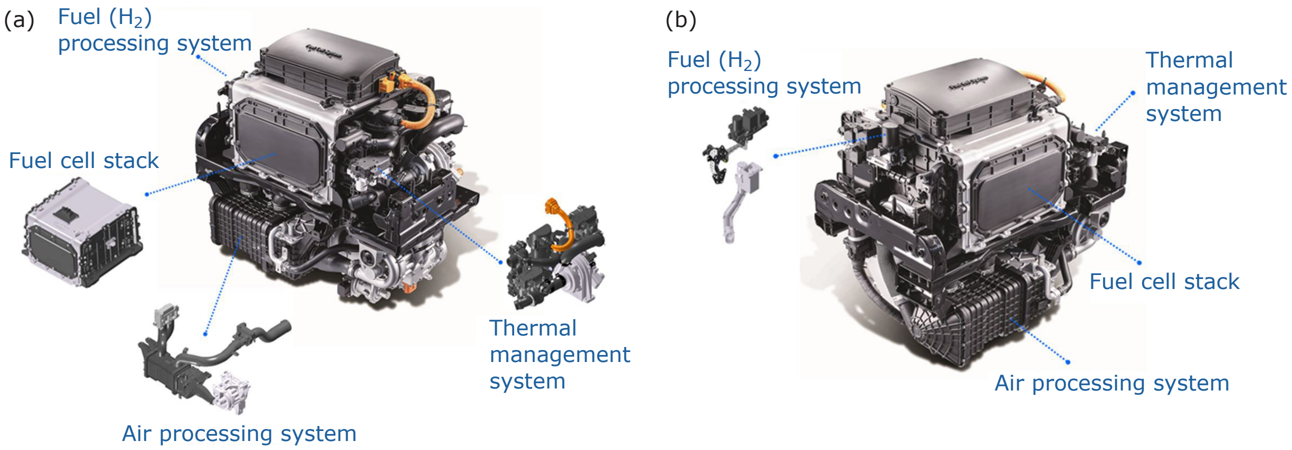

Fig. 9. An enlarged view of an integrated power module of the Nexo FCEV of Hyundai: (a) front and right-hand side view; (b) front and left-hand side view

Table I Comparison of Key Features between Tucson ix35 and Nexo FCEVs of Hyundai

Item	Unit	Tucson ix35 (2013)	Nexo (2018)
Vehicle motor power	kW	100	120
Fuel cell stack power	kW	100	95
Battery power	kW	24	40
Total system power	kW	124	135
Durability	years/km	4/80,000	10/160,000
Driving range[a]	km	415	609
Cold start-up capability	°C	–20	–30
System efficiency	%	55	60
Acceleration time (0 → 100 km h^{-1})	sec	12.5	9.2
Maximum speed	km h^{-1}	160	177
Number of hydrogen tank	–	2	3
Internal volume of hydrogen tank	l	140	156.6
Hydrogen storage capacity	kg	5.64	6.33

[a] The driving range values on a single charge were obtained from the fuel economy tests in South Korea

156.6 l and a higher hydrogen storage capacity from 5.64 kg to 6.33 kg, which has contributed to the long driving range of Nexo.

One of the biggest obstacles standing in the way of wider adoption of FCEVs worldwide is the safety concern about hydrogen. Therefore it is of paramount importance to verify the safety of hydrogen storage system in FCEVs. For the past two decades, Hyundai has done a lot of front, rear and side crashworthiness tests on FCEVs as shown in **Figure 10**. **Figures 10(a)**, **10(b)** and **10(c)**, **10(d)** represent the front and rear collision tests of the Nexo FCEV, respectively. In the rear collision or crash test, the vehicle was placed on the transparent test plate underneath which a camera was located. A mobile barrier crashed against the FCEV at the rear end, which caused damage and deformations of hydrogen storage system in the FCEV. Despite the deformations after the collision test, there was no leakage out of the tanks, verifying the safety of the hydrogen storage system. In 2018, the Nexo FCEV was awarded the highest rating in safety from the European crashworthiness test, i.e. European New Car Assessment Programme (Euro NCAP).

To date the global markets for PEMFCs for a variety of FCEV applications have been growing very rapidly in terms of both passenger vehicles and medium- and heavy-duty vehicles such as buses and trucks, which require much higher durability than passenger vehicles, i.e. 5000 h for passenger vehicles *vs.* 25,000 h for heavy-duty vehicles (21, 42, 43). In addition to automotive applications, the

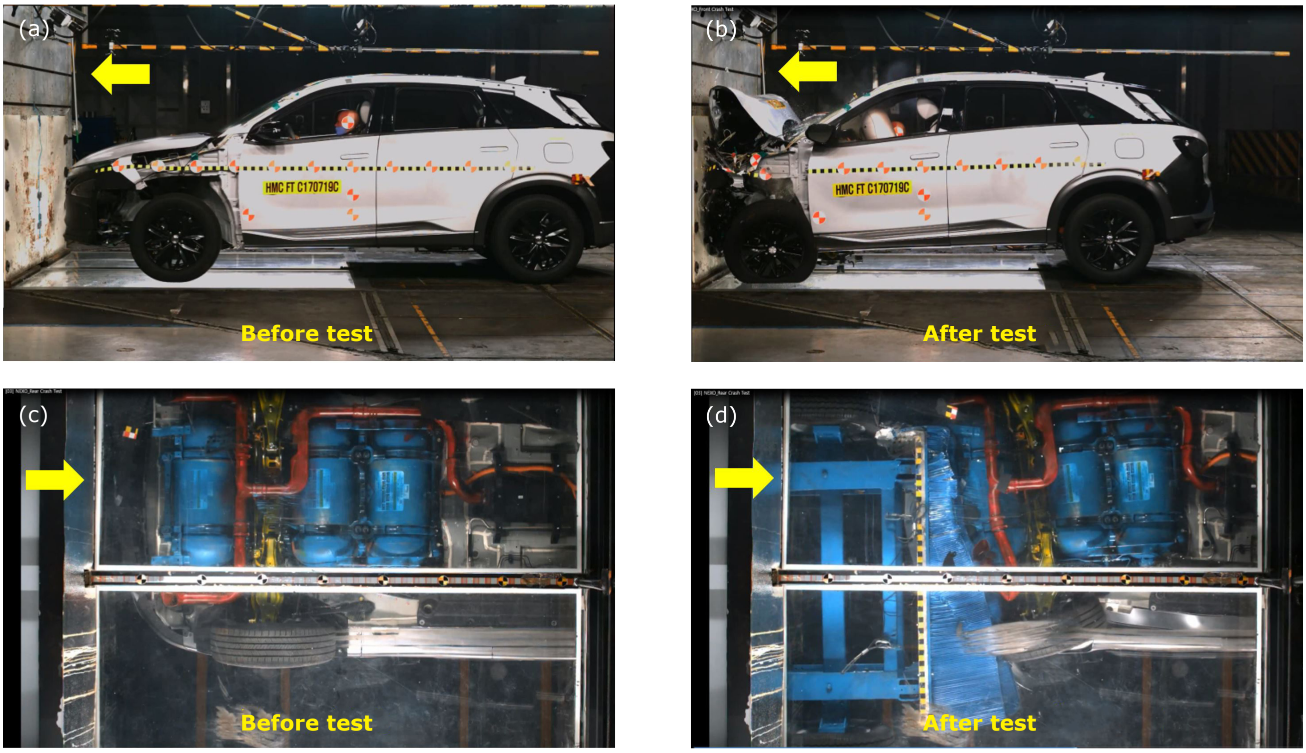

Fig. 10. Crashworthiness tests of the Nexo FCEV: (a) and (b) front collision test; (c) and (d) rear collision test. The arrows in the figure indicate the direction of collision

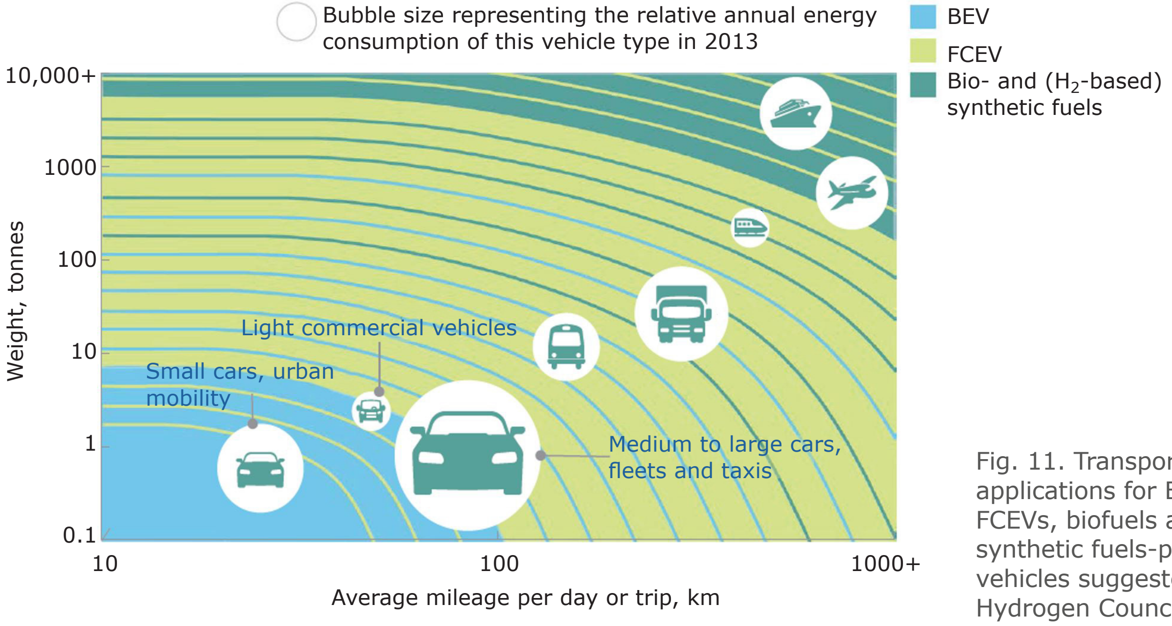

Fig. 11. Transportation applications for BEVs, FCEVs, biofuels and synthetic fuels-powered vehicles suggested by Hydrogen Council (27)

PEMFCs are also in demand for other applications such as fuel cell electric trains. **Figure 11** shows transportation applications of BEVs, FCEVs, biofuels and synthetic fuels-powered vehicles suggested by Hydrogen Council (27). The FCEVs are expected to occupy the markets of medium- to large-sized passenger vehicles, commercial vehicles including buses and trucks, and even trains.

Recently, the concept of commercialising fuel cell electric trains and trams has been materialising in the world. For instance, as an alternative to diesel-powered trains, Alstom Company, France, launched the world's first passenger train powered by hydrogen fuel cells, i.e. Coradia iLint^{TM}, to offer commercial passenger service in Germany in September 2018 (44, 45). The Coradia iLint^{TM}

fuel cell electric train was specially designed for operation on non-electrified lines, enabling clean and sustainable train operation while ensuring high performances with a maximum speed of 140 km h^{-1}. Another commercialisation project of eco-friendly trams powered by PEMFCs has been underway by Hyundai Rotem Company in collaboration with Hyundai Motor Company in South Korea since June 2019 (46). The project plans to develop a low-floor fuel cell electric tram which can travel up to 200 km at a maximum speed of 70 km h^{-1} on a single charge by late 2020.

In addition to the role of PEMFCs for transportation applications, another interesting potential of PEMFCs is their capability to produce electricity as a power generator using hydrogen energy. Accordingly, over the last few years, the potential of PEMFCs in FCEVs as distributed power suppliers has received great attention worldwide. **Figure 12** shows an illustration of the distributed power generation concept by PEMFCs in FCEVs. The FCEVs can produce approximately 10 kW under idling conditions, which can be used to provide electricity for houses and buildings.

To validate and demonstrate extensively the distributed power generation concept by PEMFCs in FCEVs and thus increase public awareness on this aspect, a vehicle-to-grid (V2G) demonstration project (i.e. Hydrogen Electric House project) using Hyundai's Tucson and Nexo FCEVs has been progressing in South Korea since August 2017. **Figure 13** shows the Hydrogen Electric House project in South Korea. The FCEVs can supply electricity, heat and water for the Hydrogen Electric House.

The FCEVs also can provide back-up power for people in emergency regions such as earthquake and typhoon disaster areas. In addition it can be used as an electricity charger for BEVs and plug-in HEVs.

Recently, a similar demonstration project showing the V2G technology through integrating an FCEV with photovoltaic power and a residential building was reported in the Netherlands to implement a net zero-energy residential building concept (47). This project showed that utilising an FCEV working in V2G mode could reduce the annually imported electricity from the grid by approximately 71% over one year and aid the buildings in the microgrid to implement the net zero-energy building target.

Another feature of interest of FCEVs differentiating themselves from other types of vehicles is their capability to clean the outside air and thus mitigate air pollution in society (2). Similar to BEVs, the FCEVs do not emit any air pollutants and particulate matter (PM) out of the vehicles while driving on the road. Unlike the BEVs, however, the Nexo FCEV of Hyundai employs an advanced air filter to filter out most of the fine dusts and micro-sized PM in the outside air, enabling to provide purified oxygen from air for the cathode in fuel cells.

On a basis of this positive perspective on hydrogen and PEMFCs, Hyundai announced its investment plan for PEMFCs and FCEVs to the public as the 'FCEV Vision 2030' in December 2018. According to this plan, Hyundai will invest US$6.9 billion and produce 700,000 PEMFC systems by 2030: specifically, 500,000 PEMFC systems for automobiles and 200,000 PEMFC systems for other applications such as forklifts, trams, trains, power generators and vessels, as shown in **Figure 14**.

Remaining Challenges and Barriers for Next-Generation PEMFCs

To realise the vision for hydrogen economy through hydrogen and PEMFCs, the fuel cell industry, investors and governments in the world will need to ramp up and coordinate their efforts (27–29). And in order to facilitate the commercialisation

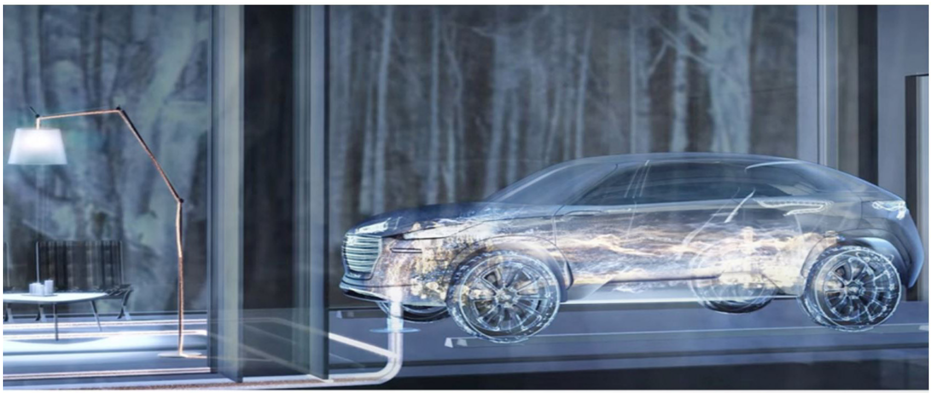

Fig. 12. An illustration of the distributed power generation concept by PEMFCs in FCEVs

Fig. 13. Hydrogen Electric House project using Hyundai's FCEVs which supply electricity, heat and water for the House: (a) a photo of the Hydrogen Electric House; (b) an FCEV generating electricity; (c) the internal structure of an FCEV by an augmented reality technique; (d) a photo showing fuel cell components and systems of an FCEV

of next-generation PEMFCs for a broad range of applications, from the technical point of view, it is of paramount importance to develop more durable and cost-effective fuel cell materials, components and systems as well as advanced fuel cell operation techniques. Here we address several key challenges to be overcome in the future.

Even though there have been extensive efforts to increase hydrogen refuelling infrastructure worldwide over the last decade, the infrastructure is still scarce to deploy the FCEVs, in particular passenger vehicles, sufficiently on the real road. Therefore, to reduce the dependence on the hydrogen refuelling infrastructure, it is necessary to turn our attention to other applications that are less dependent on the number of hydrogen refuelling stations (HRSs). These applications include trams, trains and medium- to heavy-duty commercial vehicles such as fuel cell electric buses (FCEBs) and trucks. For instance, the ideal locations for HRSs of FCEBs are regarded as the bus depot, which allows to estimate the HRS location precisely and thus minimise the cost for HRS construction, indicating no infrastructure requirements on the operation routes (23, 48–50). Fuel cell electric trucks, trains and trams appear to be in a similar condition. For an FCEB to become commercially competitive, however, it is of great importance to develop highly durable fuel cell materials, components and systems first, followed by a drastic reduction of cost, since the durability requirements for FCEBs are much higher than those of passenger vehicles such as SUVs and sedans. It was reported that ultimate lifetimes of an FCEB and its power plant should be approximately 800,000 km and 25,000 h, respectively (42, 43, 48–50), which are five times longer than that of ordinary passenger vehicles. Among core components of PEMFCs for FCEBs, the membrane failure due to pinhole formation seemed to be critical to the lifetime of FCEBs (42), requiring highly durable membranes in terms of both chemical and mechanical durability.

In the case of cathode catalysts for PEMFCs, over the last two decades, extensive research works have been performed to develop durable and cost-effective ORR catalysts with lower Pt loadings (4–6), i.e. highly active Pt-based core-shell catalysts. As pointed out clearly in the literature (5), however, intensive research efforts on developing more durable and reliable electrodes using these novel catalysts should be further exerted, since not all promising ORR activity of catalysts based on typical rotating-disk electrode (RDE) test results have translated into real-world MEA performance, causing a great mismatch between RDE and fuel cell data.

As for the anode catalysts for PEMFCs, it is necessary to develop more effective cell voltage reversal-tolerant anode (RTA) based on oxygen evolution reaction (OER) catalysts. **Figure 15** shows a schematic illustration of PEMFC operation under normal conditions with sufficient hydrogen supply for the anode and abnormal conditions of hydrogen starvation at the anode (52).

As reported in the literature (51–59), the durability of FCEVs can be significantly reduced by insufficient hydrogen oxidation reaction due to hydrogen starvation at the anode at both normal (i.e. 60~90°C) and subfreezing operation temperatures, which would eventually cause cell

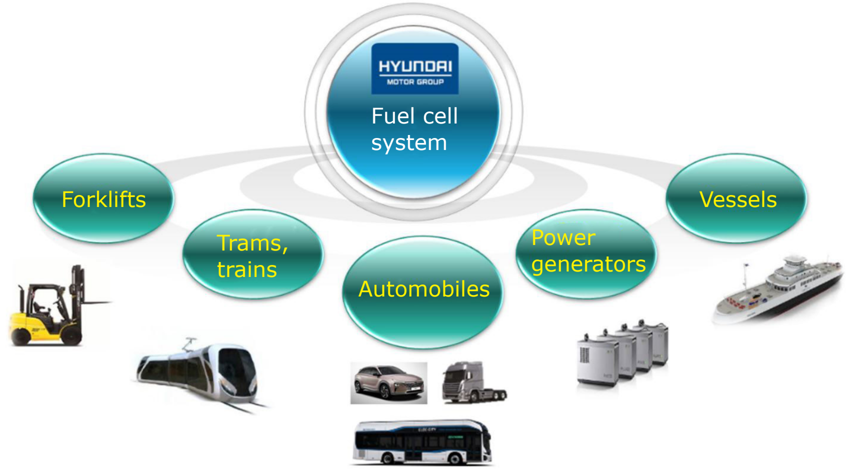

Fig. 14. An illustration showing a variety of applications for PEMFCs of Hyundai

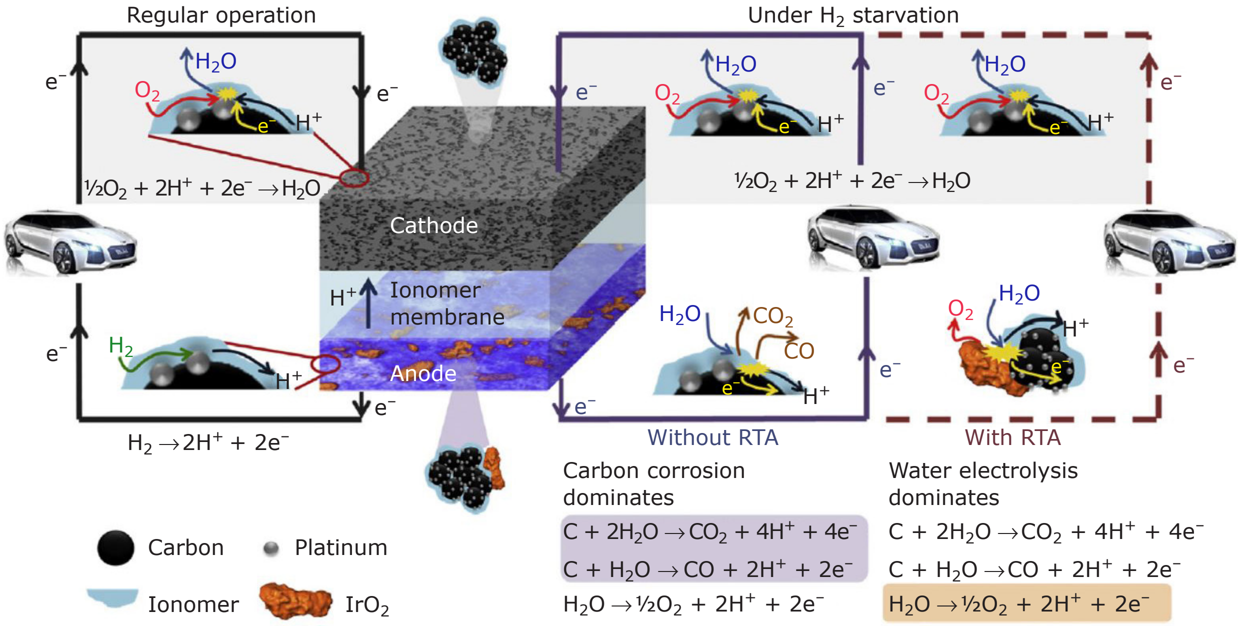

Fig. 15. A schematic illustration of PEMFC operation under normal and hydrogen starvation conditions. Reprinted from (52), copyright (2016), with permission from Elsevier

voltage-reversal problems. To mitigate the cell voltage-reversal degradation, a variety of system and operation control strategies, i.e. gas purging of anode compartment to remove accumulated nitrogen or water at the anode (60, 61), have been developed over the past decades. However, these techniques could limit the vehicle performance and make the vehicle system and operation more complicated. Therefore, as an alternative, material-based approaches have been suggested through adding OER catalysts to the anode, leading to an RTA (51–59). However, despite the recent progress on reducing cell voltage-reversal degradation through various techniques described above, it is not still sufficient to guarantee long-term reversal-tolerant durability and thus requires more robust and stable RTAs under acidic operation conditions of PEMFCs as well as much simpler and more effective system control technologies.

It is also critical to understand better the difference between the pristine and aged structures of fuel cell materials and components, i.e. membranes and electrodes in MEAs, GDLs and bipolar plates, on both micro- and nanoscales since the performance and durability of PEMFCs are closely related with these structural features. Therefore it is essential to develop more advanced imaging techniques, i.e. three-dimensional nanoscale X-ray computed tomography (62–64) and electron tomography performed in a high-angle annular dark-field scanning transmission electron microscope (65, 66) and correlate the imaging results with the performances and durability of actual fuel cells.

Conclusions

PEMFCs powered by hydrogen have received much attention as a promising candidate for FCEVs owing to their high power density, high efficiency and zero emission features. Hyundai commercialised the world's first mass-produced Tucson ix35 FCEV in 2013, followed by the manufacturing of the second generation Nexo FCEV in 2018. To date, other global automotive OEMs, i.e. Toyota, Honda, Daimler and Audi, have also focused on commercialising FCEVs, which leads to an expansion of the global market of PEMFCs for a broad range of applications. Hydrogen is regarded as an excellent alternative to fossil fuels. In comparison with the existing grey hydrogen produced by conventional fossil fuels, the share of green hydrogen produced by excess renewable energies is expected to increase considerably in the future. Hydrogen can serve as a versatile energy carrier and plays an essential role in decarbonising major sectors of the economy.

Recently the global automotive industry has been experiencing a paradigm shift from traditional internal combustion engine vehicles to next-generation vehicles based on future mobility concepts such as CASE. These technologies are closely interlinked with each other. The FCEVs could be a strong candidate for the platform of autonomous vehicles owing to their longer driving range over 600 km and shorter refueling time usually less than 5 min.

Over the last decade, Hyundai has been actively increasing the commitment to commercialising FCEVs due to their versatile potential in the future power systems. In comparison with its predecessor Tucson ix35 FCEV, the durability of the Nexo FCEV approximately doubled from 4 years/80,000 km to 10 years/160,000 km and the driving range on a single charge increased considerably from 415 km to 609 km. The cold start-up capability of the Nexo FCEV was greatly improved from −20°C to −30°C. The Nexo FCEV was also awarded the highest rating in safety from the European crashworthiness test.

The global markets for PEMFCs have been growing very rapidly in terms of both passenger vehicles and medium- and heavy-duty vehicles such as buses and trucks, which require much higher durability than passenger vehicles. The PEMFCs are also in demand for other applications such as trains, trams, power generators and vessels. Hyundai will produce 700,000 PEMFC systems by 2030. To realise this vision, it is of paramount importance to develop more durable and cost-effective fuel cell materials, components and systems as well as advanced fuel cell operation techniques. It includes the development of highly durable membrane, more cost-effective cathode catalysts, RTA and advanced imaging techniques.

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Exploring the Impact of Policy on Road Transport in 2050

Opportunities to accelerate reduction in carbon emissions

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Within the 28 member states of the European Union (EU-28), 71.7% of transport emissions in 2017 were due to road transport and a policy commitment was made to reduce emissions from the transport sector as a whole by 60% by 2050 (against a 1990 baseline) (1). Going forward, and supported by policy, a stratification of passenger car powertrain options is anticipated, with customers able to choose from a zero-tailpipe emission battery electric vehicle (BEV), fuel cell electric vehicle (FCEV) or a selection of hybridised vehicles ranging from a mild to a plug-in hybrid electric vehicle (PHEV). Further to this, technology improvements and connectivity between vehicle and energy generation and supply offer further opportunities to accelerate reduction in carbon emissions in the transport sector. The structure of this new transport paradigm is pathway dependent. Multiple conflicts exist, pulling the system in different directions and threatening its sustainability. This paper explores the link between policy and the impact this has upon the direction that road transport is taking, focusing on technology options and highlighting some of the dichotomies that exist between policy and the requirement for a sustainable road transport solution.

1. Introduction

"In these periods of major change, the established points of reference are being swept away, even in so-called traditional industries" (2).

Sustainable mobility is already on the agenda of every government in the world. The concept of sustainable development, defined by the Brundtland Commission as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (3) has permeated and is now a standard objective in all spheres of life and at government level. It is also at the core of the Sustainable Development Goals (4), recently launched by the United Nations as global objectives for 2030.

Transport plays a fundamental role for economic development and social welfare of a country. The movement of individuals and goods facilitates production and trade, enhances labour mobility and provides customers with access to goods. Transport externalities jeopardise sustainability. Transport externalities include environmental externalities (mainly climate change, air pollution and noise), but also extend to accident externalities and congestion externalities (5–7). The environmental impact of transport is substantial and "based on continuing current rates of growth for passengers and freight, and if no mitigation options are implemented to overcome the barriers, the current transport sector's GHG emissions could increase by up to 50% by 2035 at continued current rates of growth and almost double by 2050" (8).

Most policies in place and most proposed policies by design focus on existing externalities. However, the transport externalities we know today may be replaced by other problems. The world is being shaken up by new technologies and the speed of change is unprecedented. The term 'disruptive technologies' is becoming widespread, as shown by recent reports produced by McKinsey and Company, USA (9) and Deloitte LLP, UK (10). With the help of a comprehensive literature review, the aim of this paper is to understand the impact that current and proposed policy could have on the technological change in the road transport sector and how this will change the nature of the problems encountered and the sustainability.

The paper is organised as follows. Section 2 concentrates on alternative energy vehicles, with particular attention to electric and fuel cell vehicles based on their likely preponderance in the vehicle fleet by 2050. Section 3 concentrates on the UK policy in supporting the development and manufacture of electric vehicles (EVs) and Section 4 on the sustainability considerations resulting from current policy measures. Section 5 brings together the key findings and Section 6 concludes with final thoughts and direction for policy recommendations.

2. Alternative Energy Vehicles in 2050

In terms of sustainability and emissions in particular, the transport sector is coming under increasing scrutiny. The 'Paris Agreement' of 2015 aims to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change (11). Transport, as the source of nearly a quarter of all Europe's greenhouse gas (GHG) emissions (**Figure 1**), has become one of the focal points. This section focuses on technological improvements that are possible for passenger cars up to 2050 rather than on behavioural change or significant modal shift. The basis for this is that although their modal share would decrease by about 7% between 2010 and 2050, passenger cars will still represent about 67% of total passenger transport activity in 2050 based on European Union (EU) projections (13), whilst a UK study predicted a growth in overall road traffic demand of between 37% and 61% by 2050 (14).

In looking to reduce emissions from the road transport sector, the EU has taken regulatory action, which commits the automotive industry to reach a fleet average of 95 g CO_2 km^{-1} by 2020 (15). Whilst the 2020 target can still be achieved without a radical industrial transformation, the 10 g CO_2 km^{-1}, calculated as the tolerable maximum in 2050 to stay below 2°C global warming (16), will require a much more radical departure from current technological trajectories. Technological innovation will play a major role in taking on this challenge.

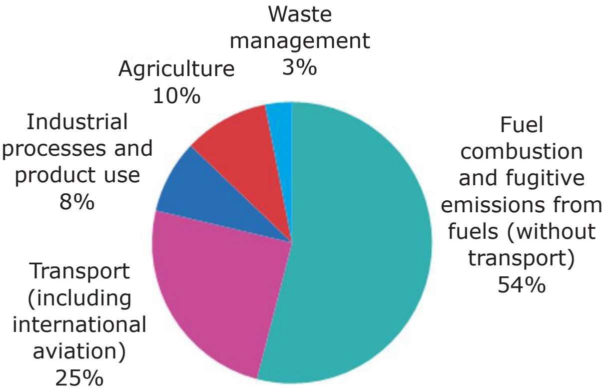

Fig. 1. GHG emission, analysis by source sector, EU-28 2017 (12)

Beyond 2020 and towards 2050, road transport vehicles are very likely to be propelled by a range of low-carbon technologies: battery electric and fuel cell electric propulsion; and varying degrees of hybridisation. Electromobility, either battery or fuel cell electric, will increasingly challenge the paradigm of internal combustion engine (ICE)-based mobility, simply because it is technically impossible to increase the efficiency of ICEs to the levels needed to achieve the emissions requirements (17). However, due to the various political and technological uncertainties, it is far from clear how fast and how radical the market penetration of these alternative energy vehicles will be, even though most predictions and forecasts give them a preponderant role in 2050 (18).

2.1 Vehicle Penetration by 2050

Obtaining accurate predictions about the market penetration rate of battery-electric, fuel cell electric and hybrid-drive technologies is problematic as forecasts diverge considerably (19). Figures vary from a long-lasting niche of a few percent and several hundreds of thousands of EVs sold in 2050 to a 50% market share for hybrids and EVs. For example, one of the future scenarios modelled by the International Energy Agency (IEA), France, termed as the 'BLUE Map' scenario, sets an overall target of a 50% reduction in global energy-related carbon dioxide emissions by 2050 compared to 2005 levels (20). Under this scenario, transport in 2050 is assumed to cut CO_2 emissions by 30%, relative to 2005 levels (21). This reduction is achieved partly by "accomplishing an annual sale of approximately 50 million light-duty pure battery electric vehicles and 50 million plug-in hybrid electric vehicles per year by 2050, which is more than half of all light-duty vehicle sales in that year" (21) (**Figure 2**).

The penetration rate of pure BEVs, PHEVs and FCEVs will be influenced by a range of factors: supplier technologies and vehicle offerings, vehicle characteristics, charging infrastructure and, as a function of these, consumer demand. However, all these factors are largely subject to international discourses and government policies. As an example, a forecast by the consultancy McKinsey and Company (22) track change in drivetrain technology up to 2050 and based on the three different g CO_2 km^{-1} targets. Whilst each of the different forecasts (10 g CO_2 km^{-1}, 40 g CO_2 km^{-1} and 95 g CO_2 km^{-1}) show the coexistence of several powertrain technologies, and with BEV and FCEV increasing their market shares in the future at the expense of petrol and diesel, the rate of change diverges considerably. In the most stringent 10 g CO_2 km^{-1} scenario, hybrid EVs (HEV) and range extended EVs (REEV) serve as a bridging technology that expands its market share for about 20 years but then declines to zero by 2050, whilst in the less stringent 95 g CO_2 km^{-1} HEVs have the dominant market share in 2050 (**Figure 3**) (22).

While predicting future technologies can be uncertain, the imperative to keep global temperature increases below 2°C and to improve urban air quality gives a clear indication that policies to promote investments in low-carbon vehicle technologies will continue. According to a report by IEA, under scenarios for decarbonisation in line with the 2°C global warming target, "three-fourths of all vehicle

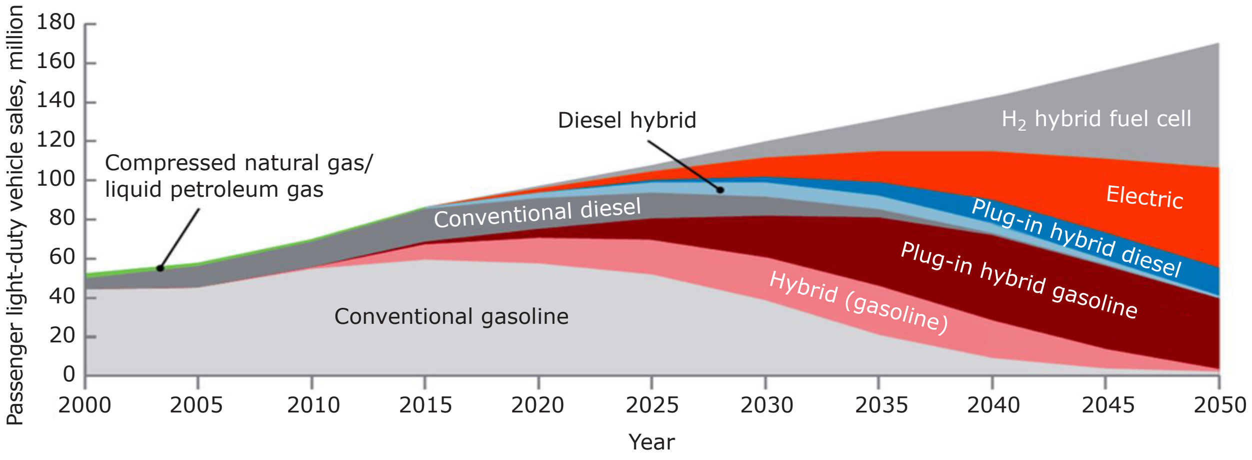

Fig. 2. Annual light-duty vehicle sales by technology type, 'BLUE Map' scenario. Source: IEA (21). All rights reserved

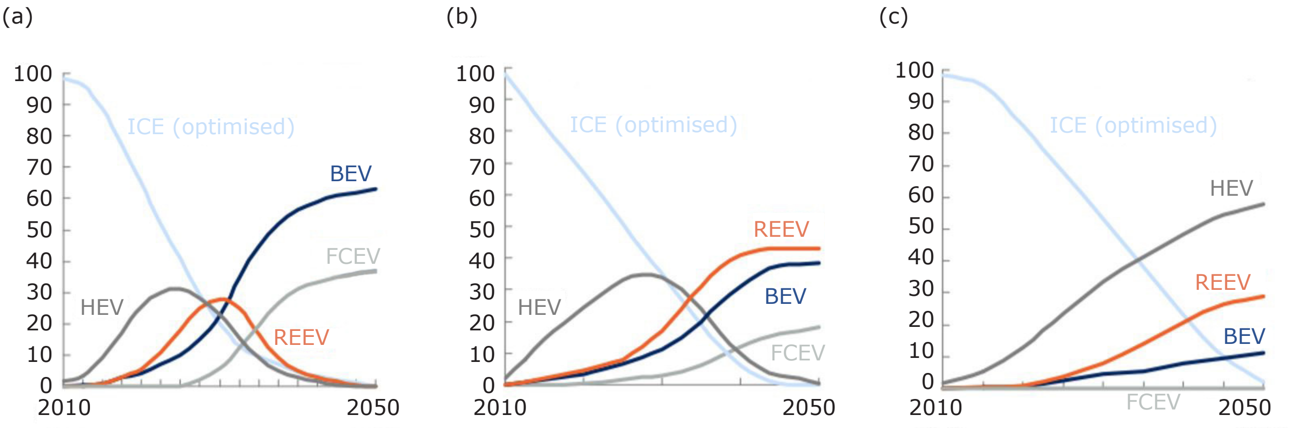

Fig. 3. Example of the predicted change in vehicle drivetrain technologies for one study and based on setting: (a) 10 g CO_2 km^{-1} cap in 2050; (b) 40 g CO_2 km^{-1} cap in 2050; and (c) 95 g CO_2 km^{-1} cap in 2050. Exhibit from (22). Copyright © 2020 McKinsey and Company. All rights reserved

sales by 2050 would need to be plug-in electric of some type" (23).

2.2 Electricity Generation and Supply

This transition to electromobility will also not be without its challenges. As the number of EVs increase, the research focus will move to issues around integration with the energy generation system and electric grids (24). Since battery charging would likely be done in residential areas, the distribution network operator will have to manage the additional consumption in order to avoid congestion on the electric grid, which would have a negative effect on voltage control, power quality (harmonics and subharmonics), supply and demand balance and relay protection. An important issue here is the unpredictable behaviour of users of EVs and their desire to recharge their vehicles when they want (uncontrolled charging).

Linking the automotive fleet to the electric grid will require a range of solutions to adapt demand to grid capacity and to ensure that access to charging is convenient for the customer. In addition, if electromobility is the solution to carbon abatement in the usage phase, then electricity generation will play a substantial role in the lifecycle CO_2 emissions of EVs. In regions that depend heavily on conventional fossil fuels for electricity generation, PHEVs and BEVs may not demonstrate a strong life cycle emissions benefit (25–27). Achieving the targets for CO_2 emission reduction in 2050 will therefore depend heavily on changes in electricity generation. If the achievement of low CO_2 electricity generation around the world does not occur in the 2050 timeframe, the CO_2 emission reduction benefits of BEVs and PHEVs will be much lower. As an example, within the UK the National Grid envisages a carbon intensity for the electricity mix anywhere between 20 g CO_2 kWh^{-1} and 72 g CO_2 kWh^{-1} by 2050 depending on the pathway adopted (**Table I**).

In relation to charging, the National Grid prediction for the UK market is for as many as 11 million EVs by 2030 and 36 million by 2040 leading to possible implications for peak electricity demand. However, if approached and managed appropriately, the charging of the BEV could avoid high peaks in demand at certain times and provide services to the grid.

Enabling an EV to communicate with the electrical grid, would allow the charging load to be spread. Smart charging would help utilities manage network overloads, voltage levels, frequency of electricity and imbalances between supply and demand – for example by absorbing the peaks observed due to more variable renewable energy generation (29). This is known as avoided curtailment. Such a system would lessen the need for additional grid and generation capacity, reducing GHG emissions and avoiding additional infrastructure cost. By 2050, and depending on the right policies being in place and providing the necessary bridge, the charging infrastructure will have been scaled up and standardised and smart charging will be part and parcel of the consumer experience.

2.3 Hydrogen as an Option?

The technology roadmaps that have been published, including those by the European Road Transport Research Advisory Council (ERTRAC), Belgium, the Advance Propulsion Centre UK Ltd (APCUK) and the Society of Automotive Engineers of China (China-SAE), share a view that both the BEV and the FCEV are viable future market solutions (18).

Fuel cell vehicles dependent on hydrogen offer the potential to be large enough to accommodate a family and travel long distances at highway speeds (22, 30–32). The hydrogen required for fuel cell vehicles is a flexible energy carrier that can be produced from any regionally prevalent primary energy source, it can be effectively transformed into any form of energy for diverse end-use applications and has the potential to facilitate significant reductions in energy-related CO_2 emissions (33).

Like BEVs, fuel cell vehicles running on hydrogen also face important challenges. These are the storage and transport of hydrogen in the vehicle,

Table I Carbon Intensity of Electricity (28)

Scenario	2017, g CO_2 kWh^{-1}	2030, g CO_2 kWh^{-1}	2050, g CO_2 kWh^{-1}
Community renewables	266	75	32
Two degrees	266	48	20
Steady progression	266	117	52
Consumer evolution	266	146	72

as well as the provision of a refuelling network. To encourage wide-scale uptake of fuel cell vehicles on hydrogen by consumers, a comprehensive hydrogen refuelling infrastructure will be required. The refuelling network for hydrogen is expected to follow a similar model to petrol and diesel refuelling (34). Hydrogen stations are concentrated in major cities and then link the cities together *via* hydrogen stations on the highway or strategic road network leading to a rapid increase in the proportion of the population with access (**Figure 4**). The question that requires answering is how to supply that network, given that the energy density of hydrogen is significantly less than the fossil fuels it is replacing i.e. simply relying on existing supply channels to meet demand would actually increase road traffic and energy use (through more vehicle movements on the supply chain side). Localised production of hydrogen through electrolysis is possible, but what are the efficiencies of such a system and how would the energy grid cope with the additional demand?

3. Policy Support in the UK

The UK Climate Change Act, which became legislative in 2008, aims to reduce the emissions of all GHGs by 80% by the year 2050 (from a 1990 baseline). The importance of the transport sector in achieving this target is illustrated (**Table II**), with transport contributing one third of all UK CO_2 emissions in 2018 compared to just over one fifth in 1990.

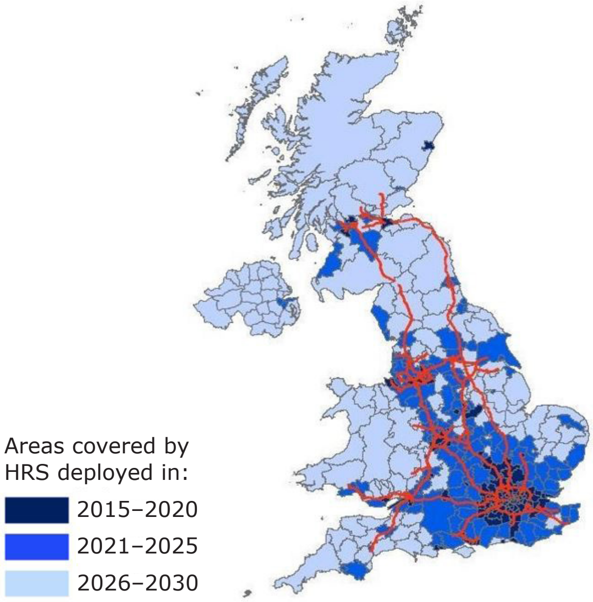

Fig. 4. Development of local hydrogen refuelling station (HRS) network coverage. Reprinted with permission from (35)

Alternative Energy Vehicles in 2050

- Road transport is a significant contributor to GHG emissions
- Regulatory '95 g CO_2 km^{-1} by 2020' not sufficient to meet 'Paris Agreement'
- Battery and fuel cell electric to replace combustion drivetrain, but fleet share uncertain
- Meeting challenges requires integration between transport and energy supply
- Requirement to integrate issues of energy policy, transport policy and social policy

To reduce transport related CO_2 emissions, the UK Government plans to phase out ICEs from new vehicle sales by 2040 and "has set ambitions to ensure that almost every car and van in the UK is a zero-emission vehicle by 2050" (37). However, these ambitions come with much uncertainty and the feasibility has been questioned.

Several risk factors will determine how quickly and deeply alternative energy vehicles will penetrate the UK vehicle mix and whether it will become a sustainable market segment. It is of strategic importance that industry understands these risks that can inform their research and development (R&D) investments. Alternative energy vehicles are a new product in a new industry and their radically different composition potentially means substantial change to production systems and value chains. The risk for industry in investing in the nascent value chain is compounded by competing alternative-vehicle technologies. Even though in the UK the government stance is to be technology neutral, government policies play a key role in how new technologies are supported by the wider stakeholder community (38). This will affect the quantitative nature of the risk and its perception in a significant way.

3.1 Creating a Competitive Electric Vehicle Manufacturing Sector

Despite the ubiquity of automobiles across the world, with around a billion such vehicles currently on the road, the car industry is a barely profitable business. The automotive industry is an extremely capital-intensive sector and the main issues in investing in new technology are capital intensity,

Table II UK Annual CO_2 Gas Emissions, 1990–2018, Headline Results (adapted from (36)[a])

	1990	1995	2000	2005	2010	2015	2017	2018
Transport, CO_2e, million tonnes[b]	125.4	126.8	131.0	134.3	123.4	122.2	124.6	121.4
Total CO_2, CO_2e, million tonnes	596.3	560.1	558.3	557.9	498.3	408.3	373.2	364.1
Transport as % of total CO_2, %	21	23	24	24	25	30	33	33

[a] (36) licensed under the Open Government Licence v 3.0
[b] CO_2e = carbon dioxide equivalents

cost requirements and amortisation of sunk costs. High volumes of output are needed to amortise these costs (39–41). The decision to build a new plant or introduce a new model is a major one, a very risky decision with uncertain outcomes. A result of the high cost of model-specific investment is conservative 'evolutions' of core models in an attempt to minimise risk.

Within this environment the electrification of the drivetrains represents a not inconsiderable challenge for today's automotive industry. Transition to an electrification of the drivetrain will require high investment, implicating a high economic risk for the industry, especially if reasonable sales numbers are not generated. This comes at the same time as the need to continue to invest in development of ICE and to ramp up investment in connected and autonomous vehicle technologies.

One result of the need to invest in electrification is that it has incited traditional manufacturers to consider joining forces and so increase their investment capacity, but also their ability to realise economies of scale. The competitiveness of a BEV is going to be directly connected to the efficiency of the value chain. In the short term the approach is for process improvements and reduction in cost focused on the areas of high value and for the EV this is the battery. Hence, new production plants with high capacities for battery systems will have to be implemented. Recent announcements around the establishment or enlargement of battery cell manufacture include: BYD Company Ltd (20 GWh by 2020) and Contemporary Amperex Technology Co Ltd (CATL) (50 GWh by 2020) in China; LG Electronics (6 GWh expanding to 15 GWh) and Samsung SDI (3 GWh) in Europe; and LG Electronics (3 GWh) and Tesla (35 GWh) in the USA (42). When these figures are taken into account together with existing installed capacity at other sites, it is clear that Asia is currently leading, with China producing twenty-two times more batteries than Europe (43). Further to this, the development of battery technology is one of the critical factors in the diffusion of EVs. Volume production, together with increasing energy density of the battery, will lead to the realisation of a driving range increase and at the same time a price decrease. In the UK, the Automotive Council commissioned roadmap on electric energy storage targets a cost reduction from around US\$130 to nearer US\$50 per kWh between 2017 and 2035 and for energy density to double from 250 Wh kg^{-1} to 500 Wh kg^{-1} over the same time period (44).

3.2 UK Government Policy in Support of Battery Development

Policy requirements call for the electrification of the vehicle fleet. The industry, in managing risk, has focused on the development and manufacture of batteries as the preferred strategy. 'Batteries for Electric Cars' is a case study in industrial strategy, written by Sir Geoffrey Owen on behalf of the Policy Exchange, UK (45). Written under consultation with government officials, financial analysts, academics and industrial experts, it provides an extensive timeline of battery innovation, highlighting how different countries came to gain technological supremacy when it comes to electrification. It also highlights the UK's "honourable place in the history of the lithium-ion battery, thanks to the work of John Goodenough and his team at Oxford University in the 1970s. Several of the scientists who worked with Goodenough, such as Peter Bruce, now Wolfson Professor of Materials at Oxford, went on to build successful academic careers and are internationally respected researchers in the battery field".

The opportunity for the UK to become a world leader in the EV industry certainly has the potential to be prosperous. The UK Government released its Industrial Strategy in 2017 which identifies government policies related to the UK's economic future (46). The transition to EVs is heavily explored in the Industrial Strategy and as part of the four 'grand challenges', specifically the future of mobility grand challenge. As a result of the 2017 Industrial Strategy, the UK Government Department for Transport produced 'The Road to Zero', a report which isolated the policies related to achieving a cleaner transportation network (47). In 2017 the UK Government also released the clean growth strategy, which includes additional policies related to the future of clean transportation (48). In addition to the plan for new cars and vans to be effectively zero emission by 2040 and for a zero emission vehicle fleet by 2050, the ambition is to put the UK at the forefront of the design and manufacturing of zero emission vehicles.

For the UK to meet the Climate Change Act 2008 transition and reduce dependency on Asia for EVs, there needs to be significant improvements in the UK's ability to develop and mass manufacture batteries. Sir Geoffrey Owen explicitly states that several considerations influenced the government's focus on the EV battery, including to ensure that UK-based car assemblies continue to build cars within the UK instead of moving abroad (the concern is that the location of the battery manufacture will provide the nucleus around which the industry gravitates as opposed to the location of the final vehicle assembly as happens at present). In response, the UK Government intention is to encourage large Asian technology companies to invest heavily in the UK, building manufacturing plants and research facilities and boosting local economies. The Industrial Strategy Challenge Fund (ISCF) Faraday Battery Challenge, created in 2017, is a direct result of the Industrial Strategy and focuses predominantly on encouraging research facilities to concert research efforts into battery technology. The challenge offers investment of £246 million, with £78 million going to The Faraday Institution, UK, £88 million to business collaborative R&D projects and £80 million going to improve the development of UK battery manufacturing capabilities (49). The Faraday Challenge is now a proven scheme which has seen research progress and increased investment is predicted for the considerable future to meet the strict 2050 deadlines in the Climate Change Act 2008.

4. Achieving the Sustainability Goal

The highly developed car industry is capable of producing sophisticated cars at low production costs. To reach the targets required to meet the Paris Agreement will require alternative drivetrain technology and for the industry the BEV is at present the most market viable solution. However, it takes courage to start the production of large numbers of EVs and the decision is not purely a technical one. It is a combination of science, technology, engineering and public policy that defines the type of EV that will be successful in the marketplace.

Policy Support in the UK Targets

- Reduction of GHG emissions (road transport a significant contributor)
- Phase out combustion drivetrain 2040
- Zero emission vehicle fleet 2050
- Investment in UK EV capability (EVs represent a high economic risk for industry)
- Support development of battery technology in UK
- Develop UK battery manufacture capacity to support UK automotive sector

The current policy framework allows for a number of potentially divergent pathways. The one discussed in the previous section focused on improving the value proposition by reducing the cost of the high value components, in this case the battery, with the objective of aligning the cost of the EV to the present combustion engine incumbent. Examples of original equipment manufacturers (OEMs) that have adopted this pathway include Jaguar, UK, with its I-PACE, Tesla, USA, with the Model S, Model X and Model 3 and Chevrolet, USA, with the Bolt. Each combines existing approach to vehicle manufacture (materials and processes), hence realising a low-cost base vehicle platform, combined with a battery that has a high energy capacity and relative low cost (achieved through economies of scale associated with the battery manufacture). A further approach, exemplified by BMW, Germany, with its i3, is to increase the overall efficiency by reducing the vehicle weight through innovative manufacturing methods and material choices. This approach recognises that the customer requirement of increasing range and reducing cost can potentially be achieved by focusing on reducing the size of the battery: a lightweight vehicle can cover longer distances with the same battery capacity. A further, and more extreme approach to lightweighting, is the Ped-elec (Coventry University, UK). The dichotomy is that mobility concepts used in urban areas are, at present, extensions of those used outside of the urban environment. They are inherently less efficient. Ped-elec responds to a call for new personal mobility based on energy used per unit mass moved (50).

Based on adoption rate (sales of each vehicle type) it is clear that the industry is gravitating to one particular pathway, reducing the cost of the high value battery whilst retaining the existing approach to manufacture of the vehicle (materials and processes). The option of weight reduction (focusing on energy used per unit mass moved) is a higher cost approach relative to providing additional battery capacity to overcome the lower vehicle efficiencies. Indeed, the need to realise increasing economies of scales in the area of battery manufacture are worrying national governments (UK included) concerned that the battery manufacture will act as the nucleus around which the rest of the industry gravitates; presently the industry gravitates around the location where final assembly of the vehicle takes place. However, whilst this is the preferred option, is it the most sustainable?

EV manufacturing requires more energy and results in more carbon emissions than manufacturing a conventional car (51). A study conducted by the American Chemical Society (ACS) estimated that the Ford Focus EV (Ford Motor Company, USA) has 39% higher 'cradle to gate' emissions then a conventional Ford Focus (52). In fact, Ellingsen *et al*. stated that EVs of all sizes may require 70,000 km to become cleaner than conventional vehicles to make up the manufacturing debt (53).

Various studies on the growth in EV and hence the demand for raw materials required in battery manufacture highlight that certain key materials (such as cobalt, nickel and copper) are at risk from supply constraints. In response, development has begun looking at materials such as iron to replace the cobalt commonly found in batteries (54) whilst research activity into the recycling of battery packs is also a priority area of research. At present there are no facilities for recycling EV batteries in the UK. Processes such as hydrometallurgical recycling and leaching are currently seen as energy efficient methods of recovering spent battery materials, aiming to reduce the cost of recycled batteries metals. Currently research is being undertaken to recycle larger percentages of battery material, with some promising results. Natarajan reports that 99.9% of lithium, 98.7% cobalt and 99.5% of magnesium were leached out of a cathode with a purity of between 98.7% and 99.4% (55). Another study, related to lithium-ion phone batteries, saw 90.02% of cobalt and 86.04% of lithium restored to maximum concentration (56). These tests are currently resigned to laboratories and not available in the UK on a commercial scale. Whilst the metals recycled from EV batteries are deemed to be of sufficient quality to be used in new EV batteries with no performance issues, due to issues of cost, recycled lithium costing three times that of new lithium, and the individual material compositions of each EV battery, bulk battery recycling on a commercial scale is currently not considered economically viable.

Achieving the Sustainability Goal

- Current policy focus is on emissions during vehicle operation
- Industry interpretation defines preferred pathway as electrification of existing solutions
- Open questions identified around preferred pathway sustainability include:
  - Raw material limitations
  - Supply chain emissions
  - Life cycle energy consumption
- Policies review or revision is required to respond to open questions

5. Discussion

In Section 2, the case for alternative energy vehicles as a response to meeting policy objectives was made. Although there is some uncertainty of the share of each technology in the powertrain portfolio, it is clear going forward that ICEs will represent only a small percentage of the total vehicle fleet or disappear altogether. It is further evident that there are multiple interest groups in the alternative energy vehicle market and that in preparation for the new mobility paradigm envisaged for 2050 investments will need to be made in new infrastructure and connectivity. Hence, there needs to be an orchestration of policy intervention to integrate issues of energy policy, transport policy and social policy.

In Section 3, there was a discussion around the policy support that the UK Government has in place to realise its ambition of a world leading UK alternative energy vehicle sector. It is clear that the industry, in transitioning to electrification, faces considerable risk. The industry chooses to leverage existing competencies in vehicle design and manufacture, and to achieve cost reduction and range improvements through a focus on the battery. In response the UK Government has put in place support for battery development, leveraging existing research competencies in this area by coordinating activities, and for battery manufacture by looking to attract inward investment and securing the future of automotive manufacturing in the UK.

In Section 4, the policies in support of transitioning to an alternative energy vehicle fleet on the one side and supporting the development of the UK capability in response were brought together in order to explore sustainability. The issue is that the way in which the industry responds to the challenge of emissions reduction creates a cleaner vehicle fleet, but does not necessarily consider optimising the efficiency or sustainability. The problem is that to square the circle – to meet the customer demand of increased range at reduced cost – the industry has looked to economies of scale at the manufacturing level and at the same time look for incremental improvements in the batteries. This enables vehicles to utilise larger batteries at less cost, but at the same time leads to heavier vehicles that fail to optimise efficiency and with increased energy demand can lead to stressing of the energy grid. A further problem is that larger batteries consume more materials and there is risk that certain material supply chains are being stressed and may not be able to respond to future demand, posing critical challenges regarding sustainability and security of supply chain. Whilst interventions, for example greater recycling and the retention of previously processed materials in the value chain, could influence this, the costs associated with these interventions would go counter to the objective of reducing the cost of the battery through economies of scale. Whilst lighter vehicles would be a move in the right direction, and a pathway exists for such vehicles within existing policy framework, the existing requirements for measuring the environmental performance of vehicles focus on emissions at the tailpipe and the move to electric drive removes a check on vehicle weight. Policy intervention is required to correct the above. This policy can target control of vehicle mass directly or can influence it indirectly through a move towards life cycle analysis of CO_2, each approach having its merits and challenges.

6. Conclusion

The transition to electrification of the vehicle drivetrain represents a considerable risk to the vehicle manufacturing sector. The UK has put in place policies to support both the production and research parts of the equation, but at the same time there is potential mismatch between the direction that is set by these policies and creating a sustainable road transport sector. New policies are required that orchestrate closer coordination across the separate policy areas: promoting lighter vehicles will reduce the stress on raw material supply chains; development of recharging networks will reduce range anxiety and align with the drive to reduce mass through enabling smaller batteries; and improvements in connectivity will lead to greater leverage of both vehicle and energy network capability.

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Sustainable Aviation Fuels

Status, challenges and prospects of drop-in liquid fuels, hydrogen and electrification in aviation

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Aviation fuel demand is expected to continue to grow over the next decades and continue to rely heavily on kerosene fuel for use in jet engines. While efficiency and operational improvements are possible ways to reduce greenhouse gas (GHG) emissions, decarbonisation will need to heavily rely on low carbon kerosene drop-in alternatives. Currently, alternative fuels make up a very small share of fuel used in aviation, but their commercialisation is making good progress. Hydrogen offers a longer-term alternative fuel option but requires aircraft design and fuelling infrastructure changes. Electrification is emerging as an option for providing propulsion in aircraft, either in pure form in small aircraft or in hybrid mode in larger aircraft. This paper reviews the status, challenges and prospects of alternative fuels and electrification in aviation.

1. Introduction

Early research into alternative fuels for aviation was conducted following the fuel price increases in the USA in the 1970s (1) driven by concern around costs and security of supply. Today, with the aviation industry responsible for around 2% of all human-induced carbon dioxide emissions (2), its estimated contribution to manmade climate change more than double this when non-CO_2 impacts are taken into account (3), and rapid growth expected over the next decades, the development of alternative aviation fuel is driven largely by concerns around climate change. Global aviation activity grew by 140% between 2000 and 2019 (4) and passenger numbers have been anticipated to continue to grow at a compound annual growth rate of 3.5% over the next two decades (5).

Policies are beginning to be put in place which aim to reduce GHG emissions from the aviation sector. In 2016 the International Civil Aviation Organization (ICAO) adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) which aims to stabilise net CO_2 emissions from international civil aviation at 2020 levels (6). Whilst the remit of ICAO only covers international aviation, an increasing number of measures are being put in place by national governments which cover domestic flights and international flights. Flights within the European Union (EU) are included in the EU Emissions Trading System (EU ETS) since 2012. Domestic aviation is included in New Zealand's Emissions Trading Scheme and other states such as Canada and China have indicated that domestic aviation will be brought within a national carbon pricing scheme (7).

Even taking into account fuel efficiency improvements that can be achieved by more modern aircraft design and improved operational measures, low-carbon fuels will be essential in order to meet targets for the decarbonisation of the sector (8). Several countries or regions including California (9), the UK (10) and The Netherlands (11) have included aviation fuel within national support schemes for low carbon fuels on an opt-in basis. Norway has introduced blending mandates for alternative fuels in aviation, and a number of other countries including Sweden and The Netherlands are considering similar policies (12).

In the past 20 years substantial progress has been made in the production and use of alternative aviation fuels. In February 2008 a Virgin Atlantic, UK, Boeing 747 (The Boeing Company, USA) became the first aeroplane flown by a commercial airline on a blend of kerosene and bio-jet fuel, and the first scheduled commercial flights on bio-jet fuel began in 2011 (13). Today more than 100,000 commercial flights have been carried out using alternative liquid aviation fuel (13), and at the time of writing there were six alternative fuel pathways certified by ASTM International, USA (14). Two additional ones have been approved in 2020.

One of the main challenges for low-carbon fuels replacing fossil kerosene is matching the same fuel energy density. The energy consumption of an aircraft is proportional to its mass and that is why the fuel energy density and the weight of aircraft components are key factors. Bio-jet has almost identical energy density to fossil kerosene, while hydrogen's volumetric energy density is an order of magnitude lower, and electrochemical batteries' volumetric and mass energy densities are also an order of magnitude lower (**Figure 1**).

This paper reviews the status of alternative fuel options for the aviation sector, covering liquid fuels, hydrogen and electricity. A schematic overview of all alternative fuel routes for aviation is provided in **Figure 2**. The paper then explores the prospects for future demand and supply of alternative drop-in liquid aviation fuels to 2030.

2. Renewable Drop-in Kerosene Alternatives

Renewable drop-in kerosene alternatives are synthetic liquid fuels produced from biogenic feedstocks or using renewable hydrogen and CO_2 (from waste streams or from the atmosphere) which are functionally identical to fossil jet kerosene. There are several possible routes to produce renewable drop-in kerosene based on different feedstocks and technology variants. **Table I** summarises their technology status.

The costs of alternative fuels are substantially higher today compared to fossil kerosene, with costs ranging between two and five times the price of conventional jet fuel (global average price paid at the refinery for aviation jet fuel in October 2019 was about US$600 per million tonne). The lowest alternative fuel costs today are associated with the most commercially mature route consisting of the large scale hydroprocessing of used cooking oils (UCOs), animal fats and raw vegetable oils (16).

The GHG emissions savings from renewable routes will generally be substantial, but vary, largely depending on the emissions associated with producing the raw materials used in their production. It is generally expected that savings will be between about 95% in the case of renewable electricity based routes and 65% for routes based on conventional crops, with savings from routes based

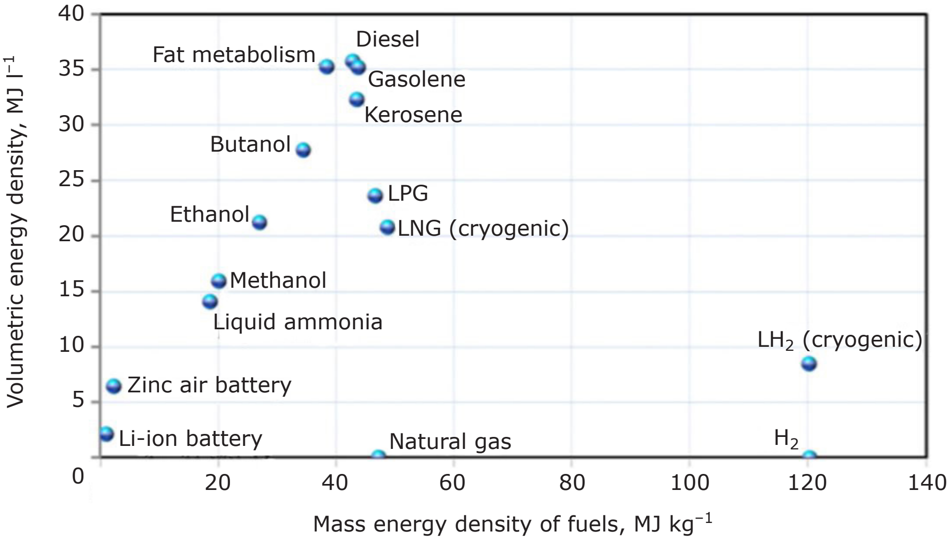

Fig. 1. Comparison of various energy sources for aviation (15)

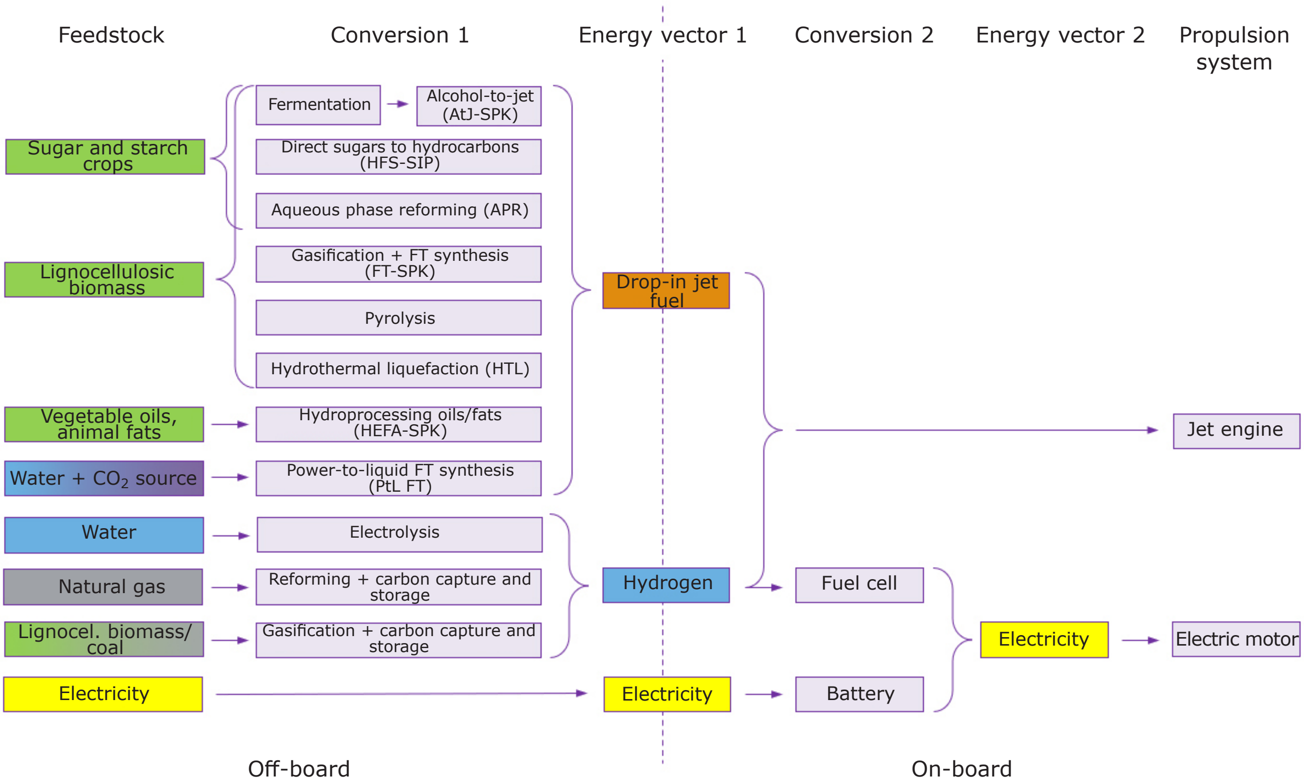

Fig. 2. Overview of alternative fuel routes for aviation

Table I Summary of Technology Readiness Level and Scale of Production of Drop-in Jet Fuels

Route	Technology status[a]	Largest plant, kilotonne year^{-1} [b]
Hydroprocessed esters and fatty acids-synthetic paraffinic kerosene (HEFA-SPK)	Commercial (TRL 8)	1653 (planned)
Alcohol-to-jet-SPK (AtJ-SPK)	Demonstration (TRL 6–7)	82 (planned)
Hydroprocessing of fermented sugars-synthesised isoparaffins (HFS-SIP)	Prototype (TRL 5, lignocellulosic sugars), pre-commercial (TRL 7, conventional sugars)	81 (operational)
Fischer-Tropsch-SPK (FT-SPK)	Demonstration (TRL 6)	225 (planned)
Pyrolysis	Demonstration (TRL 6)	138 (planned)[c]
Aqueous phase reforming (APR)	Prototype (TRL 4–5, lignocellulosic sugars), demonstration (TRL 5–6, conventional sugars)	0.04 (operational)[d]
Hydrothermal liquefaction	Demonstration (TRL 5–6)	66 (planned)
Power-to-liquid FT (PtL FT)	Demonstration (TRL 5–6)	8 (planned)[e]

[a] TRL = technology readiness level
[b] Here 'tonne' refers to a generic tonne of liquid fuel and not specifically to jet fuel
[c] Pyrolysis oil
[d] Bio-crude
[e] Blue-crude

on biomass wastes somewhere in that range (17). Electricity used to produce e-fuels is generally supplied through the grid. The renewability of this electricity needs to be guaranteed through accounting procedures which also need to assure that the same renewable electricity is not double-counted for other uses. In the case of fuels based on energy crops, it will be important to consider their sustainability with regard to land use change impacts (18).

2.1 Synthetic Paraffinic Kerosene Produced from Hydroprocessed Esters and Fatty Acids (HEFA-SPK)

The HEFA route is the most mature alternative fuel pathway (currently at TRL 8) and it is certified by ASTM International as HEFA-SPK (14). HEFA is produced through hydroprocessing of vegetable oils and animal fats. Hydrogen is used to convert unsaturated compounds such as alkenes and aromatics into paraffins and cycloalkanes, which are more stable and less reactive. The process is the same as for hydrotreated vegetable oil (HVO) production but includes an additional isomerisation step that lowers the fuel freezing point. The energy conversion efficiency of oils and fats into HEFA-SPK (and other byproducts) is about 76%, the highest efficiency of bio-jet fuel routes (17). The conversion energy efficiency is calculated as the ratio of the total energy input (feedstock, electricity, natural gas and hydrogen) to the total energy content of the liquid products (in general jet, diesel, gasoline, heavy fuel oil and naphtha). Gaseous products (for example, methane) are excluded from the denominator.

Because of its maturity and simplicity compared to other routes, HEFA is the only alternative fuel in commercial use. Depending on the plant size and deployment stage, the production cost of HVO ranges between €1100 and €1350 per tonne. Upgrading to HEFA incurs a relatively small additional cost, associated with the isomerisation step. The main limitation of this route is feedstock availability. UCO and tallow represent a relatively small resource globally, and the supply of virgin vegetable oil is constrained by land availability and sustainability concerns. Novel crops are being investigated in terms of potential and sustainability, such as camelina, carinata and oil-bearing algae. Fermentation of sugars to lipids is also being considered to produce feedstock for HEFA plants (see later subsection).

2.2 Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)

The AtJ process turns alcohols into jet fuel through the following reactions: dehydration, oligomerisation, hydrogenation, isomerisation and distillation. The alcohol used can be produced through conventional processes involving fermentation of sugar or starch crops such as sugarcane, corn and wheat, or through advanced routes from lignocellulosic feedstocks, such as woody and grassy feedstocks and wastes. Currently, most developers are focused on upgrading conventional alcohols, but there are larger demonstration plants planned using advanced routes to alcohols that may be operational by 2020. AtJ-SPK blends up to 50% v/v are certified by ASTM International since 2016, though the technology is currently at TRL 6–7 (14). Certain AtJ routes, depending on the catalytic process used, produce a jet fuel containing aromatics, and efforts are underway for certification of 100% use of jet fuel derived from these routes.

AtJ routes are attractive as they can convert various types of alcohols (such as ethanol, methanol and isobutanol) from a wide range of sources into jet fuel as well as other hydrocarbons. Additionally, the AtJ route offers logistical flexibility because the alcohol catalysis plant does not need to be co-located with alcohol production, and alcohols can be conveniently transported and stored. The main weaknesses of this pathway may be the selectivity of jet fuel production. An issue to consider in relation to this route is the opportunity cost of using the alcohols directly in transport applications (for example road and marine) as opposed to converting them to jet fuel, at the cost of additional capital expenditure and some efficiency loss. Jet fuel costs produced *via* this route could be 20–40% higher than the ethanol feedstock on an energy basis, with the lower end of the range being for high ethanol input prices and the higher end of the range for lower ethanol input price.

2.3 Synthesised Isoparaffins Produced from Hydroprocessed Fermented Sugars (HFS-SIP)

Genetically modified microorganisms can be used to convert sugar into hydrocarbons or lipids. These routes are known as direct sugars to hydrocarbons (DSHC) routes, and there are three main routes under development whose products can be further processed into jet fuel: heterotrophic algae or yeast converting sugars into lipids within their cells; genetically modified yeasts which consume sugars and excrete long-chain liquid alkenes (such as farnesene); genetically modified bacteria consuming sugars and excreting short-chain gaseous alkenes (such as isobutene). Currently biological routes almost exclusively use conventional sugar feedstocks, although pilot projects are testing cellulosic sugars. DSHC routes using conventional sugar feedstocks are at TRL 7–8, while the same processes based on cellulosic feedstocks are at TRL 5. A specific route based on the production of farnesane from sugar is certified as hydroprocessing of fermented sugars (synthetic iso-paraffinic fuels (HFS-SIP)) and can be blended with fossil kerosene up to a maximum of 10% (14).

However, at present, potential DSHC developers are targeting the chemical, pharmaceutical, food and feed markets, which are generally higher value than bulk transport fuels. This in turn helps to prove the technology and reach the scale and lower production costs that may be required for fuels. The complexity and low efficiency of converting lignocellulosic sugars into fuels through DSHC translates into high feedstock cost and high energy consumption, which makes DSHC the most expensive alternative fuel route. HFS-SIP costs have been projected to remain high at above €4000 per tonne (19).

2.4 Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)

The gasification with Fischer-Tropsch (Gas+FT) synthesis process transforms lignocellulosic biomass or solid waste into fuels, such as naphtha, gasoline, diesel and jet fuel, as well as other valuable coproducts. The process consists of the following key steps: feedstock pretreatment (sorting, sizing and drying), gasification, syngas clean-up and conditioning, FT catalysis, distillation and hydrocracking. And may involve additional steps such as isomerisation and catalytic reforming depending on the type of fuel produced. The jet fuel produced through the Gas+FT route is certified as FT-SPK and can be blended with fossil kerosene up to 50% (14). While a commercially mature route exists for coal and natural gas-to-liquid routes, the bio-based route is only now approaching TRL 7–8.

While the individual components of a biomass gasification to FT fuel route are commercially demonstrated in different applications such as biomass gasification to heat and power applications and coal-to-liquid plants, the integrated application of biomass gasification to FT fuel has yet to be demonstrated at scale. Challenges faced by this route are the economic viability of scaling down processes to scales suitable for biomass and waste-based systems, the design of processes and catalysts better suited to relatively small scale systems, including catalyst selectivity, the design of systems that can cope with biomass and syngas heterogeneity and the overall efficiency of integrated systems (20). An option for this route could be to produce FT waxes that could then be co-processed at oil refineries.

2.5 Pyrolysis and Upgrading

Pyrolysis transforms lignocellulosic biomass or solid waste into an intermediate bio-crude oil, which can then be upgraded to fuels. The fast pyrolysis to bio-crude oil process is at TRL 8, with several first commercial facilities selling the pyrolysis oil for heating applications. However, refinery upgrading of pyrolysis oils to a finished fuel product is only at the early demonstration stage (TRL 6), with batch production in limited trial runs. The dedicated upgrading of pyrolysis oil *via* hydro-deoxygenation (HDO) is currently at TRL 3–4, with pilot activities such as the Horizon 2020 4REFINERY project (21). Therefore, the overall route from pyrolysis to jet fuel is at most at TRL 6. KiOR, USA, had embarked on the ASTM International certification process for bio-kerosene from fast pyrolysis but the company filed bankruptcy (22). By 2019, the catalytic pyrolysis process (IH^2), developed by Shell, the Netherlands, was in Testing Phase 1 of the ASTM International's ASTM D4054-19 qualification procedure (14).

A range of pyrolysis-type technologies are possible that can process a wide range of feedstocks (even low-quality wet feedstocks). Bio-crude oil could be transported to centralised dedicated or fossil refinery facilities for upgrading to fuels. The challenges with crude pyrolysis oil are its high water, acidity and oxygen content, as well as viscosity and chemical instability, though the quality of the oil is heavily dependent on the pyrolysis process (20). Transport of pyrolysis oil may require some pre-processing and specialist infrastructure. To date there is no commercial process for upgrading pyrolysis oil to finished fuel in dedicated plants. However, research into materials and catalysts for such systems is ongoing (23).

2.6 Aqueous Phase Reforming

The APR process catalytically converts biomass-derived oxygenates (such as sugars, sugar alcohols and polyols) in an aqueous solution into hydrogen, CO_2 and a mixture of alkanes, acids, ketones and aromatics (24). A series of condensation reactions then lengthen the carbon chains in the mixture of hydrocarbons. This mixture then undergoes hydroprocessing, isomerisation and distillation.

APR using conventional sugars is at TRL 5–6 as a result of pilot scale plants operated by Virent Inc, USA. APR derived bio-crude using lignocellulosic sugars has been produced and upgraded to bio-kerosene at laboratory scale (25). Aviation kerosene produced *via* APR is in Phase 2 of the ASTM International certification procedure and referred as hydro-deoxygenated synthetic kerosene (HDO-SK) (14).

Unlike other reforming processes, APR operates in wet conditions which reduces the costs of dewatering certain feedstocks like sugars. However, this process has low selectivity to liquid hydrocarbons (high gaseous yields) and short catalysts lifetime due to deactivation and coking (20). These two characteristics make APR expensive from a capital and operational cost standpoint. APR is also gaining interest as a route for biochemicals production (26), which could lead to higher value products.

2.7 Hydrothermal Liquefaction

Hydrothermal liquefaction (HTL) is a process where biomass and water are heated at very high pressures to produce a bio-crude. The near and supercritical water acts as a reactant and catalyst to depolymerise the biomass. The bio-crude produced can then be upgraded similarly to the pyrolysis route. The higher molecular weight distribution makes HTL oil more suitable for diesel production, but gasoline and jet are possible adding hydrocracking steps. HTL is well suited to process very wet biomass (sewage sludge, manure, micro and macro algae), as well as some lignocellulosic feedstocks. Bio-crude production of HTL oils is currently at TRL 5–6 with small scale demonstration activities ongoing (27). Dedicated upgrading to jet fuel is at laboratory-scale (TRL 3–4). The upgrading of HTL oil in refineries is being tested as part of the Horizon 2020 4REFINERY project (28). This route has not entered the ASTM International certification procedure and is still in pre-qualification stage (14).

HTL oils typically have much lower water content, higher energy content, lower oxygen content and greater stability than pyrolysis oils, hence are expected to be cheaper to transport and require less extensive upgrading. It is expected that HTL oils could be used at high blends in refinery fluid catalytic cracking (FCC) units. With mild hydrodeoxygenation, it might be possible to co-process the bio-crude with fossil crude oil in the front end of existing oil refineries (29). Challenges of this route are the high pressure and corrosive conditions under which the process operates.

2.8 Power-to-Liquid with Fischer-Tropsch Synthesis

The PtL FT route produces liquid fuels by catalytically combining a carbon source with a hydrogen stream produced *via* electrolysis. This pathway requires three ‘feedstocks’: electricity, water and a concentrated source of CO_2. The maturity of the PtL FT route depends on the maturity of single components and the design configuration chosen, with some systems being demonstrated at small scale (TRL 5–6). High-temperature PtL employs solid oxide electrolysers (SOE), which are more efficient but less mature than other electrolysis technologies (for example, alkaline electrolysers) (30). CO_2 from concentrated sources like biogas upgrading, ethanol production or beer brewing or CO_2 waste streams from industrial processes are commercially available, but other sources, such as direct air capture, are at an earlier stage of development and commercialisation (TRL 6–7) (31). FT synthesis is a well-established process at large scale, but at the demonstration stage for small scale applications (TRL 6–7) (20). FT-SPK produced through PtL is certified under ASTM International as long as the FT synthesis is based on iron or cobalt catalysts (D7566 Annex 1, article A1.4.1.1).

Operating costs for this route can be very high depending on the cost of electricity. Specific capital costs are currently high as the technology is at the early demonstration stage, and the potential to reduce these through scaling and learning remains to be demonstrated (32). Technology developers are also working on different FT catalysts with different selectivities that could provide more direct routes to desired fuels and be more economically viable at relatively small scales. The technology also requires concentrated flows of CO_2, which might constrain the location of these plants in proximity to large industries. Despite being at very early stage with just a handful of active developers, PtL is a pathway attracting widespread interest as a result of its potential to produce fuels with very low GHG emissions and subject to less feedstock constraints and sustainability issues compared to bio-based fuels.

2.9 Demand and Supply Scenarios for Drop-in Kerosene Fuels

Today global use of aviation fuel for commercial international and domestic aviation is around 280 million tonne year^{-1} (33), however less than 0.1% of this is currently alternative or low-carbon fuel (34).

The current global capacity for HEFA production from dedicated hydroprocessing and co-processing in refineries is around 5 million tonne year^{-1} (35). With incentives for the use of alternative fuel in the road transport sector substantially stronger than in the aviation sector, the majority of the output from hydroprocessing plants today goes to substituting diesel in the road transport sector, as opposed to producing HEFA for aviation. Therefore, in 2018 less than 0.1 million tonne of HEFA aviation biofuel was actually produced (34). Nevertheless, hydroprocessing outputs require relatively minor treatment to produce aviation HEFA, meaning that HEFA production could scale-up fairly rapidly if policy were to make the use of alternative fuels in the aviation sector competitive with their use in the road transport sector.

Production capacity of sustainable aviation fuel (SAF) from all other routes is substantially lower (less than 0.1 million tonne in total), but plants are planned or being built that will progress the commercialisation of these routes (shown in **Figure 3**).

For example, Fulcrum BioEnergy, USA, is building a 31,000 tonne year^{-1} jet fuel plant based on gasification of municipal solid waste and FT synthesis (36); Lanzatech, USA, in collaboration with Virgin Atlantic are planning an AtJ plant in the UK (37); and Velocys, UK, in collaboration with British Airways, UK and Shell have provided funding to support development of a plant based on gasification of municipal waste and FT synthesis also in the UK (38).

As HEFA is currently the only SAF production technology at commercial scale, it is likely to dominate global SAF production capacity over the next decade or so. However, production of HEFA relies on the use of oils and fats as feedstock, and concerns around the sustainability of oil crops means that HEFA production is likely to be increasingly limited to the use of waste fats and oils unless other sustainable sources of oils are developed. Estimations from a number of sources suggest that around 20 million tonne year^{-1} of UCO and tallow could be collected globally (total arisings will be higher, but not all can be collected and used). E4tech Ltd, UK, carried out analysis based on Ecofys Ltd, UK, 2014 (39) and World Bank, USA, data on population (40). Even assuming that virgin vegetable oil currently used for fatty acid methyl ester (FAME) production (24.4 million tonne in 2017) was diverted into HVO or HEFA production instead, the total available feedstock would still be fairly limited compared to aviation fuel consumption.

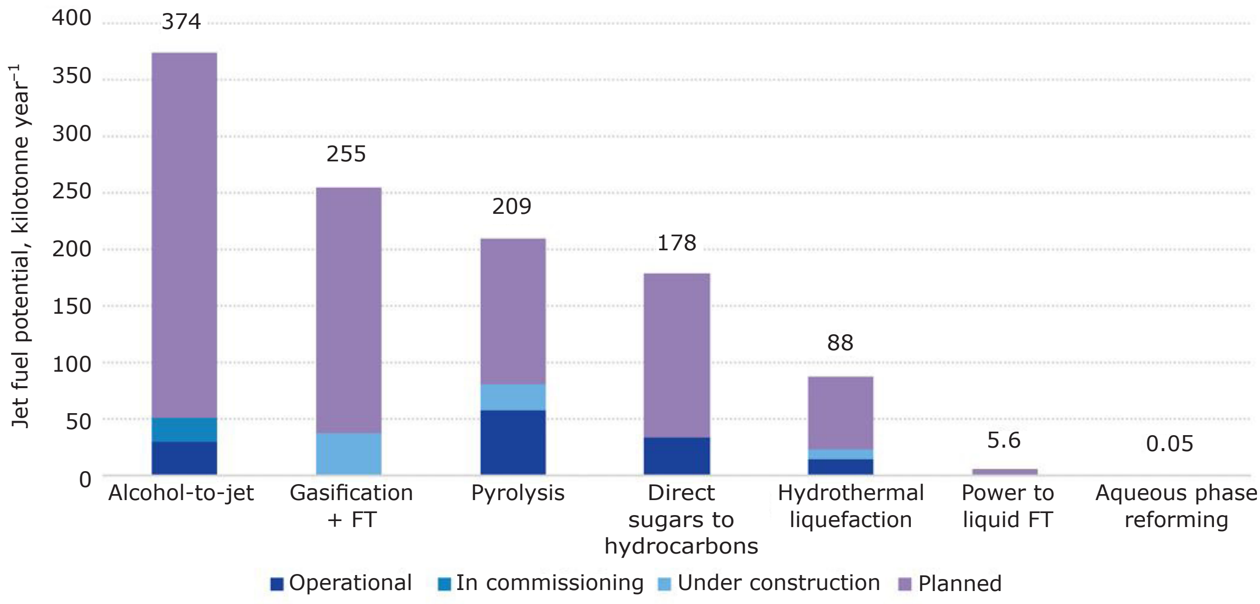

Fig. 3. SAF potential production capacity (excluding oil-based routes) as of June 2019 (35). Operational capacity refers to potential jet fuel production volumes. Pyrolysis oil and farnesene produced in the pyrolysis and DSHC plants are not currently being upgraded to jet fuel

Therefore, in the longer-term SAFs are likely to be produced from a range of lignocellulosic waste biomass sources, lignocellulosic or oil crops with a low risk of causing direct and indirect negative environmental and social impacts and renewable electricity (**Figure 4**).

However, the technologies to process lignocellulosic feedstocks into SAF are still at an early stage of development and commercialisation. Ramping-up from the demonstration-scale or first-of-a-kind commercial FT and AtJ plants, currently planned or under construction, to the construction of multiple commercial-scale plants will happen over a period of at least 10 years. Other biofuel routes and PtL routes are likely to take longer to achieve multiple commercial scale plant output, as they are at earlier stages of development and demonstration, there are fewer companies currently developing them and production costs are high.

Despite the current low production volumes, the opportunity for SAF production is large, and the imperative is strong if decarbonisation targets are to be met. The International Energy Agency (IEA, France) 2°C scenario (2DS) anticipated that even with substantial improvements in aviation efficiency and modal switching to high-speed rail for some journeys, there would still be a requirement for around 150 million tonne year^{-1} of SAF in 2060 from international aviation alone (45). With the introduction of the CORSIA mechanism over the next decade, and an increasing number of governments considering the introduction of SAF blend mandates or other policy measures to promote the uptake of SAF, growth is likely to accelerate over the coming years.

3. Hydrogen

A transition to hydrogen in civil aviation requires major aircraft and infrastructure changes. However, the potential for hydrogen as a widespread clean energy source in the future also leads to interest in its use in aviation. In August 2019 the German government announced the 'Leipzig Statement for the Future of Aviation', proposing the introduction of a hydrogen in aviation strategy by the end of 2019 (46). Use of hydrogen, both as a source of propulsion power and on-board power, has the potential to reduce noise pollution, increase efficiency and reduce GHG emissions associated with the aviation sector as long as hydrogen is produced from a renewable source, from other potentially low carbon energy sources such as nuclear or from fossil sources with carbon capture and storage.

While hydrogen has a much higher gravimetric energy density than kerosene, its volumetric energy density is much lower and both characteristics are critical to airframe design and performance (**Figure 1**). Due to hydrogen's low volumetric energy density, redesign of the airframe is required to accommodate the highly-insulated tanks required to store liquid hydrogen (LH_2) (47).

3.1 Hydrogen Turbofan

In 2000, the European Commission commissioned a study to Airbus called 'Cryoplane' (48), one of the objectives being to explore the conceptual design of an aircraft equipped with hydrogen-fuelled turbo-

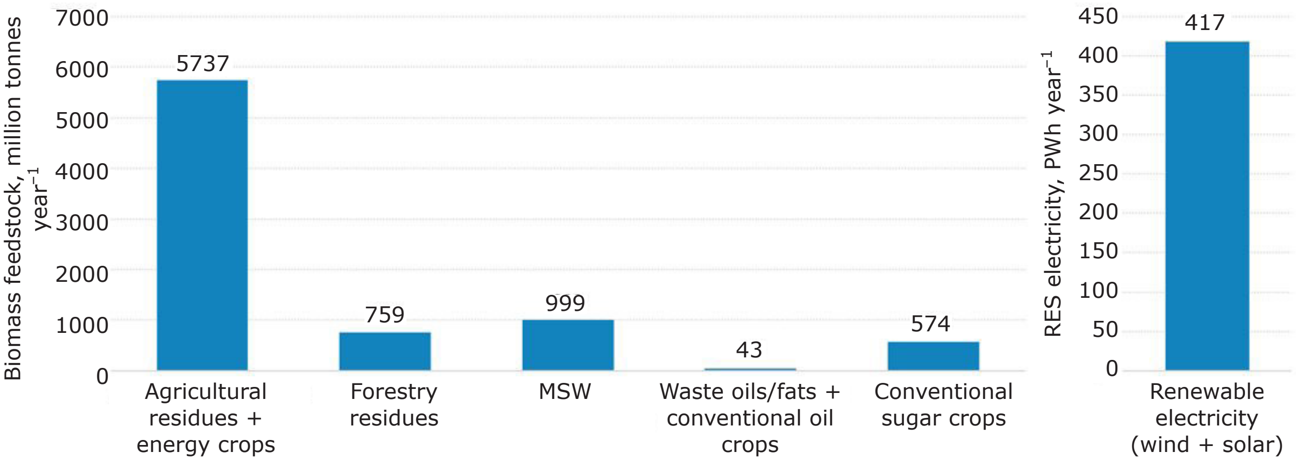

Fig. 4. Global 2050 feedstock availability (E4tech Ltd analysis based on (39, 41–44)

engines and cryogenic tanks to store LH_2. The study found that energy consumption increases by 10% compared to a reference kerosene aircraft, due to the additional weight of the hydrogen tanks (48). More recent studies (49, 50) argue that the Cryoplane project adopted a 'minimal change' approach to wing planform and engine design for the hydrogen aircraft. They show that when airframe and engine design are optimised for a hydrogen-fuelled aircraft then an energy saving up to 12% is achievable on long-haul aircraft compared to a kerosene benchmark. However, short-haul flights are penalised in terms of energy consumption when switching to hydrogen.

Modifications to the turbo-engine are required when using hydrogen due to a different composition of combustion gases and variations between the properties of hydrogen and kerosene (for example calorific value and volumetric density). Modifications affect several engine parts, such as burners, fuel ducts, cooling system and turbine blades (47). Adoption of hydrogen as an aviation fuel will also require redesign of the fuel supply chain, including on-the-ground storage and refuelling.

3.2 Hydrogen Fuel Cell Aircraft

Hydrogen can also be used in fuel cells (FCs), and both the proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) are options being considered for use in aviation. Hydrogen FCs convert chemical energy into electrical energy that could power on-board electrical equipment, or an electric propulsion system.

FCs could be used on-board in parallel to or in place of auxiliary power units (APUs). Traditional APUs consist of a small gas turbine supplying power for electrical and pneumatic loads when the aircraft is stationary as well as back-up power while cruising. FCs could see a gradual integration in aircraft APUs through powering systems currently powered by batteries, such as emergency door systems (47). A report by The Boeing Company suggested hydrogen SOFC-powered APUs for all non-propulsion loads in the aircraft would reduce fuel consumption for on-board energy by 40% during cruising compared with traditional APUs (47). However, it is important to bear in mind that auxiliary units account for a small portion of the total energy consumption of an aircraft.

There have been several projects to develop hydrogen FC aircraft, focusing on small low-speed aircraft. The HyFlyer project, led by ZeroAvia, USA, aimed to decarbonise medium range, six-seater aircraft by replacing the conventional propeller powertrain with a compressed (5000 psi) hydrogen PEMFC system (51). ZeroAvia flight tested its prototype powertrain, using a Piper PA-46 Light Sport Aircraft (Piper Aircraft, USA) (52, 53). National Aeronautics and Space Administration (NASA), USA, funded a project by the Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETA) to develop an aircraft that uses a LH_2 PEMFC system to power fully electric fans. One of the aims of the project was to demonstrate the potential of cryogenic hydrogen for larger aircraft (54). A research consortium led by The German Aerospace Center (DLR) developed HY4, a four-seater hydrogen FC aircraft (55), which completed its first flight in 2016 (56). The powertrain consists of a PEMFC coupled to a single 80 kW electric motor and supported by a battery. About 10 kg of hydrogen is stored in gaseous form in a tank at 437 bar. HY4 has a maximum weight of 1.5 tonne and can fly at 145 km h^{-1} for about 1000 km.

4. Electricity

Aviation electrification has been a trend since the 1960s, with many auxiliary systems increasingly electrified owing to the relative lightweight and higher efficiency compared to mechanical systems. Electric propulsion has also seen development since the 1970s, but so far it has been limited to demonstration or leisure activities (57). Electrically enhanced propulsion could provide significant benefits, including fuel and emissions savings and noise reduction, but technical challenges associated with battery energy and power density remain yet. Like automotive electrification, various degrees of electrification and different architectures are possible.

4.1 Hybrid Electric Aircraft

In hybrid-electric systems, where an electric motor and a turbofan are configured in series or parallel, an electric battery can supply power to optimise overall flight energy consumption and emissions. The electric motor runs together with the turbofan when high thrust is needed, or alone when low thrust is needed such as during cruising. This mechanism enables downsizing of turboengines and increased fuel economy (58).

Large industry players have worked on demonstrating the hybrid-electric architecture for future application in the large commercial aircraft segment. In 2017, Airbus, Siemens AG, Germany, and Rolls-Royce, UK, established a collaboration to develop the E-Fan X, a hybrid-electric aircraft demonstrator (59). They planned to replace one of the four jet engines in a BAE 146/RJ100 airliner with a 2 MW electric motor powered by a Rolls-Royce AE2100 gas turbine power-generation system and a lithium-ion battery pack (60, 61). Boeing and NASA partnered in a study called Subsonic Ultra Green Aircraft Research (SUGAR), to develop a hybrid-electric aircraft named 'Volt' (62) equipped with twin-engines. The engines were designed to burn fuel when the power requirement is high (such as during take-off), and to use electricity to supplement or replace power from the turbo engines while cruising. The EU Horizon 2020 Modular Approach to Hybrid Electric Propulsion Architecture (MAHEPA) project was set up as a collaboration between small and medium-sized enterprises (SMEs) and academic parties including Pipistrel Vertical Solutions, Slovenia, DLR and Delft University of Technology (TU Delft), The Netherlands. The team worked on developing two four-seater aircraft with the objective, among others, of collecting real-world data on hybrid-electric flights. The configuration of the first prototype being built by MAHEPA is a series hybrid-electric powertrain based on a reciprocating internal combustion engine connected to the propeller (63). The second prototype is a four-seater aircraft based on a FC hybrid powertrain.

4.2 Full-Electric Aircraft

Full-electric propulsion (battery as the only energy storage) could lead to zero onboard emissions and very high levels of energy efficiency and noise reduction. For these reasons policymakers are starting to show interest in electric planes. Norway, for example, has announced that all of its short-haul flights will be electric by 2040 (64).

At the time of writing, there were more than 150 electric aircraft development programmes around the world, although the majority of them focused on the urban air taxi, also known as passenger drone, and general aviation (defined as civil non-commercial aviation, i.e. small aircraft for private transport and recreational activities) (57). The general aviation segment is seen as a 'test bench' for further development. With lighter weight and short range, the technical requirements of the general aviation segment are more suited currently to a higher degree of electrification.

One of the innovations, enabled by full-electric propulsion, which is expected to deliver the benefits of full electrification is 'distributed electric propulsion'. This propulsion strategy is based on the optimal placing of multiple electrically driven propellers across the aircraft wetted surface. An example of distributed propulsion is the Lilium Jet (Lilium GmbH, Germany): a full-electric five-seater aircraft, with 36 fans distributed to enable vertical take-off and landing (VTOL). With a range of 300 km, the Lilium Jet was designed for intracity and regional commuting. In 2019, Lilium GmbH announced the aim of launching its air taxi service in several cities by 2025 (65, 66).

Several initiatives, involving tech and aerospace actors, have been set up to develop novel aircraft designs using full-electric powertrains aimed at the air taxi market. For example, Kitty Hawk, USA, backed by Google, USA, worked with Boeing to develop a two-seater with a 100 km range using 12 lifting rotors, which was expected to be used by Air New Zealand for air taxi (67). Uber Technologies Inc, USA, the ride-hailing app company, has been linked with at least five aircraft manufacturers developing VTOL technology (68). One of these manufacturers is Aurora Flight Sciences, USA, a subsidiary of the aerospace major Boeing. Airbus also began an air taxi project called Vahana (69).

Another player, Eviation Aircraft Ltd, Israel, has produced a full-electric prototype (Alice) designed to take up to nine passengers, with a range of 650 miles, and capable of flying at 240 knots at 10,000 feet. It utilises Honeywell's fly-by-wire avionics, three electric motors producing around 900 kW of power, and Li-ion batteries supplying 900 kWh of energy, with a recharge ratio of 2:1, meaning 30 min of charging are needed for every hour in the air (70).

Despite very promising benefits, full-electric propulsion is confronted with a fundamental limitation with regard to energy storage in the form of battery energy density. Current state of the art Li-ion battery has an energy density of 0.9 MJ kg^{-1}, which theoretically could go up to 1.4 MJ kg^{-1}, but this is still an order of magnitude smaller than jet fuel's 43 MJ kg^{-1}. One promising novel battery chemistry, $Li-O_2$ is claimed to have a theoretical gravimetric density of 12 MJ kg^{-1}, still far short of kerosene (71). A further limitation is posed by the power-to-weight ratio of electric propulsion systems which has been historically lower than turbofans, though significant advances have been made in motor power density (72).

Electrification of aviation requires significant developments in battery energy and power density, as well as in other areas as airframe design, motor design, power electronics, cooling, heat recovery and power systems integration. Issues such as battery safety, charging and power infrastructure also need consideration for an increased electrification of aviation.

5. Conclusions

The SAF and propulsion options described in this review span across different levels of technical maturity, economic viability and current applicability to different types of aircraft. **Table II** provides a summary of these options, highlighting key technical, environmental and economic characteristics.

Renewable drop-in kerosene is an attractive decarbonisation option for aviation because it does not require modification of the aircraft airframe and engine and refuelling infrastructure. Today it is commercially produced in low volumes for use in commercial flights from a limited number of airports. Its production cost is currently significantly higher than the fossil kerosene price, representing the main challenge to its uptake, which will depend on strong policy support. While hydrogen is a very appealing fuel that can be derived from a range of renewable sources and produced from fossil sources with carbon capture and storage, its use in medium and long-haul aircraft requires a radical redesign of the engine and airframe, as well as the fuel supply chain, including on-the-ground storage and refuelling, leaving it a prospect for the long term.

Hybrid and full electric aviation are gaining traction with several projects and prototypes being developed to demonstrate the technology and trial new aircraft concepts, involving research organisations, small companies, as well as major aircraft manufacturers. Small full-electric planes (up to 10-seaters) are likely to see commercial deployment in the near term. But, the technical requirements of medium and long-haul aircraft (weight, seat capacity, speed and range requirements) cannot be met with current battery technology. Without a breakthrough in battery chemistry, electric propulsion is unlikely to be used in commercial aviation beyond the smaller short-haul flights. However, as technological progress is made, hybrid electric solutions could emerge for larger aircraft, furthering hybrid powertrain and airframe integration and contributing to the reduction of fossil kerosene use in aviation.

Glossary

APR	aqueous phase reforming
APU	auxiliary power unit
AtJ	Alcohol-to-jet
CAAFI	Commercial Aviation Alternative Fuels Initiative
CHEETA	Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DSHC	direct sugars to hydrocarbons
FAME	fatty acid methyl ester
FC	fuel cell
FCC	fluid catalytic cracking
FT	Fischer-Tropsch
GHG	greenhouse gas
HDO	hydro-deoxygenation
HEFA	hydroprocessed esters and fatty acids
HFS	hydroprocessing of fermented sugars
HTL	hydrothermal liquefaction
HVO	hydrotreated vegetable oil
LH_2	liquid hydrogen
MAHEPA	Modular Approach to Hybrid Electric Propulsion Architecture
PEMFC	proton exchange membrane fuel cell
PtL	power-to-liquid
SAF	sustainable aviation fuel
SIP	synthesised isoparaffins
SK	synthetic kerosene
SOFC	solid oxide fuel cell
SPK	synthetic paraffinic kerosene
SUGAR	Subsonic Ultra Green Aircraft Research
TRL	technology readiness level
UCO	used cooking oil
VTOL	vertical take-off and landing

Table II Summary of SAF and Propulsion Technology Options

Technology option	Maturity	CO_2 emissions	Range	Passengers	Economics
Fossil jet – turbofan (medium-haul)	Nth commercial	110 g CO_2 RPK^{-1} (73) [a]	Medium	~150	Fossil jet price ~€530 $tonne^{-1}$
Fossil jet – turbofan (long-haul)	Nth commercial	75–95 g CO_2 RPK^{-1} (73)	Long	~400	Fossil jet price ~€530 $tonne^{-1}$
Bio-jet – turbofan	1st commercial	20–90% CO_2 savings (@ 100% bio-jet) compared to fossil jet depending on feedstock (74)	Short, medium, long	Up to 400	Bio-jet price ~3–5 times fossil jet
Hydrogen – turbofan	Prototype	17 g CO_2 RPK^{-1} using green hydrogen from solar photovoltaic (66 g CO_2 kWh^{-1} H_2) (50)	Short, medium	Up to 400	Higher capital expenditure (CAPEX) compared to conventional aircraft due to insulated H_2 tanks. Current H_2 prices ~10 times fossil jet, on energy basis (75)
Hydrogen – FC + motor	Prototype	6 g CO_2 RPK^{-1} using green hydrogen from solar photovoltaic (66 g CO_2 kWh^{-1} H_2) (76)	Short	Up to 10	Higher CAPEX compared to conventional aircraft due to insulated H_2 tanks + FC system, but lower maintenance required. Current H_2 prices ~10 times fossil jet (on energy basis) (75)
All electric – battery + motor	Prototype	63 g CO_2e RPK^{-1} @ 315 g CO_2 kWh_e^{-1} grid (EU28, 2015) 19 g CO_2e RPK^{-1} @ 100 g CO_2 kWh_e^{-1} grid (77) [b,c]	Short, medium	Up to 150	High CAPEX battery packs, but potentially lower maintenance required. Current electricity prices ~3 times fossil jet (on energy basis) (78), partially offset by higher efficiency for short-haul aircraft
Hybrid electric – battery + motor/ turbofan	Prototype	Up to 53% energy savings compared to conventional equivalent (79)	Short, medium, long	Up to 150	Cost of additional electric system (battery + motors) offset by reduced fuel expenditure

[a] RPK = revenue passenger kilometres
[b] CO_2e = CO_2 equivalents
[c] kWh_e = kilowatt hour electric

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Hydrogen Fuel Cell Vehicle Drivers and Future Station Planning

Lessons from a mixed-methods approach

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The market for hydrogen fuel cell vehicles (FCVs) continues to grow worldwide. At present, early adopters rely on a sparse refuelling infrastructure, and there is only limited knowledge about how they evaluate the geographic arrangement of stations when they decide to get an FCV, which is an important consideration for facilitating widespread FCV diffusion. To address this, we conducted several related studies based on surveys and interviews of early FCV adopters in California, USA, and a participatory geodesign workshop with hydrogen infrastructure planning stakeholders in Connecticut, USA. From this mixed-methods research project, we distil 15 high-level findings for planning hydrogen station infrastructure to encourage FCV adoption.

1. Introduction

Hydrogen FCVs are establishing themselves in consumer and fleet markets worldwide, with 11,200 FCVs and 376 hydrogen refuelling stations (HRSs) open to the public and fleets by late 2018 (1). However, the lack of a convenient refuelling infrastructure remains a barrier to greater FCV diffusion.

There is robust discussion regarding network deployment of initial HRSs to address this (2–8), although there is not agreement on how best to geographically arrange stations to do so (9, 10). This area of literature began before the initial market diffusion of FCVs, and relied on surveys of drivers of conventional vehicles about hypothetical station scenarios, or of analogue populations of diesel or natural gas vehicle drivers, to predict FCV adoption and refuelling behaviour (11–15). Since the roll-out of HRSs and FCVs, recent studies have surveyed initial FCV drivers about their station usage (16), but a key outstanding research area is how prospective FCV adopters, accustomed to the ubiquity of gasoline stations, evaluate the spatial arrangement of the full network of HRSs when adopting FCVs. That is the primary emphasis of our National Science Foundation (NSF)-funded research project, which employed a mixed methods research design to address a set of related questions (**Table I**). In this short paper, we distil 15 high-level insights from these studies for regions and companies planning a rollout of HRSs and FCVs. We refer readers to current and future publications and presentations for greater detail on the methods and results than is possible here.

Table I Studies Within our NSF Project in This Paper[a]

Research questions	Research methods	Study area	Study size
Which HRSs were drivers intending to rely on at the time they decided to buy or lease their FCV? **How did their list of HRSs change over time?**	Online revealed preference survey, network GIS analysis, statistical modelling	California	*n* = 129
How do early adopters describe in their own words how they decided to buy or lease a FCV?	Ethnographic interviews, content analysis	Greater Los Angeles, California	*n* = 12
What decision process do potential early adopters use to decide whether or not to get a FCV?	Ethnographic decision tree modelling	California	*n* = 71 (ongoing)
Where should HRSs be planned to maximize early adoption of FCVs according to industry stakeholders?	Geodesign workshop	Greater Hartford, Connecticut	17 participating stakeholders

[a]Publications and presentation materials are available from Arizona State University (ASU) (17)

2. Mixed Methods Approach

Our mixed-methods research design involved a combination of (a) revealed preference survey research, (b) qualitative ethnographic approaches that analyse consumers' decision-making processes and language and (c) geodesign participatory planning (18–20).

We conducted this research in California and Connecticut. By November 2019 over 7700 FCVs had been sold or leased in California, supported by 42 public HRSs (21), allowing an opportunity to evaluate how recent early adopters evaluated FCVs and HRSs when they got their vehicles. Connecticut is one of eight Northeast US states with Hydrogen and Fuel Cell Development Plans updated in 2018 (22), making it a compelling location to evaluate stakeholder opinions and prospective FCV adoption.

2.1 Survey Research

A web-based survey collected responses from 129 FCV adopters in California in the spring of 2019. To recruit, we posted links on Facebook groups for FCV owners there. Drivers listed HRSs that they intended to use when they decided to adopt their FCV, and using an interactive web map, where they lived, worked and frequently visited at the time, and whether their list of stations changed over time and why.

Using a detailed street dataset, we conducted geographic information system (GIS) network analysis to estimate travel times between stations and respondents' recorded locations. We also computed the deviations required (in miles and minutes) to visit the stations listed as the difference between the fastest direct route from home to destination and the fastest route that included the station as an intermediary stop. We conducted these analyses for stations they initially intended to use, used after experience or did not use. Results were analysed statistically using t-tests and logistic regression, and customer-derived trade areas were estimated in GIS. The GIS and statistical analysis provide insight into the revealed preferences of early adopters, while enabling comparisons with their stated intentions expressed in the survey and their subsequent behavioural changes.

2.2 Ethnographic Content Analysis and Decision Tree Modelling

Ethnography is a qualitative research approach that aims to understand decisions from the subject's individual and culturally specific point of view, and has been used to study automobile purchasing (23). We conducted structured ethnographic interviews of FCV adopters in California to understand their decision-making process. Interviews began with the request to "walk us through your decision-making process," with follow-up prompts for further explanation and reminders to keep responses relevant to the time they were deciding to adopt the FCV. We analysed these data using two ethnographic research methods.

We conducted content analysis using 12 hour-long interviews with FCV adopters in greater Los Angeles (24). All statements in the interview were coded using theoretically derived themes from the FCV adoption literature, and supplemented with additional inductive codes generated after analysing the transcripts. For the ethnographic decision tree model (EDM), we are conducting two rounds of interviews: one for constructing an initial tree model and one for testing and modification. An EDM represents the common or shared decision criteria about this behavioural choice by members of a cultural group (25). The EDM evaluates how most people move through a branching decision-making process to arrive at a yes-or-no decision. This has been used to model automobile purchases (26), but not for FCVs. For both rounds it is essential to sample drivers who (a) ultimately decided in favour of getting an FCV, and (b) seriously considered doing so but decided against it. For the first round, we conducted 25 hour-long interviews with drivers from the Los Angeles and San Francisco Bay regions, and then constructed an initial EDM tree.

Shorter second-round interviews followed, where the interviewer asked about each of the decision factors identified in the first round. In both rounds, the EDM tree was evaluated by the percentage of correctly predicted "yes" and "no" responses.

2.3 Geodesign Workshop

In October 2019, our research team led a seven-hour geodesign workshop in Hartford, Connecticut. In consultation with the host Connecticut Hydrogen-Fuel Cell Coalition and the University of Connecticut, we invited 71 stakeholders from related industries, regional government agencies and local universities. Seventeen participants that included representatives from each of these broad stakeholder groups worked together to propose, vet, negotiate and recommend a plan for a network of HRSs to support the initial rollout of FCVs in the region, following the established geodesign process. Participants worked in breakout groups with an online user-friendly mapping tool (27).

3. Results: Lessons Learned

We distil our findings from this mixed-methods approach into 15 primary lessons.

3.1 Motivations for Fuel Cell Vehicle Adoption

Ethnographic interviewees adopted FCVs for a diversity of reasons, including interest in new technology, perceived social status, free fuel and high-occupancy vehicle (HOV) lane access (24). Given available subsidies, adopters saw FCVs as a more affordable environmentally friendly option than electric vehicles (EVs), with faster refuelling times. FCV adoption also avoided the cost of upgrading residential wiring to accommodate Level 2 EV charging.

3.2 Fit Between Vehicle and Driver

In addition to thinking about whether the FCV would meet their needs, ethnographic interviewees described their degree of fit to the vehicle, in terms of being the type of person who plans refuelling trips, has flexibility due to being retired or has a long commute (24).

3.3 Convenience to Home is the Most Important Factor

California FCV adopters most frequently cited proximity to home as the main reason for choosing their primary intended HRS at the time of purchase. This was true for both the online survey participants (65%) and the ethnographic interviewees (50%).

3.4 Perceived Convenience to Home Varies

Ethnographic interviewees used a broad range of times and distances to describe stations' convenience to home. **Figure 1** shows that 36% of survey respondents planned to rely on HRSs within ten minutes of home because they were "near home" while still others said the same thing for a station an hour or more away.

3.5 Stations Near Work or On the Way Can Substitute for Near Home

Over 35% of survey respondents, and even more in the ethnographic interviews, did not consider their primary HRS to be near home. For primary stations, near work (36%) and on the way to a common travel destination (30%) were the next most important geographic factors.

3.6 Secondary Stations

Early adopters plan to rely on multiple stations to meet their needs when they get their FCV, averaging 2.98 HRSs, while only 18% listed one.

3.7 Station Trade Areas

Trade area analysis for the four HRSs that survey respondents in Southern California

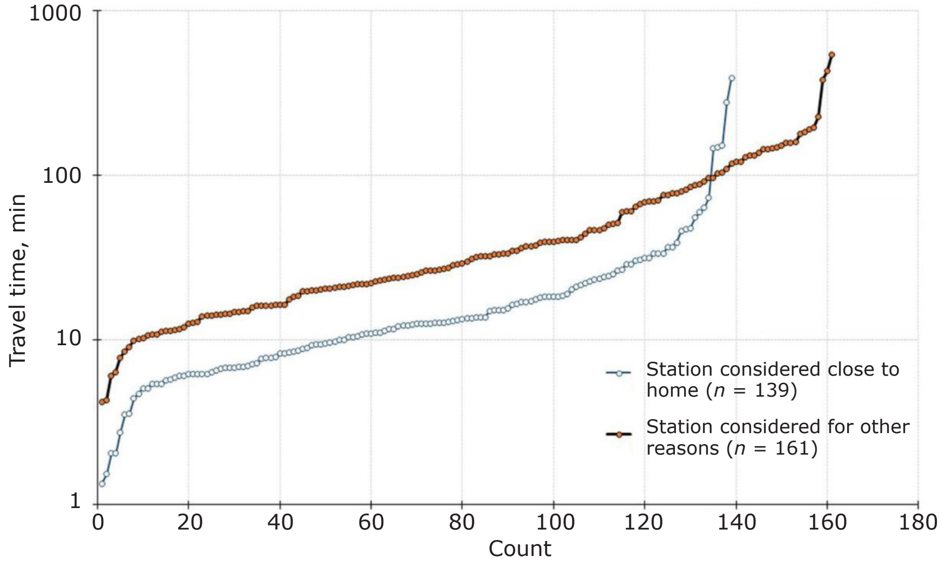

Fig. 1. Ordered estimated shortest travel times between home and hydrogen stations considered (n = 300) by early California FCV adopter survey respondents (n = 124), for stations described by drivers as "near home" and stations considered by drivers for other reasons

Fig. 2. Estimated trade areas for the four stations in Southern California most frequently listed by respondents. These trade areas include the nearest 65% of customers who purchased an FCV intending to rely on these HRSs (customers could list up to five stations)

listed most frequently at the time of adoption encompass a broad area (**Figure 2**), suggesting that respondents living across the region felt comfortable adopting an FCV while intending to use these stations.

3.8 Station Reliability and Backup Stations

Some adopters were aware of HRS unreliability: nearly 50% of secondary HRSs listed by survey respondents were considered to be backup stations. Seven out of 12 ethnographic interviewees required backup stations near home or work.

3.9 Secondary Vehicles

In addition to secondary stations, availability of a secondary vehicle was prominently noted by ethnographic interviewees. These are needed for longer trips and different carrying capacity needs, and to accommodate station reliability issues. Respondents mentioned additional household internal combustion vehicles and EVs, along with rental cars.

3.10 Convenience to Freeways

Ethnography interviewees often cited the proximity of stations to freeway exits near destinations or along routes, and associated time savings, as a reason for frequenting certain HRSs. Stakeholders in the Hartford geodesign workshop prioritised locating HRSs near points of freeway ingress and egress, citing high potential local demand and convenient access and service for New York–New England through-traffic.

3.11 Planned Stations

Ethnographic and survey respondents were willing to adopt an FCV in anticipation of planned HRSs while relying on less convenient, existing HRSs in the meantime, though expressed frustration about HRSs that were anticipated to come online but never did.

3.12 Changing Refuelling Stations

Nearly 60% of survey respondents did not change the list of HRSs that they initially planned to use over time. If their initial list included HRSs conveniently near home, work and along the way to their primary destination, they were less likely to change this list. However, for drivers with an FCV for at least 20 months, more than half did change their list.

3.13 New Stations After Experience

We used logistic regression to analyse the differences between stations that survey respondents initially intended to use when they got the vehicle ($yi = 0$) and those stations added over time that were not initially considered ($yi = 1$). We separately analysed the addition of HRSs that were: (a) available both at the time of adoption and when the respondent took the survey, and (b) planned at the time of the survey that later became available (**Figure 3**). Added HRSs are more likely to be farther from home than those initially considered. Reliability is significant for adding HRSs that were initially available, while shorter deviations are significant

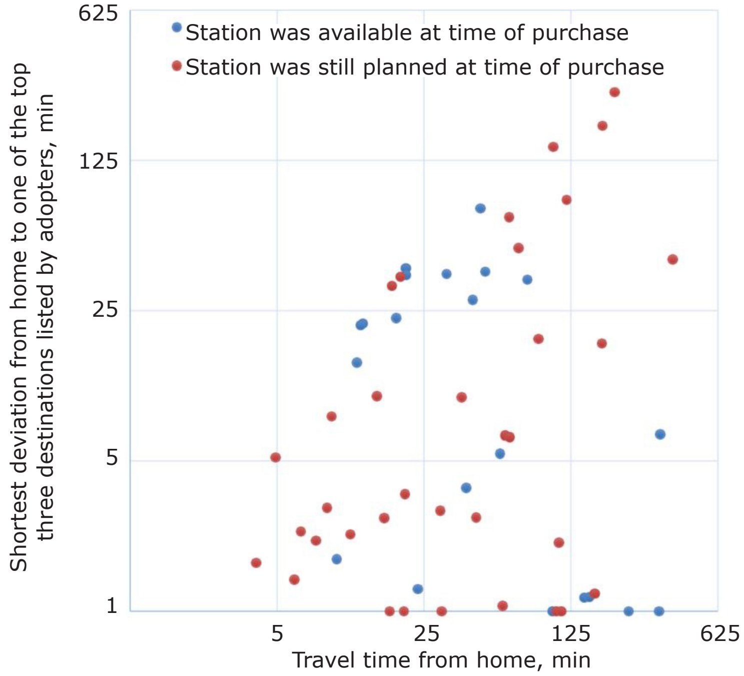

Fig. 3. Stations later added by California FCV adopters to their list of HRSs, that is, HRSs they were not initially intending to use (n = 56)

for adding HRSs that were initially planned and became available.

3.14 Demographics and Stakeholder Priorities for Placing Initial Stations

Geodesign workshop participants suggested placing the first three HRSs near wealthier neighbourhoods to maximise initial FCV adoption. While this reflects conventional wisdom and is consistent with the demographic characteristics we observed in our California ethnographic interviewees, it is possible that those with different demographic characteristics would adopt FCVs if similar outreach, incentives and HRSs were made available to them.

3.15 Sufficient Initial Number of Stations

While further research is needed to reliably predict how many HRSs are needed to encourage regional FCV adoption, there was consensus in the geodesign workshop that adding three new HRSs to the two existing or under construction would be (a) realistic within a few years, (b) sufficient to give potential early adopters several stations they could use and (c) sufficient to satisfy automakers to begin selling FCVs in Hartford (population 1.2 million).

4. Ongoing Research

Finalising the EDM for FCV adoption in California will require completing additional interviews, especially with drivers who seriously considered adopting an FCV but ultimately did not. In addition, we recently completed data collection for the stated preference survey in Connecticut, which prompts respondents to evaluate their willingness to get an FCV given three maps that show different pre-generated spatial arrangements of initial HRSs.

5. Conclusions

The consistent lesson is that these early FCV adopters are diverse in their motivations for wanting an FCV and in the list of stations and refuelling strategies they planned to use at the time of adoption. Drivers consider everything from lifestyle to image, and from incentives to station locations when deciding to get an FCV. A station "near home" is important to many drivers, but it is neither necessary nor sufficient for others. What is subjectively "near home" varies from minutes to over an hour away. Station reliability, secondary stations, freeway access and convenience to a variety of destinations all are important, especially while awaiting the opening of planned stations. Over time, drivers begin using stations they initially did not consider to support travel farther from home, with reliability and short detours also playing important roles.

The key implication is that stations should be located to serve not only 'targeted' nearby residents but also others who may visit or pass nearby regularly. Likewise, developers should also locate stations far from these neighbourhoods to benefit the wider travel of these residents and local travel of those who live elsewhere.

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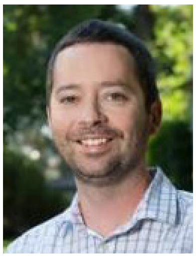

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Battery Materials Technology Trends and Market Drivers for Automotive Applications

Challenges for science and industry in electric vehicles growth

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With the electric vehicle (EV) market set to grow rapidly over the coming years, the industry faces a challenging ramp-up of volume and material performance demands. From the current trend towards high-energy high-nickel cathode materials, driven in-part by consumer range anxiety, to the emergence of solid-state and beyond lithium-ion technologies, herein we review the changing requirements for active materials in automotive Li-ion battery (LIB) applications, and how science and industry are set to respond.

Introduction

Outdoor air pollution is linked to an estimated 4.2 million deaths each year worldwide (1). Tailpipe emissions from conventional internal combustion engine (ICE) vehicles are a major contributor to urban air pollution, and as such have been subject to ever tighter legislation for decades, requiring increasingly innovative improvements and catalytic emissions controls. We have now reached the point where a move away from the ICE is required to continue air quality improvements, with several countries going so far as banning new purely ICE vehicles in the coming years. This is where EVs will play their part – both pure EV and hybrid systems powered by LIB technologies, as well as fuel cell technologies, are set to see increased uptake and demand as we strive for cleaner air. In this article, we will add to the automotive-focused literature (2–4) and review what technologies are required to drive the uptake of pure EVs, and what the industry is doing now to respond to consumer requirements as this market rapidly grows.

There are several characteristic battery parameters that it is important to consider and contrast with consumer behaviours and expectations for automotive applications: perhaps most significant, the energy or capacity of the cell equates to the 'miles in your tank', and is an area where EVs have lagged behind the ICE in previous years. This is evolving, with the most successful EVs on the market now having an average range of 350 km (5). Range anxiety, equating to energy density, is a major theme for the battery materials industry, with contributions from and innovations required in three areas: the cathode, anode and electrolyte. Cost is also an important factor; as well as the material costs for the active components, analysis has shown that the electrode thickness within the cell is a major contributor to automotive cell costs (6) – materials with increased volumetric energy density are therefore additionally attractive from this perspective. There is also the practical cost benefit afforded by developing systems that can operate at higher voltage cut-offs (7), owing to the usable advantages, towards which multiple cell components can be developed and optimised. Herein, we review one topic of significant industry focus from each area: high-Ni cathode materials, with lithium nickel manganese cobalt oxide (NMC) 811 and beyond being commercialised within the next three years; high energy silicon anode technologies, expected to be at commercial scale in the next three to five years; and solid-state electrolytes, with significant progress expected from the next five years and beyond.

High Energy Cathode Advancements

Whilst the cathode active material technology landscape remains diverse, with no one material that will meet all EV requirements, the general trend for passenger EVs is using high-Ni NMC, and lithium nickel cobalt aluminium oxide (NCA) materials. The layered Li Ni oxide (LNO), has been studied for the past 25 years, ever since the commercial application of the isostructural Li Co oxide (LCO) by Sony, Japan, in 1991; the relative low cost of Ni compared to Co was an initial driver for this work – and continues to be a factor today (8–12). Until relatively recently, automotive industry uptake was focused on lower Ni NMC variants, such as $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC 111), and lower energy chemistries such as Li Mn oxide (LMO), and Li iron phosphate (LFP). Tesla, USA, bucked the trend; as an early adopter of higher-Ni NCA materials, it was ahead in the EV mileage stakes. Now, driven by consumer demand for more range, high-Ni is in vogue – the key for research and industry alike is to innovate-out the technical problems associated with LNO regarding its stability.

LNO tends towards non-stoichiometry, owing to the relative instability of Ni^{3+} compared to Ni^{2+}, and the similar ionic radii of Ni^{2+} (0.69 Å) and Li^{+} (0.73 Å) (12, 13). It has been shown that synthesis conditions are key to prevent the formation of Ni^{2+} anti-site defects, with near-stoichiometric LNO requiring control of calcination temperature, atmosphere and Li content (12, 14). LNO is also known to undergo several phase transformations on electrochemical cycling; whilst a capacity of over 200 mAh g^{-1} can be achieved, these transformations lead to significant capacity fade over the first cycles (15). Early research showed the benefits of incorporating relatively small amounts of other metals, most notably Co, Al and Mn, into the structure to impart stability and significantly improve capacity retention. Owing to the isostructural nature of its end members, all compositions in the series $LiNi_{1-x}Co_xO_2$ (x = 0–1) can be formed; Co^{3+} imparts stability by hindering the formation of Ni^{2+} anti-site defects (16). Conversely, doping Mn into the LNO structure has been shown to detrimentally effect the reversible capacity but to impart thermal stability benefits – a key property for battery safety (17, 18). The beneficial effect of Al substitution at low levels is two-fold: an improvement in capacity retention by minimising detrimental phase transformations and an increase in thermal stability (18, 19). There is, however, a limitation to the amount of Al that can be usefully incorporated into the structure; the addition of high-levels of an electrochemically inactive dopant will result in a reduction in capacity, and Al^{3+} has been shown to segregate and create localised defects within the lattice, due to the different ionicity of Al–O and Ni–O bonds (20).

This combined work has ultimately led to continued focus on the multiple metal dopant strategies found in NCA and NMC, where greater benefits are observed than in single dopant systems. Whilst not as catastrophic as those in LNO, NCA and high-Ni NMC materials (such as NMC 811) undergo significant structural changes on cycling, which their lower Ni counterparts (for example NMC 622, NMC 111) do not (**Figure 1**): at high states of charge, a transformation from the second hexagonal phase (H2) to the third hexagonal phase (H3) occurs in high-Ni materials that is associated with *c* lattice contraction and capacity fade (21–23). The addition of dopants to the bulk structure of LNO such as cobalt, manganese, aluminium, magnesium, titanium and combinations thereof has been shown

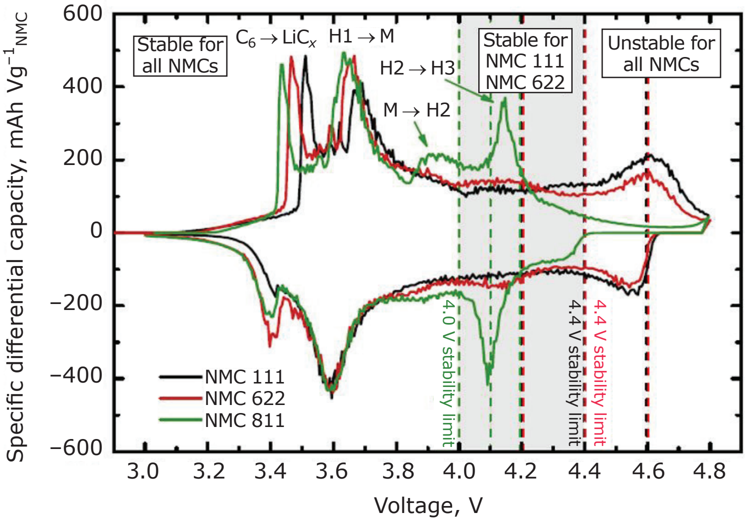

Fig. 1. Differential capacity *vs.* cell voltage of NMC-graphite cells recorded at a 0.1 C-rate (3rd cycle). The peaks are assigned to their corresponding phase transitions with H1, H2 and H3 representing the three hexagonal phases and M the monoclinic one. C6 → LiC_x indicates the lithiation of graphite (21) Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND)

to influence stability by affecting the volume change on cycling associated with the H2/H3 phase transformation (24–26).

Coating strategies have been employed to high-Ni NCA and NMC systems, providing benefits in two key areas: handling and performance. The handling and processability of high-Ni materials is a well-known challenge, with surface reactivity towards the ambient resulting in the formation of Li hydroxide and Li carbonate impurities, and the resultant propensity of electrode slurries to gel: this creates obvious challenges before materials have even reached the cell (27–29). Once in the cell, these surface impurities contribute to resistance growth and side reactions resulting in gassing (30, 31). Moreover, the high-Ni surface itself is known to undergo phase changes upon cycling, with the formation of the rock salt phase Ni oxide also contributing to instability and capacity fade (32, 33). In its simplest sense, the application of an inactive coating such as Al oxide passivates the surface with respect to these undesirable side reactions, creating more benign materials that are easier to handle; but only so much of this type of coating can be applied before either significant capacity loss or resistance gains are observed (34). As such, the move toward active coatings, where the removal of an inherent risk of capacity loss does not limit the amount or depth of coating that can be applied, is very attractive. A notable example in this area is the extensive work by the Sun group, who have developed several generations of active coatings and complex morphologies for high-Ni materials (**Figure 2**): starting with a core@shell

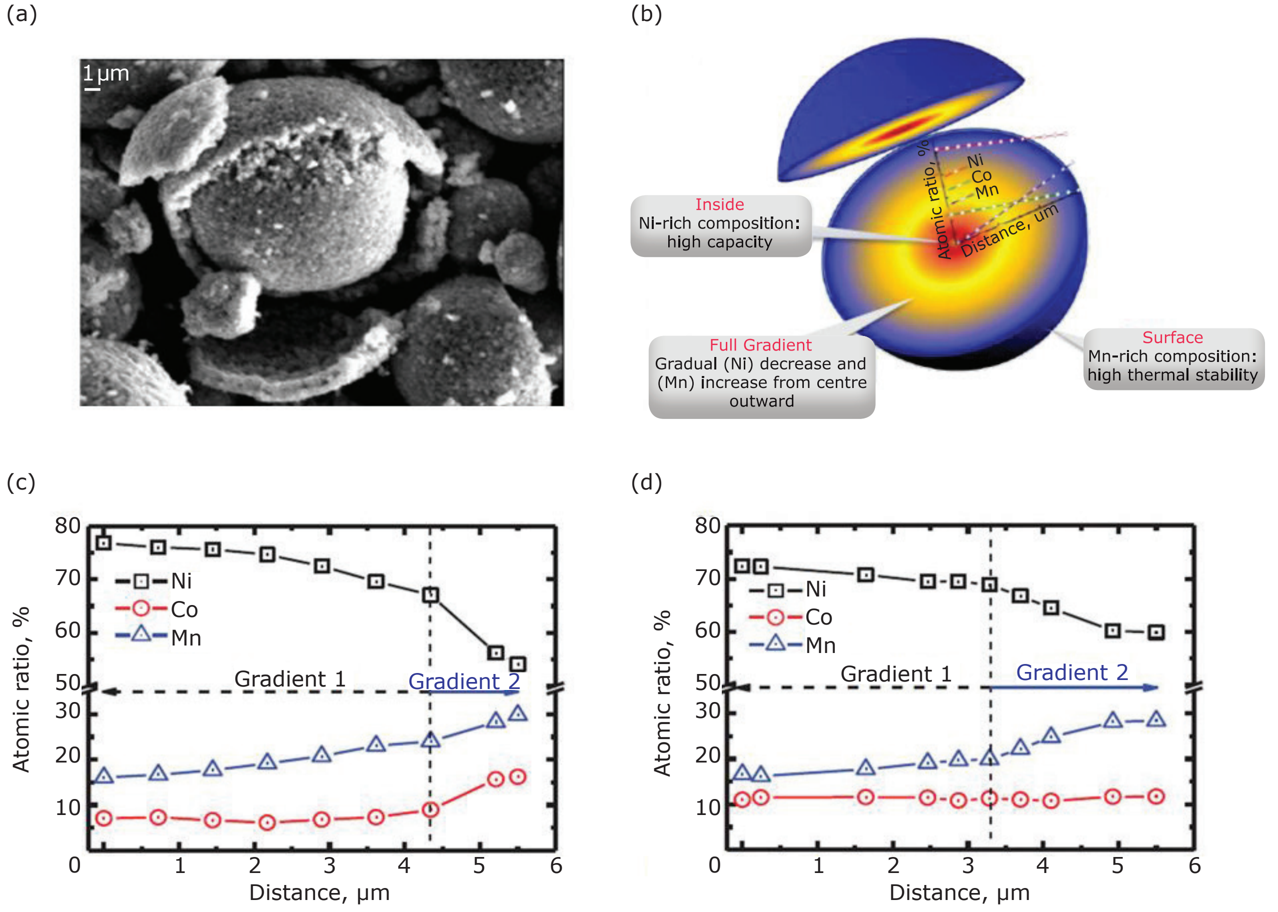

Fig. 2. Development of core@shell and gradient NMC materials: (a) scanning electron microscopy image of Ni-rich core and Mn-rich shell, showing interfacial cracking after cycling, reprinted with permission from (35), Copyright 2005 American Chemical Society; (b) schematic diagram of full gradient material, reprinted with permission from (36), copyright 2012 Springer Nature; (c) electron probe microanalysis (EPMA) line scan of the integrated atomic ratio of transition metals as a function of the distance from the particle centre to the surface for the precursor; and (d) EPMA line scan of the integrated atomic ratio of transition metals as a function of the distance from the particle centre to the surface for the lithiated gradient material, reprinted with permission from (37), copyright 2015 John Wiley and Sons

strategy, a low-Ni NMC was applied to the surface of a high-Ni NMC, creating a system that combined a high-energy core with a high-stability surface and building a system that was electrochemically active throughout (35). The drawback of this system was the observation that the shell layer broke away from the core on cycling, due to the mismatched volume changes within the core and shell NMC layers. To counteract this, the group developed a gradient coating strategy, whereby a lattice expansion or contraction mismatch was avoided by creating a continuous region of gradual compositional change, thus removing a core@shell interface (38). The Sun group further extended this work to look at deeper and multi-component gradients and their potential benefits (36, 37, 39). Such gradient systems can be viewed as a sophisticated hybrid between bulk doping and surface coating strategies, helping to mitigate the trade-offs associated with each strategy alone.

These gradient systems demonstrate the importance of considering morphology and process alongside composition in materials engineering. Another area of interest is the mitigation of microcrack formation through the control of primary particle shape, size and interfaces; fewer cracks means a more stable cathode electrolyte interface (CEI) layer, alleviating resistance growth and gas-generating side reactions (33, 40, 41). Most recently, this has led to particular interest in single crystalline morphologies, which promise greater long-term cycling stability compared to their polycrystalline counterparts by minimising the number of interfaces where microcracks can occur. The majority of published research in this area has focused on lower-Ni NMCs (i.e. NMC 622 or less), where reduction in gassing has been observed compared to polycrystalline counterparts, albeit at the cost of rate capability (42, 43). This lower Ni focus is in part due to the challenging nature of high Ni synthesis at the typically elevated temperatures required to form single crystalline materials compared to those used to generate polycrystalline materials. There are examples demonstrating similar advantages for a single crystalline morphology with up to 80% Ni content and efforts are clearly growing in this area: single crystalline NMC 811 has been shown to exhibit less gassing than its polycrystalline counterpart during high temperature storage (30). Zhu *et al*. undertook a broad study looking at NMCs from NMC 111 to NMC 811 prepared by multiple approaches and demonstrated the need to tune synthesis conditions to Ni content (44).

The engineering opportunities to overcome the challenges presented by high Ni materials continue to grow. As the automotive industry strives for higher energy, the drive to increase the Ni content of NCA and NMC type materials is clear – the common theme across the industry is to move from NMC 622 to NMC 811 and toward 90% Ni content to meet energy requirements, but also to reduce the Co content required, due to sourcing and cost challenges. Ultimately, a combination of the strategies reviewed above are required to develop and commercialise materials with a Ni content of 80% and above to meet the energy and stability requirements of the automotive industry.

High Energy Anode Advancements

Aligned with the drive toward higher energy cathode materials, there is a requirement to enhance and optimise LIB anode materials toward greater energy density, improved cycle life, lower cost per kilowatt hour and improved gravimetric and volumetric densities (3, 46). In particular, the use of higher energy cathode materials allows increased ampere hour per geometric area and volume of active cathode which is important to retain realistic active material loadings and thicknesses and achieve battery EV (BEV) cell and pack targets. A commensurate improvement in storable energy per area and volume of anode electrode is therefore also required. Cell manufacturers and original equipment manufacturers (OEMs) are increasingly moving beyond todays natural and synthetic graphite materials (or combinations of these) toward blending graphite with a higher energy density Si or Si oxide component to enhance cell level energy gravimetric and volumetric density (47). **Table I** illustrates examples of such Si containing materials (48).

The high natural abundance of Si and low operating voltage (0.2 V discharging potential compared to Li/Li^+) single out Si as a highly promising anode material for LIBs (49). However, Si containing materials as battery anodes exhibit a number of challenges, with the greatest of these being significant volume expansion during the lithiation process (see **Table I**). Particle cracking or fragmentation, loss of electrical contact, ongoing parasitic reactions between electrolyte and 'fresh' surfaces, cell swelling and gassing all contribute to cycle life issues (see **Figure 3** and **Figure 4**) (46). Various approaches can be deployed to address the volume change issue for pure Si anodes, including nano-engineering of the Si

Table I Comparison of Anode Materials[a]

Anode material	C	Si	SiO_x
Volume change % during lithiation	12	280	160
Lithiated phase	LiC_6	$Li_{15}Si_4$	Li_xSi, Li_2O, Li_4SiO_4
Initial theoretical specific capacity, mAh g^{-1}	372	3579	3172
Typical initial coulombic efficiency, %	90–95	77.5–84	65–95

[a] Reproduced from Chen *et al*. and references therein (48)

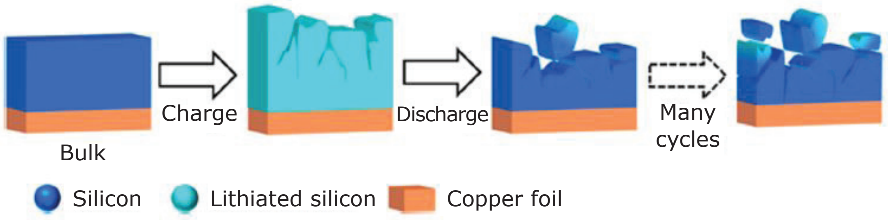

Fig. 3. Schematic of the changes occurring at the surface during electrochemical cycling of bulk Si, illustrating how large volumetric changes result in cracking, fragmentation and loss of electrical contact to active material, reprinted with permission from (46), copyright 2017 American Chemical Society

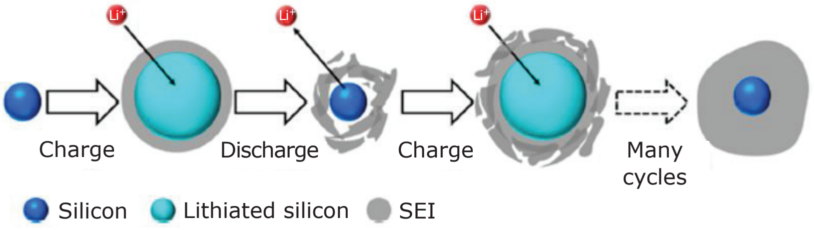

Fig. 4. Illustration of the evolution of Si particle solid electrolyte interface (SEI) with repeated cycles, reprinted with permission from (46), copyright 2017 American Chemical Society

electrode structure (nanowires and nanoparticles, formation of secondary agglomerates) along with advanced binder combinations to create a flexible electrode structure (46, 50, 51). The addition of carbon dioxide into pouch cells has also been trialled to limit parasitic reactions (52). Formation of nanocomposites of Si–C *via* mechanical or chemical deposition processes, addition of other alloying components or the choice of a SiO_x material (where first cycle lithiation allows an irreversible reaction creating stabilising LiO_x and Li silicate components within the structure) can all bring improvements (50, 53). Incorporation of conductive carbon also addresses the challenge posed by the intrinsic low conductivity of Si containing materials (54).

A strategy of blending Si containing materials with existing graphite types is already in progress to achieve moderate capacity increase and lessen volume change, as illustrated by cell level calculations for this approach (for example Si:C 1:3 with capacity of 1100 mAh g^{-1} by Andre *et al*.) (3, 47). **Table I** illustrates an additional challenge present in Si containing anodes in the form of lower first cycle efficiency (FCE) *vs*. graphite, related to reactions consuming Li between the electrolyte and anode, the formation of the SEI and associated reduction in useful Li inventory in the working cell, reducing effective watt hour per kilogram. Pre-lithiation approaches, where sacrificial Li containing materials are added to the Si anode during electrode fabrication or strategies such as electrochemical pre-lithiation of formed electrodes ahead of cell assembly are possible (55, 56) along with chemical pretreatments 'artificial SEI formation' (57, 58). However, these all represent additional steps and cost in a cell manufacturing process, also pre-lithiated materials and electrodes and Si nanoparticles require careful handling due to the reactivity of the materials with moisture and air (48).

Careful optimisation of the liquid electrolyte additives is also crucial to achieve prolonged cycle life and good FCE, with fluorinated additives, especially fluoroethylene carbonate (FEC), showing benefit (59). The discharge and charge voltage profile of Si containing anodes is slightly different to graphite-only examples, leading to reduced chance of Li plating during charging in Si anodes, but typically slightly lower discharge voltage with graphite, thus adjustments to cell balancing and understanding of the operational state of charge window in the usable voltage range are important for full cell (60).

Assessment of the sustainability of changing to Si containing anode components and advanced higher energy cell chemistries is also vital as electrification of the power train advances worldwide (61).

Higher Energy Through Solid-State Electrolytes

A further driver to increase the energy density of cells is to replace existing anode materials with metallic Li. Li metal was used as the first anode material in rechargeable Li-ion cells due to its very high energy density (3860 mAh g^{-1}) and low electrochemical potential (–3.040 V *vs.* the standard hydrogen electrode). However, numerous challenges prevented its widespread adoption, including low cycle life predominating from issues such as the formation of dendrites and unstable solid-electrolyte interfaces. Recently, there has been increasing investigations into using solid-state electrolytes to mitigate the challenges of using metal anodes, whilst maintaining their advantages.

In addition to potentially enabling the use of Li metal anodes, the evolution to solid state batteries has other advantages to conventional Li-ion cells (62). The primary reason is the displacement of the highly flammable cocktail of organic electrolytes that is used currently. This both reduces the risk of unwanted thermal events in the instance of cell misuse or damage, but it also results in a simpler packaging, further increasing the energy density (63) (**Figure 5**). In addition, solid state materials could offer increased electrochemical stability windows in comparison to existing organic electrolytes; potentially enabling alternative materials, such as higher voltage cathode materials, to be deployed.

Polymer Gels

The use of polymers as electrolytes in batteries was first pioneered in the 1970s (64, 66). This enables cells with high degrees of safety to be manufactured in various form factors. Polymer-based systems

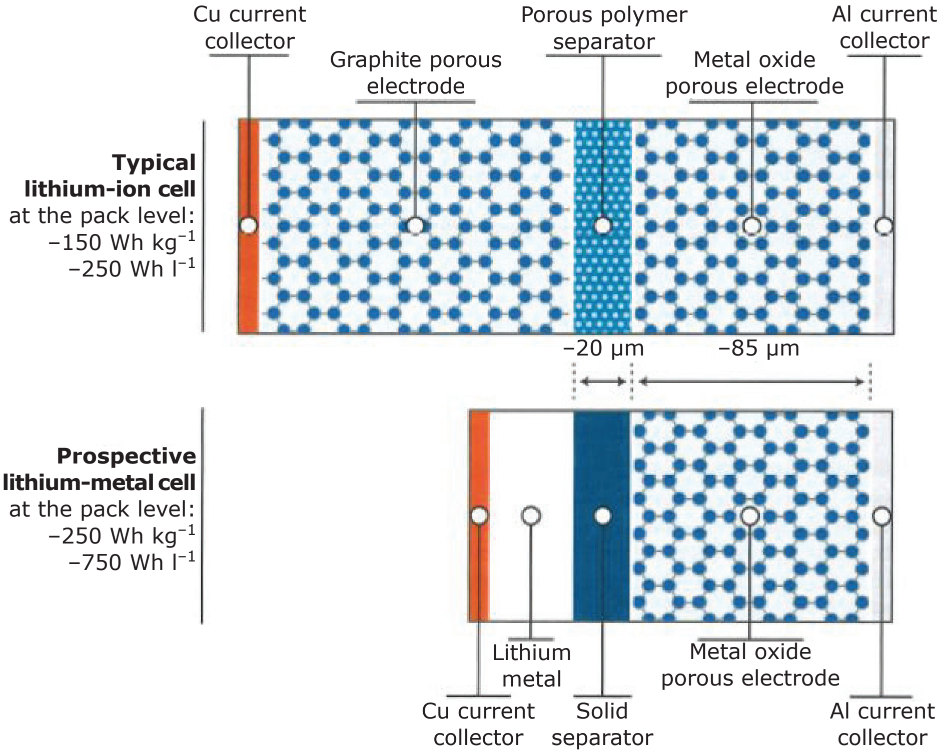

Fig. 5. What is the advantage in energy density of a cell? Reprinted with permission from (64), copyright 2018 Springer Nature

such as polyethylene oxide (PEO), polyvinylidene fluoride (PVDF), polyacrylonitrile and polymethyl methacrylate (PMMA) based electrodes have all been widely studied as polymer electrolytes (67). PEO-based polymer electrolytes have been studied the most due to their advantageous properties including lower cost, ability to solvate a wide variety of ions, relatively high chemical stability and the use of their moderate mechanical strength (~10^6 Pa) to supress the growth of dendrites (68, 69). However, the low conductivity (~10^{-7} S cm^{-1}) of the electrolyte systems, due to the crystallinity of the polymer chains, has been a limitation (70). Overall, the general uptake of polymer gel cells has been restricted by their lower energy densities and poor electrochemical stability compared to liquid electrolytes.

All Solid-State Batteries

More recently, researchers have explored a range of solid inorganic materials, which allow ionic mobility through the solid. Numerous classes of these are currently being explored, all possessing different advantages and disadvantages (63, 71, 72). A summary of these are highlighted in **Table II**.

Researchers have looked to examine inorganic electrolyte materials with high ionic conductivities, such as $Li_{10}GeP_2S_{12}$, which exhibits high conductivity at RT (73). However, sulfide-based solid electrolytes are generally expensive, more challenging to synthesise and are sensitive to moisture, potentially releasing toxic gases. This brings challenges in their handling and subsequent fabrication.

Although most solid electrolytes have been shown to react with Li metal, garnet materials (such as $Li_7La_3Zr_2O_{12}$ (LLZO)), have shown the greatest stability (74, 75). In addition, they have relatively low costs and a wide electrochemical window (~6 V *vs.* Li metal) potentially enabling the use of higher voltage cathode materials; and are therefore attracting increasing investigations (74). The cubic phase of LLZO is found to offer greater ionic conductivity than the tetragonal phase. A typical strategy to promote this is to dope elements such as Al, tantalum and gallium into the structure thus stabilising the highly conductive cubic phase at RT (76).

Despite these advantages, a challenge in using LLZO remains its instability in the ambient atmosphere, due to CO_2 and moisture (77). This results in increased complexity upon subsequent material handling and processing. Further challenges include poor interfacial compatibility of LLZO with electrodes. To overcome this, methods to increase the wettability of the electrolyte have been explored, such as the atomic layer deposition of Al_2O_3 to reduce interfacial resistance by the formation of a desirable Li-Al-O layer (73); or alloying Li with other elements (such as Si, Al, Ge) to increase compatibility (72).

In addition to the preparation of materials capable of high levels of Li-ion conductivity, it is vital that these materials can be manufactured at an industrial scale at a reasonable cost. While there has been considerable interest in the use of oxides for an all solid electrolyte, their brittleness and fragility impose new challenges for mass production (78, 80). As a result the scale up of such activities is being explored using a variety of different processing technologies (**Figure 6**). Mature slurry-based technologies have been shown to provide dense layers using high throughput techniques. However, subsequent high temperature sintering inhibits the co-firing of solid electrolytes and cathode particles.

Table II Selected Parameters for Key Classes of Solid-State Electrolytes

Type	Example composition	Ionic conductivity at room temperature (RT), S cm^{-1}	Electrochemical stability to Li
Sulfide	$Li_{10}GeP_2S_{12}$ (73)	1×10^{-2}	Stable
Garnet	$Li_7La_3Zr_2O_{12}$ (74)	3×10^{-4}	Stable
Sodium superionic conductor (NASICON)	$Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ (75)	7×10^{-4}	Unstable
Perovskite	$Li_{0.34}La_{0.51}TiO_{2.94}$ (76)	2×10^{-5}	Unstable
Lithium phosphorous oxynitride (LiPON)	LiPON (77)	6×10^{-6}	Stable
Anti-Perovskite	Li_3OCl (78, 79)	9×10^{-4}	Stable
Argyrodite	Li_6PS_5Cl (80)	1×10^{-3}	Stable

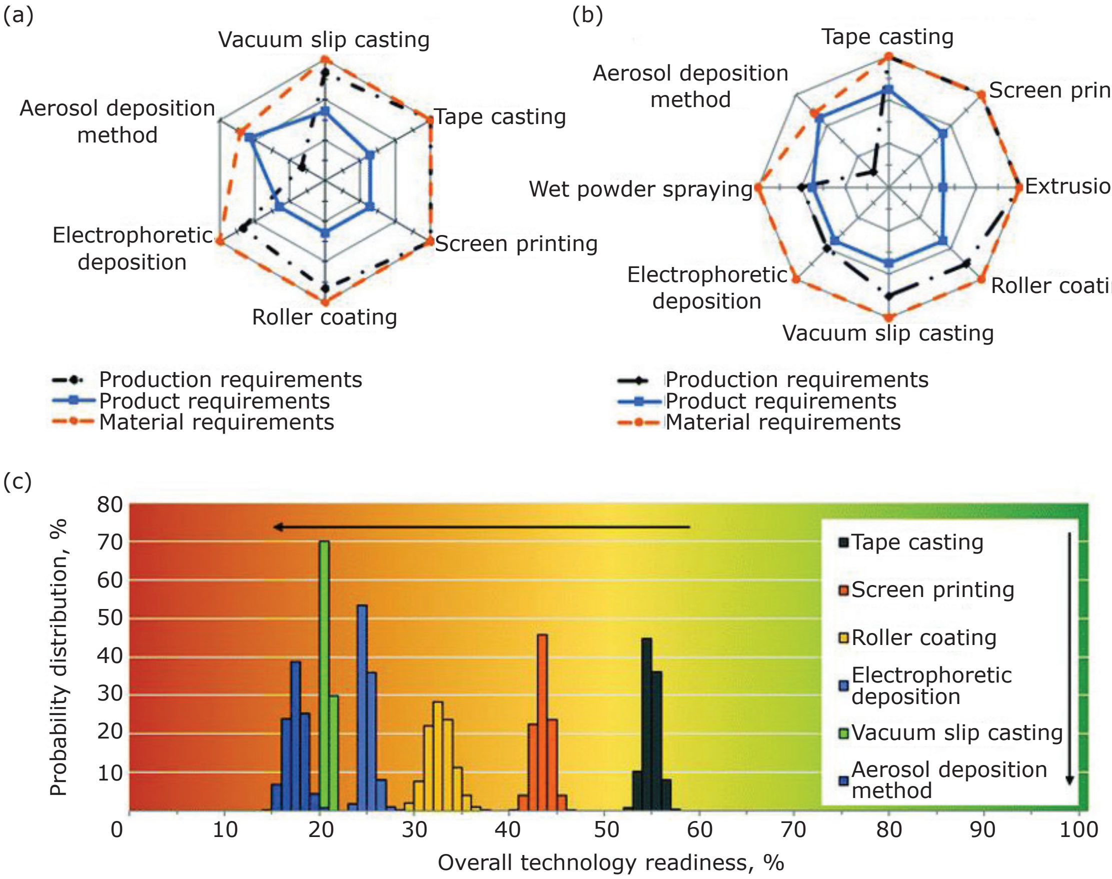

Fig. 6. Technology readiness of current solid-state electrolyte processing options: (a) technical feasibility – solid electrolyte fabrication; (b) technical feasibility – cathode composite fabrication; and (c) technology readiness – solid electrolyte fabrication, reprinted with permission from (78), copyright 2019 Royal Society of Chemistry

When using Li metal as an anode material it is vitally important to prepare dense electrolyte layers in the absences of holes. It has been suggested that a critical relative density of >93% are required to eliminate the formation of dendrites in LLZO electrolytes (79); with short circuits believed to propagate through voids and grain boundaries (81). To obtain highly sintered garnet-based solid electrolytes by conventional sintering techniques, generally high temperatures (>1200°C) and long sintering times (>30 h) are required. Such conditions can result in the decomposition of the solid electrolytes and loss of Li from the structure.

To overcome these challenges, alternative processes such as hot pressing, field-assisted sintering and spark plasma synthesis have been investigated to fabricate the optimal dense ceramic layer (82–85). To that end further evaluation of deposition and sintering technologies will be required to provide an economically viable solution.

Beyond Lithium-Ion

There are also multiple technologies (such as Li-sulfur and Li-air chemistry) that have the potential to deliver significant advances in performance, such as increased energy density (86). For example, Li-S chemistry benefits from the low cost and high abundance of S and an energy density significantly higher than current Li-ion cells (~2500 Wh kg^{-1}) (87, 88). However, these technologies currently suffer from technical challenges that limit their uptake. To fully maximise the benefit of these technologies, it is necessary to overcome the challenges of working with a Li metal anode. The use of solid-state electrolytes is a recent area where people have been exploring with the aim of enabling the technology *via* anode protection.

Summary

The demand for cleaner air is accelerating and this is giving rise to increased electrification in the automotive drivetrain. There is also a growing acceptance of vehicles with varying degrees of electrification, and this trend looks set to continue. Current concerns for increased energy density to counter consumer's 'range anxiety' are leading to material developments to meet this. In particular, the careful design and manufacturing of cathode materials with high amounts of Ni and anode materials with increasing Si content are steadily improving these key parameters. Furthermore, significant exploration into next generation technologies, such as solid-state electrolytes, opens the possibility of redesigning the cell. While options to the type of material used and their processing remain; the replacement of conventional liquid electrolytes promises to deliver further improvements in energy density as well as other benefits, such as safety performance. These three examples highlight the major trends being investigated and introduced into automotive cells to meet the demands of society.

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Adaptable Reactors for Resource- and Energy-Efficient Methane Valorisation (ADREM)

Benchmarking modular technologies

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Following the global trend towards increased energy demand together with requirements for low greenhouse gas emissions, Adaptable Reactors for Resource- and Energy-Efficient Methane Valorisation (ADREM) focused on the development of modular reactors that can upgrade methane-rich sources to chemicals. Herein we summarise the main findings of the project, excluding in-depth technical analysis. The ADREM reactors include microwave technology for conversion of methane to benzene, toluene and xylenes (BTX) and ethylene; plasma for methane to ethylene; plasma dry methane reforming to syngas; and the gas solid vortex reactor (GSVR) for methane to ethylene. Two of the reactors (microwave to BTX and plasma to ethylene) have been tested at technology readiness level 5 (TRL 5). Compared to flaring, all the concepts have a clear environmental benefit, reducing significantly the direct carbon dioxide emissions. Their energy efficiency is still relatively low compared to conventional processes, and the costly and energy-demanding downstream processing should be replaced by scalable energy efficient alternatives. However, considering the changing market conditions with electrification becoming more relevant and the growing need to decrease greenhouse gas emissions, the ADREM technologies, utilising mostly electricity to achieve methane conversion, are promising candidates in the field of gas monetisation.

1. Introduction

The tremendous growth of the global economy is directly related to increased energy demand and (currently) high greenhouse gas emissions. Substantial reduction in global emissions is required to minimise environmental hazard and ongoing climate change. Legislations are pushing for energy transition, replacing fossil fuels with alternatives for reduced emissions. Wind, solar and biomass are key-players for the energy future, as depicted in the latest statistics and forecast (1, 2). According to one of the possible energy transition scenarios, to accommodate the increasing energy demands with the least environmental impact, renewable sources will rapidly grow their share in the energy mix, while natural gas is foreseen to maintain a key role during the transition phase (1, 2). However, natural gas contributes to CO_2 emissions, with approximately 7 billion tonnes of CO_2 being produced on a yearly basis, with approximately 5% of this amount attributed to flaring (**Figure 1**). This percentage adds to both the environmental problem and to the waste of an important resource, methane (3–5).

ADREM (EU project Horizon 2020 No. 636820), focused on the development of novel reactor concepts that are capable of converting methane to higher chemicals with a compact, modular and flexible process design. The University of Zaragoza (UniZar), Spain; Delft University of Technology (TU Delft), The Netherlands; and SAIREM, Décines-Charpieu, France, investigated microwave reactor technology for methane non-oxidative coupling (MNOC). Katholieke Universiteit Leuven (KU Leuven), Belgium and Kemijski inštitut in Ljubljana, Slovenia, worked with plasma technology for methane non-oxidative coupling and dry reforming respectively. Ghent University, Belgium, investigated the gas solid vortex reactor (GSVR) for oxidative methane coupling (OCM). In the present paper, we give an overview of the technologies that were developed, the status, the main bottlenecks and the path forward.

2. Technology Breakthrough

2.1. Microwave Non-Oxidative Methane Coupling with Both a Multistage Monomodal Reactor and with a Travelling Wave Reactor

Two different reactor setups were used for MNOC: (i) multistage monomodal, and (ii) travelling-wave. The microwave concept relies on highly energy-efficient selective heating of catalyst since the required heat for the endothermic reaction is directly generated within the microwave-susceptible catalysts or catalytic support. The endothermic reaction occurs only at the (heated) catalytic surface, eliminating possible side reactions and unnecessary pre-heating of the gases. Julian *et al.* (6), focused on structured reactors, with various monolith configurations and compositions. The structured catalysts have low pressure drop and minimum mass transfer limitations. Methane at ambient conditions was supplied to the heated structured catalyst to produce C2-C10 (**Figure 2**). Julian *et al*. (6) reached the optimum performance of 15% methane conversion, with a yield to C2 and C6 equal to 6% for both compounds, comparable to conventionally heated non-oxidative methane coupling. The tailor-made monolith

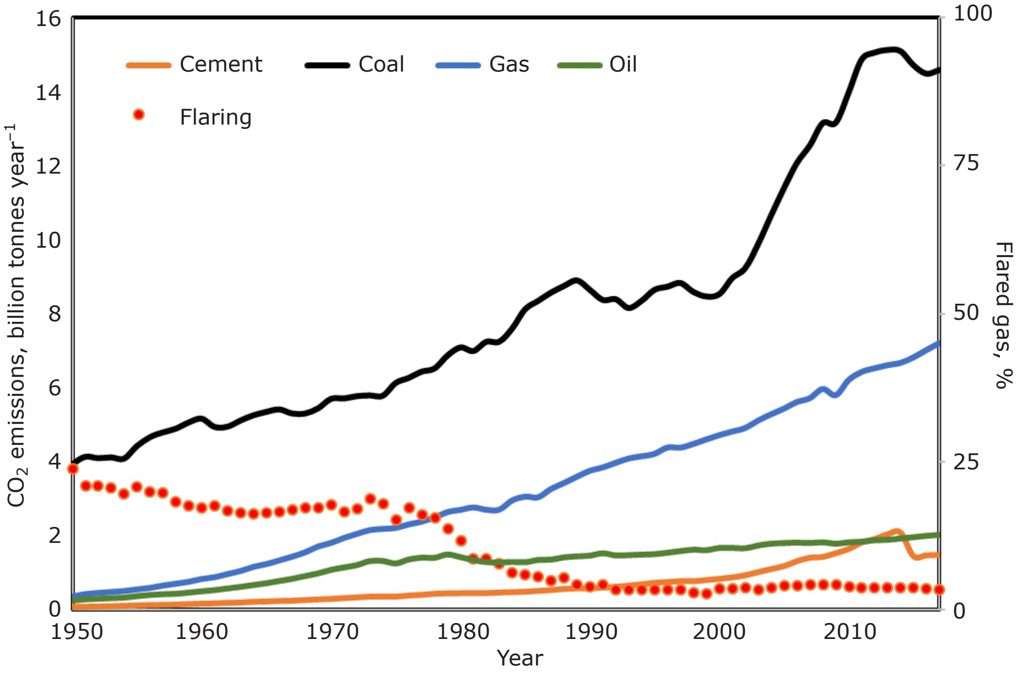

Fig. 1. CO_2 annual emissions from cement, coal, gas and oil and flaring percentage on gas (5)

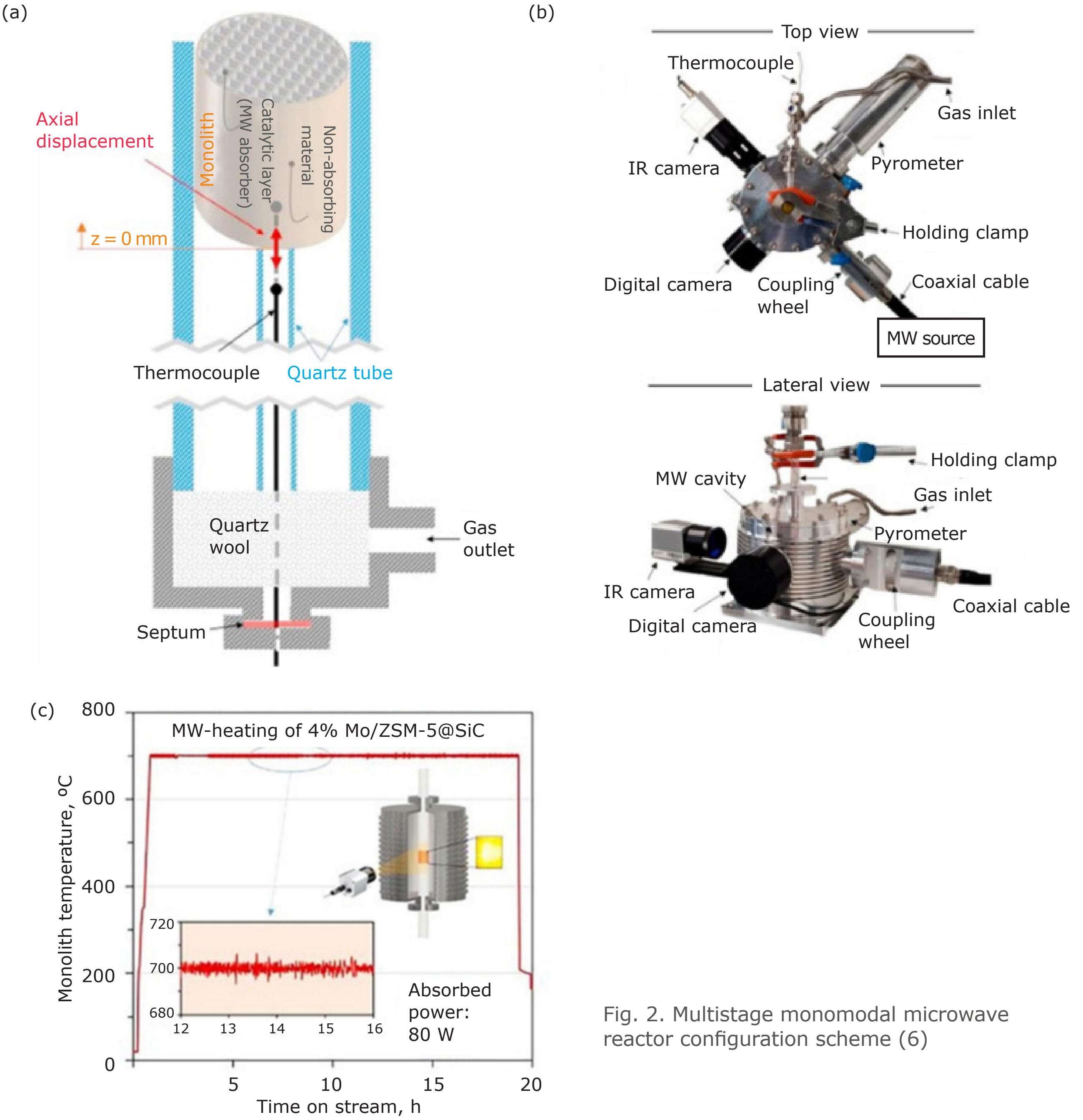

Fig. 2. Multistage monomodal microwave reactor configuration scheme (6)

(Mo/ZSM-5@SiC) showed a stable performance of reaction-regeneration for approximately 20 h. The main limitation for continuous operation is coke deposition that deactivates the catalyst and creates hotspots. For TRL 5 validation, an upscaled fully automated system has been successfully tested at the Danish Technology Institute.

TU Delft investigated the same chemistry in the travelling-wave microwave reactor concept. In contrast to mono- and multi-mode resonant applicators, the travelling-wave reactor concept has the potential for generating highly uniform microwave heating by avoiding resonant conditions (7, 8). Since the travelling-wave reactor ensures uniformity of the electromagnetic field inside the reactor, it enables energy-efficient operation, with a flexible (in terms of upscaling potential) design. TU Delft has designed and constructed the travelling-wave reactor and has simulated its performance. Also, heating tests with 5 mm beta silicon carbide extrudates, supplied from SiCat-Germany, have been conducted in the fixed-bed configuration (**Figure 3**). The microwave heating experimental results showed that uniform

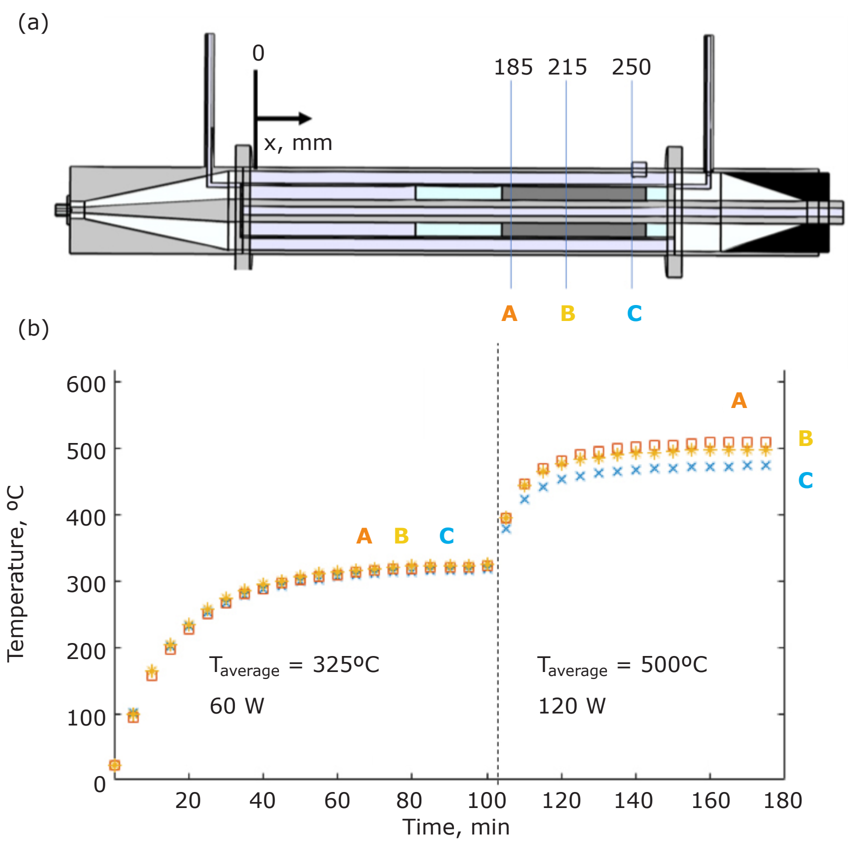

Fig. 3. (a) Schematic view of the travelling-wave microwave reactor; (b) transient temperature profile. A, B and C represent the temperature measurement points

temperature distribution can be achieved, with average temperatures of 325–500°C with MW inputs of 60 W and 120 W respectively.

2.2. Plasma Non-Oxidative Coupling of Methane

MNOC was investigated in nanosecond pulsed discharges (NPD). Plasma, a cloud of chemically active species namely radicals, ions and excited molecules, is initiated *via* (high energy) electron and molecule collisions. These active species can rapidly undergo several chemical reactions to form other products at ambient temperature and pressure conditions. Eventually, the electric energy is channelled into chemical rather than into gas heating, minimising heat losses. Two plasma-assisted process alternatives have been developed and optimised by Stefanidis and co-workers aiming for: (i) a direct gas conversion to ethylene at elevated pressures without utilising any catalyst (9); and (ii) a stepwise gas conversion to acetylene followed by acetylene-to-ethylene catalytic hydrogenation in the post-plasma zone (10) (**Figure 4**). Different plasma geometries (co-axial and plate-to-plate) and operating conditions (i.e. pulse frequency, inter-electrode gap and pressure) towards high ethylene yields at relative low energy costs have also been tested. Collectively, in case of serial plasma-catalyst integration and global thermal insulation of the plate-to-plate reactor system, the ethylene energy cost can be as low as ~900 kJ mol^{-1} C_2H_4 for ~32% C_2H_4 yield. Periodic air plasma ignition enables reactor decoking, allowing for extended operating periods (11). The plate-to-plate reactor, unmanned and fully automated has been tested (TRL 5) in Johnson Matthey's facilities.

2.3. Oxidative Coupling of Methane with a Gas-Solid Vortex Reactor

In OCM, methane reacts with oxygen to produce C2 compounds together with carbon monoxide and CO_2 in an exothermic reaction. To avoid formation of oxygenates, short and controlled residence times are preferred. In the GSVR, a rotating fluidised bed is obtained by tangential gas injection at high velocities (**Figure 5**). Centrifugal force counteracts the drag force, resulting in a dense fluidised bed and a higher gas solid slip velocity, increasing heat, mass and momentum transfer and decreasing the gas residence time (12). The gas enters the GSVR through a single inlet and is distributed around the annulus. Gas enters tangentially into the reaction chamber *via* rectangular slots and then exits the reactor through a central exhaust (**Figure 6**). The

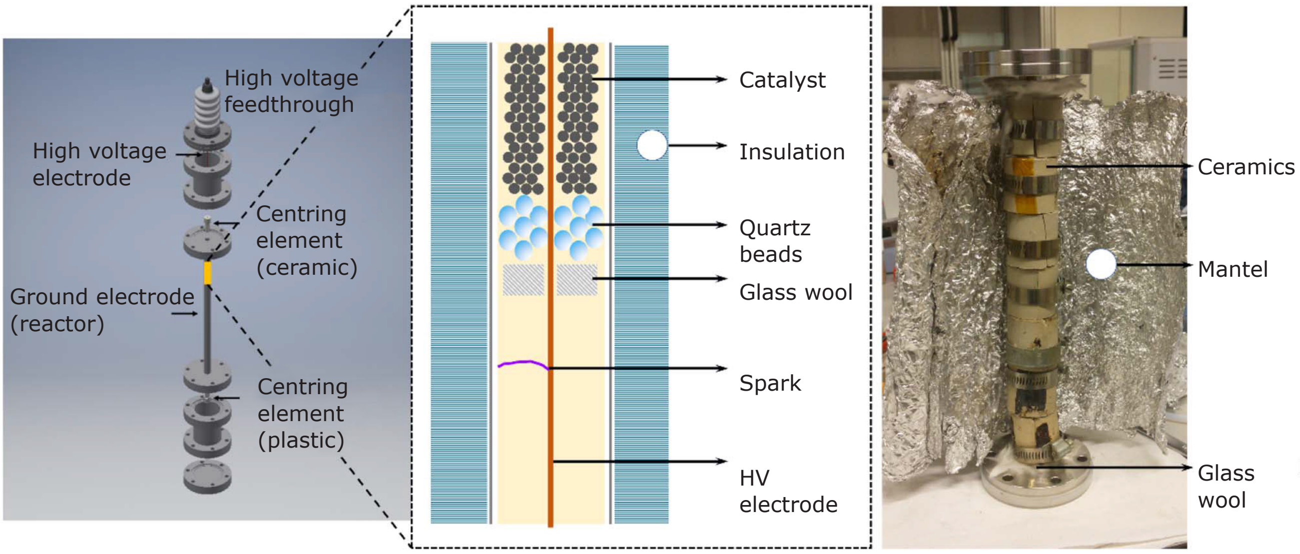

Fig. 4. Hybrid plasma reactor configuration scheme (10)

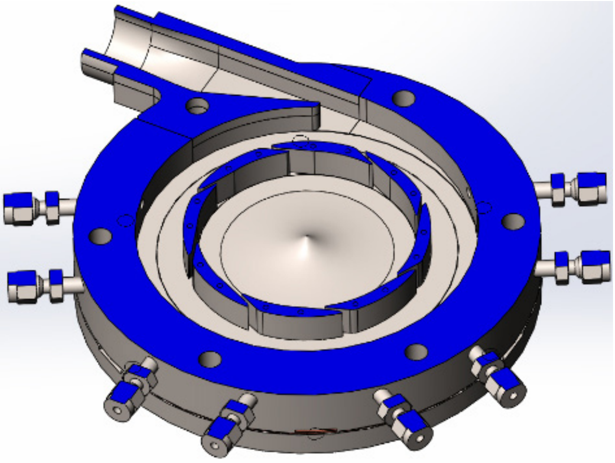

Fig. 5. Schematic representation of GSVR

reactor combines the characteristics of plug flow kinetics for the gas phase with continuous stirred tank reactor (CSTR) kinetics for the fluidised bed. High throughputs can be accommodated in a small footprint, leading to an intensified OCM process. However, the high exothermicity of the OCM reaction could potentially make the reactor system hard to control, but also creates opportunities for operation on an ignited branch (13). The high reaction temperature, the high solid velocity and the low space times require catalysts with high attrition resistance, high thermal stability, high activity and suitable size distribution. To this end, a novel catalyst material was developed that combines high activity with excellent mechanical and thermal stability. Catalytic tests in a fixed bed reactor demonstrate a stable methane conversion rate of 100 mmol CH_4 kg_{cat}^{-1} s^{-1} at 850°C, with a C2 selectivity exceeding 60%. Simulations indicate that for inlet temperature of 520°C and an oxygen-to-methane molar ratio of 1:5, a methane conversion of 55% and a C2 selectivity of 47% can be expected.

Initial proof-of-concept experiments have verified the potential of this reactor for OCM.

2.4. Plasma Dry Reforming

Dry reforming was evaluated with plasma technology. The system at Kemijski inštitut is a spark plasma reactor, designed such that the inlet tubes act also as electrodes, which enables the introduction of reactant gases directly into the discharge for maximum gas coverage with plasma. The reactor design also allows for the usage of a unique structured porous foam nickel-based catalyst, which was designed at Johnson Matthey, to further convert the energy provided by the electron collisions in plasma. The process was evaluated under different operating conditions:

- reagent ratios
- gas flow rates
- applied plasma voltages and
- catalysts.

It was determined that the optimal CH_4:CO_2 reagent ratio is 2:3, at which 90% methane conversion was reached. The product syngas H_2:CO ratio can be tuned by increasing the CH_4 content in the feed, however, significant coke generation was observed under such conditions. Coking could destabilise

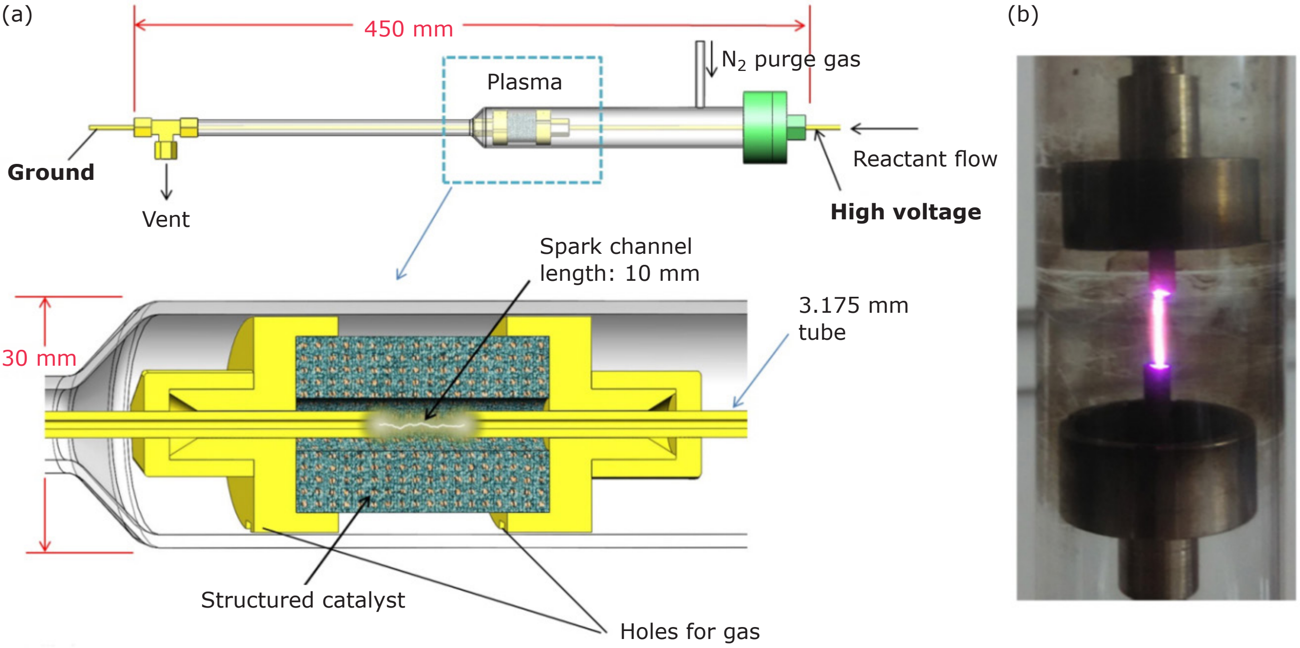

Fig. 6. The spark plasma reactor used for dry reforming: (a) reactor design; and (b) photo of the discharge in pure nitrogen

the plasma, so an efficient strategy was developed where coke is removed *in situ* by periodically applying pure CO_2 plasma while maintaining a high duty-cycle.

3. Benchmarking New Technologies

To assess the potential of the reactors that were developed in ADREM, a case study of valorising associated (flared) gas has been simulated. The feed is rich in methane (>95% vol) with a flowrate of 1000 $Nm^3 h^{-1}$. All the cases include pretreatment for sulfur and CO_2 removal, while for comparison purposes, the downstream processing follows the conventional approach, with either cryogenic separation (for C2+ hydrocarbons) or methanol loop (for syngas to methanol conversion). The end product consists either of mixtures of products (i.e. ethane/ethylene) or product at low purity (for example, raw methanol). Further purification in centralised units is necessary to reach the required quality.

The specific energy (**Table I**) of each technology consists of the reactors' energy demands and the downstream processing (DSP) intensity (the latter being directly related to methane conversion and productivity). The microwave and GSVR technologies have the lowest specific energy consumption, as a result of the upscaled microwave reactor design of SAIREM and the exothermic OCM reaction respectively. The plasma technology is more energy intensive predominantly due to numbering up of the modules in order to accommodate the required flow. The technologies that produce BTX and ethylene would obviously benefit from replacement of the cryogenic separation by energy-efficient and modular alternatives (for example, ethane/ethylene membranes (14) or adsorption based technology) to decrease the energy demand. For the plasma dry reforming, the product syngas enables alternative downstream processing (for example, a methanol reactor), but the high operational pressure of such a design still adds to the overall energy efficiency and complicates the modularity of the plant. However, the modular methanol reactor is already available in commercial scale (3).

The capital intensity (**Table I**) is a function of the conversion and selectivity and the ease of upscale. On one hand, low conversion results in a large recycle flow (due to unconverted methane), and more energy-demanding units. On the other hand the numbering up strategy to accommodate the required throughput implies high capital requirements for all the technologies. The MW reactor with the realised upscaled concept and the GSVR that can accommodate high flowrate, appear to be the most cost-competitive at the present development stage. Collectively, the first step of further development for the ADREM reactors is

Table I Overview of the ADREM Technologies

	Unit	Microwave MNOC – UniZar	Plasma MNOC	GSVR	Plasma dry reforming
CH_4 conversion	mol%	15	35	55	81
Product		C6/C2	C2	C2	H_2/CO
Yield[a]	mol%	6/6	28	26	NA
Coking	%	13	7	0	19
Specific energy[b]	kJ C-mol^{-1} of product	392.7	1127	603.4	1091.9[c]
Capital investment	–	High	Very high	Medium	Very high
Ease of scale up	–	Medium	Medium	Good	Medium
DSP cost	–	Very high	Very high	Very high	Very high
Utilities use	–	High	High	High	High
CO_2 emissions[d]	–	Low	Low	Medium	Low

[a] Hydrocarbon yield is defined as the product of conversion by selectivity

[b] The specific energy is calculated including up- and down-stream processing of reservoir gas (that is typically flared). Pre-treatment of the gas includes desulfurisation and CO_2 removal, while downstream consists of H_2 removal (optional) and cold box (for the C2+ products) or methanol loop (for the methanol product)

[c] The energy is expressed in kJ per mol methane

[d] CO_2 emissions from electricity are assumed to be zero (green electricity)

to improve the reactor performance in terms of conversion and selectivity.

Compared to flaring, for all the technologies the CO_2 emissions are low (25–80% decrease, depending on the technology), with the highest CO_2 emissions coming from the GSVR reactor (where CO_2 is a product) and the lowest emissions coming from plasma dry reforming (where CO_2 is the reactant). Applying the ADREM technologies in situations associated with gas flaring in remote locations will have a huge environmental benefit when renewable electricity is available in abundance.

4. Conclusions and Path Forward

During the project, partners have been developing new small scale gas-to-liquids (GTL) technology, where methane is valorised to chemicals. Two of the reactor technologies have been successfully demonstrated in TRL 5 (microwave and plasma). With tighter regulation on greenhouse gas emissions and flaring, there are clear opportunities for the ADREM technologies to find applications. The UniZar reactor has efficiently been upscaled (32x) and the GSVR reactor is designed in such a way that it can accommodate relatively high flowrate. The plasma reactors (both NPD and dry reforming) showed the highest conversions and selectivities, but they still need to improve the upscale strategy.

For further upscaling and demonstration of the technologies, it is required to improve productivity, conversion and mitigation of carbon formation. Different operating conditions (in terms of pressure, temperature, catalysis or reactor geometry) or *in situ* product separation could potentially enable higher conversions and selectivity and are planned for the next steps of development. Improving the reactor performance will decrease the unit size for each technology and simplify the downstream processing. Downstream processing is an essential point that should be developed and optimised once the selectivity and conversion are improved.

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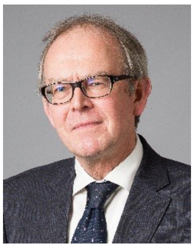

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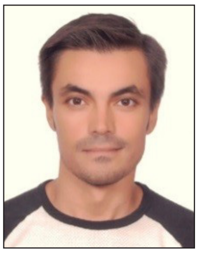

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Electric Vehicles and Their Role in the Energy System

Decarbonising transport and electricity in Great Britain

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Electric vehicles (EVs) can help decarbonise both transport and electricity supply. This is both *via* reduced tailpipe emissions and due to the flexibility in charge and discharge that EV batteries can offer to the electricity system. For example, smart charging of EVs could enable the storage of roughly one fifth of the solar generation of Great Britain for when this energy is needed. However, to do this, the market needs to align vehicle charging behaviour to complement renewable generation and meet system needs.

1. Introduction

The energy system is rapidly transforming, driven by political, economic, environmental, technological and consumer pressures. These changes include the rise in renewable electricity generation and the use of EVs and substantial further changes will need to take place for the UK to meet its decarbonisation goals by 2050. As the electricity system operator (ESO) for Great Britain, National Grid ESO is responsible for moving electricity safely, reliably and efficiently through the system. Great Britain refers to England, Scotland and Wales excluding Northern Ireland. National Grid ESO operates the electricity system in Great Britain only, its Future Energy Scenarios (FES) publication covers Great Britain in detail and makes fewer assumptions about Northern Ireland.

National Grid Electricity Transmission (NGET), UK, a legally separate company to the ESO, owns the transmission network of pylons and cables that are used to transport high voltage electricity throughout the country. Smaller regional operators, known as distribution network operators (DNOs), reduce the voltage and take electricity to people's homes. The ESO is responsible for balancing the system and ensuring that supply always matches demand so that homes and businesses always have access to power (**Figure 1**).

National Grid ESO publishes a FES document for Great Britain annually (1), setting out a range of credible scenarios for how the energy system might develop over the next 30 years. This helps us to better understand the range of uncertainties for the future of energy in the country. As ESO, we are in a privileged position that enables us to draw on insight and data that cut across both electricity and gas in developing FES. We develop a whole system view of energy, helping the industry to understand how low-carbon solutions can be delivered reliably and affordably for the consumer of the future. FES is the starting point for planning long-term regulated investment in gas and electricity systems and is also used by stakeholders as a sound consistent reference point for a range of different published reports. This article references data from FES

Fig. 1. National Grid structure, showing the legal separation and relationships between the National Grid ESO, NGET and National Grid Gas (NGG)

2019. This was published in July 2019 and based on analysis conducted before the UK's decarbonisation target was changed from an 80% reduction by 2050 to meeting net zero. Analysis in FES 2020, launched 27th July, suggests that meeting net zero will only increase the importance of electricity system flexibility and the ability of electric vehicles to facilitate decarbonisation.

Climate change is one of the biggest challenges facing the world and decarbonising our energy system is a major part of responding to this. The UK was the first country to set a legally binding emissions reduction target through the Climate Change Act 2008; this legislated for an 80% reduction in greenhouse gas emissions by 2050 from a 1990 baseline (2). In June 2019 the parliament revised this target to require the UK to become net zero by 2050 in line with a recommendation from the Committee on Climate Change, UK. Net zero means any greenhouse gas emissions would be balanced by schemes to offset an equivalent amount of carbon from the atmosphere, such as planting trees or using technology like bioenergy carbon capture and storage (BECCS).

Transport is clearly a major area of change in the energy system. As take-up of electric cars increases, this shifts energy demand from oil (to produce petrol and diesel) to electricity (to charge car batteries). When combined with the decarbonisation of the electricity system, we will see carbon emissions from transport reduce dramatically. This shift increases demand on the electricity system and may present additional challenges depending on when and where these vehicles are charged. One of the key messages from FES 2019 was that EVs can help decarbonise both transport and electricity supply for Great Britain. This is through the use of smart charging (managing the times vehicles are charged so this avoids existing peak demand times on the network) and through vehicle-to-grid (V2G), where electricity stored in the battery of an EV can be supplied back into the network through a two-way V2G enabled charger. This article explores the potential for electric cars to enable the decarbonisation transition in greater detail.

2. Change in the Energy System

This section explores the change in the energy system that has taken place over the last decade and how we expect it to change in future. This encompasses the rapid rate of decarbonisation in the electricity sector we have seen since 2010 and the ongoing disruption in the transport sector.

2.1 Growth in Electric Vehicles

In July 2018 the UK government's Road to Zero Strategy was announced, including the ambition to see at least half of new cars to be ultra low emission vehicles (ULEV) by 2030 (3). ULEVs are vehicles that emit less than 75 g of carbon dioxide from the tailpipe for every kilometre travelled; in practice, the term typically refers to battery EV (BEV), plug-in hybrid EV (PHEV) and fuel cell EVs. This built on the government's commitment to "end the sale of new conventional petrol and diesel cars and vans by 2040".

There are over 200,000 ULEVs in the UK as of the second quarter of 2019 (4) and while total ULEV registrations are still low, this is growing rapidly for several reasons, including government tax incentives and consumer appetite for decarbonisation. 2019 saw an 87% year on year increase in BEV registrations and a corresponding decrease in PHEV registrations due to subsidy changes (5). In this article the term EV is used to refer to both BEVs and PHEVs; currently EV stock is split between these two types, however in 2050 we expect most cars to be BEVs.

To model the uptake of various road transport types and fuels in our 2019 FES we utilise a total cost of ownership model. Assumptions on the increase and decrease of various factors including battery costs, fuel costs, vehicle efficiency and subsidies available for different scenarios feed into this model. The uptake rates for the different scenarios, in relation to the expected sales projections for all vehicles (determined by the total cost of ownership and the rate at which older vehicles are scrapped) gives the expected number of low carbon vehicles on the road (**Table I**).

The slowest growth scenario in FES projects only 2.3 million EVs to be owned in 2030 compared to a maximum of 11.5 million EVs in 2030 in the highest growth scenario. This represents 6.8% and 35% of cars being electric respectively in each scenario. By 2050 we expect almost all cars to be electric in all scenarios, although some petrol and diesel fuelled

Table I Electric Vehicle Growth Projections (1)

	2019	Scenario modelling		
			2030	2050
Number of electric cars	209,000	Minimum	2.3 million	31.3 million
		Maximum	11.5 million	33.6 million

vans and heavy goods vehicles (HGVs) still exist in the slower decarbonisation scenarios. Although this shift towards EVs will cause an increase in overall electrical energy demand, the greater challenge lies in charging; i.e. where, when and how these vehicles are charged.

2.2 How the Grid Decarbonises

Traditionally the grid has been supplied by a relatively small number of large generators, primarily coal, gas and nuclear power stations. The energy system is transitioning from this centralised system where there were under one hundred generators primarily connected to the transmission network with flexible fossil fuel plant to help meet demand peaks, to the current state where there are thousands of smaller decentralised generators such as wind and solar farms mainly connected to the distribution network. Over the past 10 years this growth in renewables has led to new challenges in system operation, with wind and solar generation presenting issues due to generation variability.

Significant progress has been made decarbonising the electricity system since 2010 thanks to this growth in renewable generation. The carbon intensity of electricity is a measure of the level of CO_2 emissions that are produced per kilowatt hour of electricity consumed. The average carbon intensity of electricity has fallen 53% from 529 g CO_2 kWh^{-1} in 2013 to 214 g CO_2 kWh^{-1} in 2019 (6). The trend in emissions reduction is shown in **Figure 2**.

2.2.1 Phase Out of Coal

One of the major factors in the reduced carbon intensity of UK electricity generation is the phase out of coal. In 1990 coal provided over 60% of UK electricity generation, and while this decreased over time following increased investment in gas-fired power plants, as recently as 2012 it made up over 38% of UK electricity generation (7). UK and European Union (EU) decarbonisation policies have led to reducing profitability and the closures of coal plants since 2012, with coal making up only 5.1% of Great Britain's electricity generation in 2018 (8).

Electricity from coal generation has been replaced through a mixture of increases in gas generation and renewable generation, primarily wind and solar. The carbon intensity of coal generation is typically over twice as high as that of gas, at 900 g CO_2 kWh^{-1} for coal compared to 352 g CO_2 kWh^{-1} for gas. This has meant that the switch from coal to gas has been a major contributor to the rapid fall in emissions intensity since 2012. In 2015 the UK was the first national government to announce a commitment to phase out unabated coal use, setting a target date of 2025. Great Britain has since experienced its first 24 h period of coal-free electricity in April 2017 and set a record of over a month without coal in May 2020.

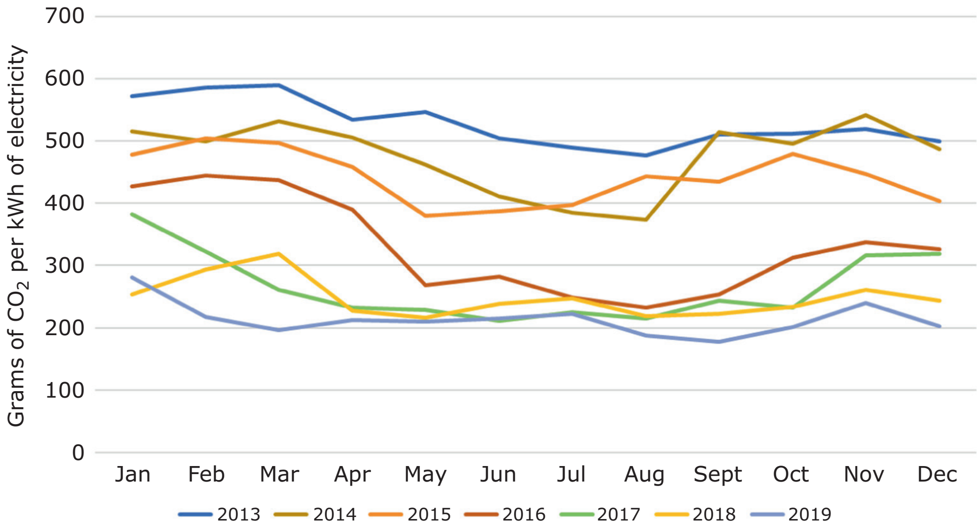

Fig. 2. Electricity supply carbon emissions intensity. The Carbon Intensity data includes CO_2 emissions related to electricity generation only. This includes emissions from all large metered power stations, interconnector imports, transmission and distribution losses and accounts for national electricity demand, embedded wind and solar generation (6)

2.2.2 Increase in Renewable Generation

The UK has seen significant growth in renewable electricity generation over the past 10 years. This has been supported by government renewable subsidy schemes such as the Renewables Obligation and the Feed-In Tariff, which have both now closed. Over this time the cost of wind and solar installations has dropped sharply, with the technologies entering a virtuous cycle of falling costs, increasing deployment and technological progress. Strike prices for contracts for difference (CfD) for new offshore wind projects have fallen from £114 MWh^{-1} in 2015 to below £40 MWh^{-1} in 2019 (9, 10). Global weighted average levelised cost of electricity (LCOE) of solar photovoltaic (PV) has fallen 77% between 2010 and 2018 to US\$0.085 kWh^{-1} (11). These cost reductions have made the technologies significantly more attractive and they are beginning to compete in a subsidy free environment.

Generation capacity is the maximum power that an installation can generate. Renewable generation capacity has increased rapidly in the last decade, primarily made up of wind and solar in 2010, from 5.4 GW of wind and 0.1 GW of solar to 21.8 GW of wind and 13.1 GW of solar installed in 2018 (8). The capacity factor or load factor of a technology refers to the electricity generated by a technology as a proportion of the maximum potential generation over the period. Variable renewable technologies typically have a substantially lower load factor than fossil fuel generation due to the nature of the resources they are harnessing, for example solar PV generation is limited by hours of daylight.

Average UK load factors over the last five years range from 11% for solar PV, 27% for onshore wind and 39% for offshore wind through to 77% for plant biomass combustion (8). This means that generating an equivalent amount of energy, as currently coming from fossil fuels, would require significantly higher installed renewable capacity. The shift towards renewable energy comes with additional challenges however, particularly managing variability. This causes an issue when renewable output is low, for example on winter evenings with no wind or sun, but also when the renewable output is high, and generation exceeds demand, for example at midday in the summer when you may see coincident peak output from both wind and solar generation. Managing this variability as renewable penetration increases is a key challenge in enabling decarbonisation for the ESO.

2.3 Need for Flexibility Due to Variability and Changes in Demand

The Office of Gas and Electricity Markets (Ofgem), UK, defines flexibility as "modifying generation and/or consumption patterns in reaction to an external signal (such as a change in price) to provide a service within the energy system" (12). Demand on the electricity network varies throughout the day and across seasons. Peak demands are seen on winter weekday evenings, between 5 pm and 7 pm, with minimum demands seen historically overnight during the summer. The country needs electricity capacity to meet peak demand, which is variable, and hence the ability to increase this capacity through flexibility or to decrease the peak is pivotal.

Renewable generation always generates where it can as it has zero marginal cost. This is currently backed up by fossil fuel generation that can be turned up and down as required to help meet demand peaks. Between April and September solar generation meets a larger portion of demand during the daytime; generation is at its peak in the middle of the day when the sun is brightest. Solar generation provides relatively little contribution towards meeting evening peaks in demand, however. Wind generation output depends on the weather systems over the UK but is typically higher in winter. It is highly variable however, and the system needs to be able to manage multi-week spells with low levels of wind generation which can occur when a high-pressure system settles over the UK.

Output from large-scale transmission-connected generation is visible to the ESO and instantaneous changes in generation can be clearly seen and managed. Small-scale distribution-connected generation however, particularly embedded solar, may show up only as reduced demand on the transmission system which can make it difficult to forecast and manage.

3. How We Add Flexibility Today

The decarbonisation of the electricity system comes with several challenges from a system operation perspective. As the ESO we are responsible for balancing the system and ensuring that generation always matches demand and have a licence obligation to control system frequency at 50 Hz plus or minus 1%. If there is more demand for electricity than there is supply, frequency will fall and if there is too much supply, frequency will rise.

We make sure there is sufficient generation and demand held in readiness to manage all credible circumstances that might result in frequency variations.

Fossil fuel generators are dispatchable and able to ramp production up or down, while the UK's nuclear reactors were designed to run continuously at high load and so cannot easily ramp up and down. Generation from variable sources such as wind and solar can be curtailed where necessary to help match supply and demand but cannot be ramped upwards unless they are already at part load and spilling energy. As greater levels of variable generation come onto the system, replacing fossil fuel generators, we will need to use alternative means to maintain system stability, for example procuring services through our frequency response auctions.

The need for greater flexibility in future to enable a zero-carbon future is clear. Demand will need to become more active in response to the increasing need for flexibility on the gas and electricity systems. Currently, when output from renewable electricity generation is low, one of the primary sources of flexibility is provided by gas-fired power stations and other thermal peaking plant, this is supply side flexibility. In a net zero future, these generators will need to be fitted with carbon capture and storage (CCS) technology or retired. As such, other forms of flexibility will become more important. This includes interconnectors from Great Britain to Ireland and mainland Europe, energy storage and forms of demand side response (DSR). It could also include the use of electricity to produce hydrogen through power-to-gas or power-to-X where electricity is used to produce synthetic natural gas, synthetic liquid fuel or hydrogen. This could be operated flexibly to support the energy system, while producing dispatchable fuel for times of undersupply or for other sectors that cannot be electrified.

National Grid ESO runs a stakeholder-led programme called Power Responsive which aims to make sure there is a level playing field for both supply side and demand side solutions in Great Britain's energy markets. Businesses which have the flexibility to increase, decrease or shift their electricity use can benefit from financial incentives to do so and help balance the network through forms of DSR. Our ambition is that, by 2025, we will have transformed the operation of the electricity system such that we can operate it safely and securely at zero carbon whenever there is sufficient renewable generation online and available to meet the total national load (13). This will require innovative systems, products and services to ensure that the network is ready to handle 100% zero carbon operation.

3.1 Current Electric Vehicle Charging Profiles

To understand the impact of EVs on the electricity system it is necessary to understand how they charge today and how this may change in future. We commissioned a Network Innovation Allowance (NIA) project to develop a comprehensive picture of current charging profiles (14). The study successfully gathered together a database of over eight million real world charge events and generated a representative full year charging demand profile at hourly resolution across a range of different location types and charger sizes. This evaluation has delivered an improved understanding of charging behaviour and enabled us to generate a more nuanced and informed view of the future impact of EV growth on electricity demand.

Existing electricity system peak demand typically occurs between 5–6 pm on weekdays, which is earlier than the peak demand for EV charging (**Figure 3**). This evening peak in EV demand is dominated by residential charging and is likely the result of commuters plugging into charge when they arrive home from work (it tails off as those vehicles plugged in earlier finish charging). Workplace and public charging contribute to another smaller peak mid-morning on weekdays between 9–10 am. The reduction in workplace charging rates after 10 am suggests that generally commuter vehicles plugged in to workplace chargers when they arrive are fully charged by mid-morning and remain plugged in and no longer charging subsequently until they leave.

Other learnings from this study include the effect of temperature on demand, where average kilowatt hour of energy per EV per day increases by 1.6% for each one degree decrease in temperature. During public holidays demand also drops, particularly over Christmas and Easter where, despite an increase in demand at (primarily motorway based) rapid chargers, this is offset by a significant decrease in other types of charging. Weekend demand is also on average 25% lower than weekdays and shows a broader demand profile shape that peaks an hour earlier.

It is clear from the data that current charging patterns will contribute to increased peak loads on the electricity network at both distribution and

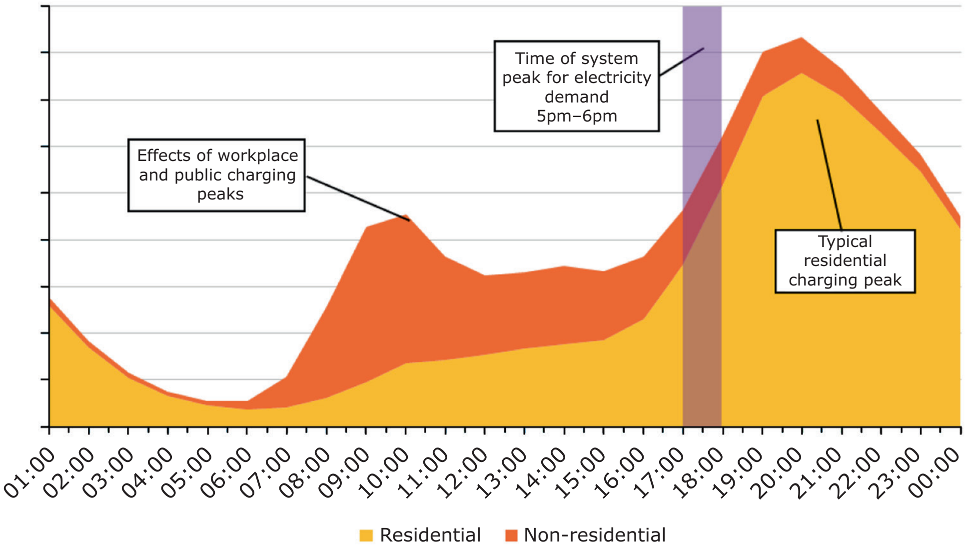

Fig. 3. Typical EV weekday charging profile (FES 2019) (1)

transmission levels. This may present more of a problem for the distribution network where the existing peak demand is often later than on the transmission network. If charging patterns can be shifted to increase levels of overnight and daytime charging at the expense of evening charging this could have a beneficial network effect and help reduce carbon emissions, as peak demands are more likely to be met by dirtier fossil fuel generation peaking plants.

This study has captured the charging demand of plug-in cars, but as other vehicle segments electrify demand will change. This, for example, includes depot-based vans, taxis and buses that may show different demand profile characteristics and present different opportunities.

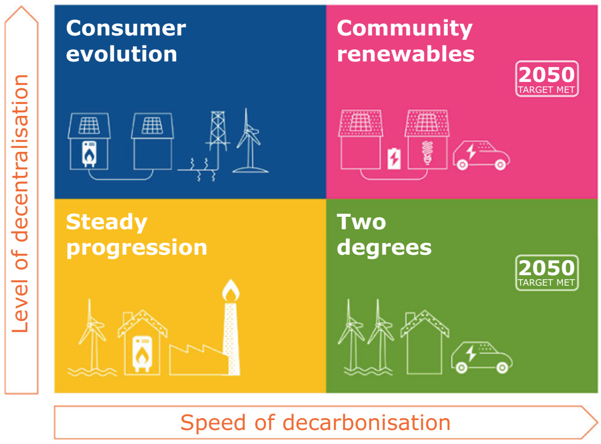

Fig. 4. Scenario framework for National Grid ESO's FES 2019 (1)

3.2 Future Energy Scenarios Range of Outcomes

As part of FES 2019 we developed four scenarios setting out a credible range for how energy demand and generation could develop out to 2050 (**Figure 4**). This includes projections of the levels of renewable generation, EV take-up and flexibility.

Two of our scenarios met the national decarbonisation target at the time of an 80% reduction in 1990 emissions by 2050. These are Two Degrees, which relies primarily on centralised generation and Community Renewables which has a greater proportion of decentralised generation. The UK government has since tightened the 2050 target to net zero CO_2 emissions. It is likely that new policy and support will be put in place to achieve this aim, therefore we would expect that by 2030 the electricity system would be closer to Two Degrees and Community Renewables than the other two scenarios which did not meet the 80% reduction target. Net zero in 2050 was modelled as a sensitivity in FES 2019 and will be included in core scenarios in FES 2020.

Figure 5 shows the installed electricity generation capacity of different technologies in 2018 and the projected changes to this under the different scenarios in 2030 and 2050. In all scenarios overall capacity grows, but this is particularly noticeable in the faster decarbonising scenarios, Two Degrees and Community Renewables. These two scenarios

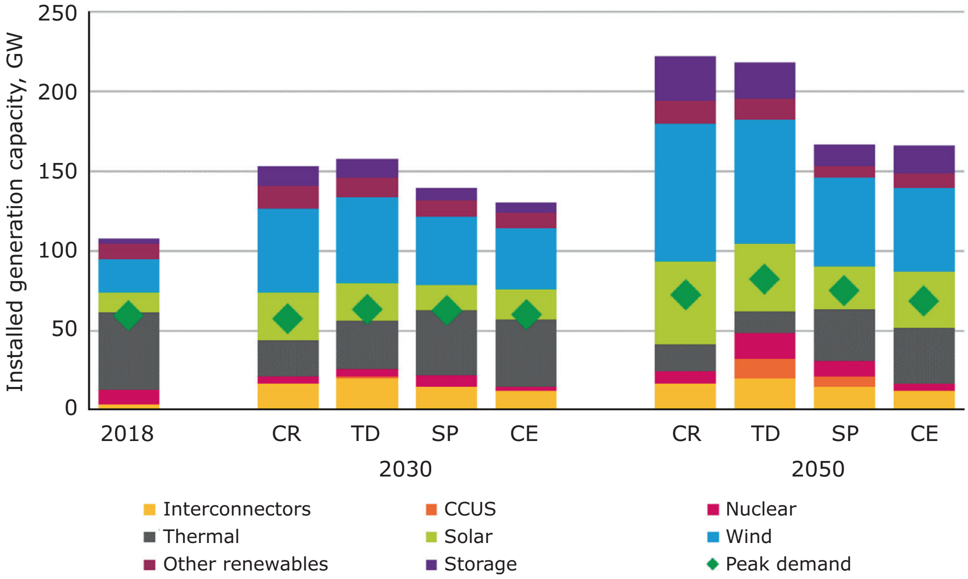

Fig. 5. FES 2019 installed electricity generation capacity (1)

have a higher proportion of renewable generation and much of this capacity is variable, with a low load factor, meaning more generation capacity is required to meet overall energy requirements at times of high demand, particularly in winter. The total installed capacity significantly exceeds forecast peak demands to account for this. Due to their lower load factor and variability, renewables are de-rated when calculating the capacity required to keep the lights on as they will not always be available to contribute at peak times (15).

Figure 5 also shows potential future avenues to add flexibility, with significant increases in interconnector capacity and storage capacity, particularly across the more decarbonised scenarios. Interconnectors will allow the UK to trade more electricity with mainland Europe at times of high demand or excess generation. Shorter duration storage projects could meet small periods of increased demand or provide flexibility services such as frequency response. Longer duration storage is well suited to covering longer periods of, for example, high or low wind, potentially co-located with generation. Some of the other key outputs from FES 2019 are set out in **Table II** for 2030.

3.3 Oversupply of Electricity

In the faster decarbonising scenarios of Two Degrees and Community Renewables, the growth of low-carbon capacity will contribute to periods of oversupply of electricity, particularly in the summer months beyond 2030. Inflexible renewable generation capacity will at times produce more electricity than total demand. The annual amount of excess electricity rises to 20–25 TWh (around 6% of total annual output) after 2040 in Community Renewables. Our modelling shows that at times of likely oversupply, excess electricity cannot be exported, as other countries that have decarbonised are likely to be facing similar issues. Nor can it be stored, as available storage is full.

Future markets will determine how this electricity could be used, stored or curtailed in the most efficient way; this could include use of electricity to produce hydrogen or charge EVs. This is likely to be attractive to consumers as power prices will be very low or negative at times of oversupply meaning consumers could be paid to use the electricity when carbon emissions are also likely to be low.

National Grid ESO has developed a Carbon Intensity forecasting tool (**Figure 6**) (6) in partnership with Environmental Defense Fund Europe, UK, University of Oxford Department of Computer Science, UK, and the World Wide Fund for Nature (WWF), Switzerland. It uses machine learning and power system modelling along with Met Office, UK, data to forecast the carbon intensity and generation mix 48 h ahead for each region in Great Britain. The forecast carbon intensity figures are accessible *via* a website, the National Grid ESO app and an application programming interface

Table II Future Energy Scenarios 2019 Assumptions to 2030 (1)

Technology	Change from now to 2030	Uncertainty factors
EVs	Large increase from 150,000 today to between 2.3 million and 12 million	Large range to reflect uncertainty, but technology and policy direction suggests high end of range
Interconnectors	Large increase from 4 GW today to between 12 GW and 20 GW	Large range reflecting project risk, but minimum backed by Ofgem’s cap and floor regime and projects under construction
Transmission-connected gas generation	Scenarios range from no change to a large decrease. From 31.1 GW today to between 9.7 GW and 33.3 GW	Economic pressure suggests a reduction is most likely as other sources of supply, such as wind and interconnectors, take market share
Offshore wind	Large increase from 8.5 GW today to between 20.9 GW and 33.6 GW	High growth expected due to sector deal of 30 GW by 2030 and falling costs as seen in the September 2019 CfD results of < £40 MWh^{-1}. Costs have fallen significantly from £120 MWh^{-1} for round one projects
Distributed generation – installed capacity	Large increase from 30.9 GW today to between 38 GW and 70.3 GW	Charging reviews likely to reduce growth in the shorter term, but growth is still expected in the longer-term due to falling costs of distribution-connected solar, onshore wind and gas peaking plant displacing transmission-connected combined cycle gas turbine (CCGT)
Distributed generation – contribution to peak demand	Large increase from 9.4 GW today to between 12.9 GW and 26.2 GW	Charging Reviews likely to have an impact in the shorter term, but growth likely due to falling costs of distribution-connected solar, battery storage, onshore wind and gas peaking plant displacing transmission-connected CCGT
Electricity storage	Large increase from 4 GW today to between 7 GW and 13 GW	Increasing levels of variability from renewables, tightening environmental restrictions on gas peaking plant and falling costs of storage expected to strengthen storage business cases
Carbon intensity of electricity	Large decrease from 248 g CO_2 kWh^{-1} to between 112.7 g CO_2 kWh^{-1} and 24.9 g CO_2 kWh^{-1}	High uncertainty dependent on delivery of low carbon supply above

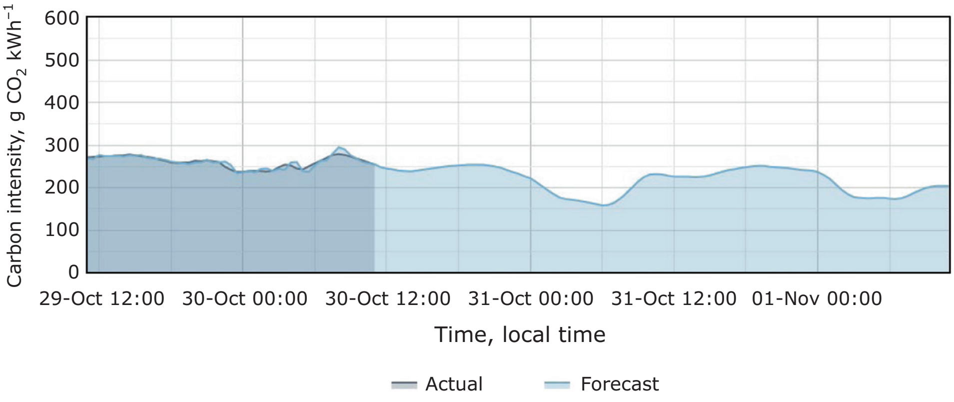

Fig. 6. Carbon Intensity tool output showing 24 h of historic data and a 48 h forecast from 30th October 2019 (6)

(API) to allow developers to produce applications that will enable consumers and smart devices to optimise their behaviour to minimise carbon emissions. WWF have implemented the API into a widget that can help people plan their energy use, switching devices on when energy is green and off when it is not.

3.4 Smart Charging and Vehicle-to-Grid

The data from our EV innovation project suggests that EVs typically spend long periods of time plugged into residential or workplace charge points and current charging patterns result in vehicles starting to charge as soon as they are connected to the charger with little to no smart management of charging. Smart charging enables consumers to manage the time when their vehicle is charged. This could be to take advantage of lower prices or lower carbon electricity or to respond to external signals from third parties such as aggregators or network companies.

The government's Automated and Electric Vehicles Act 2018 (16) sets out requirements for all new charge points sold or installed to be 'smart'. This means they must be able to receive, process and react to information or signals, such as by adjusting the rate of charge or discharge; transmit, monitor and record information such as energy consumption data; comply with requirements around security; and be accessed remotely. This legislation aims to avoid infrastructure being a blocker to future smart charging developments.

EV batteries can be considered as a form of storage within the wider energy system, though the impact of EVs is fundamentally different to other forms of storage. This is because not all vehicles are connected to the system at any point in time, meaning that the available storage capacity from EVs is constantly varying. This creates natural diversity in availability and charging behaviour for EV batteries and means that the potential for EVs to increase, shift or decrease demand varies and is a fraction of the total capacity of EV batteries in Great Britain at any one time. BEV batteries are typically five to 10 times larger than PHEV batteries, so the relative mix of PHEVs to BEVs will also affect the total energy capacity available.

Consumers can be incentivised to take part in smart charging and delay the start of their charging period through time-of-use (ToU) tariffs and be guided by tools such as National Grid ESO's Carbon Intensity app; these are already available to consumers to allow them to schedule their EV charging for times of lower prices or carbon emissions. A more dynamic form of smart charging involves in-home automation and smart management and optimisation of charging while the vehicle is plugged in without active involvement from the consumer. This would remove barriers for consumers to get involved and have a significant impact on the electricity system and resulting carbon emissions. This will become more important as the number of EVs on the system grows. These ToU tariffs are already available for consumers from some innovative energy suppliers such as Octopus Energy, UK, and are expected to become more widely available over time.

An additional avenue for EV to have a positive impact on the electricity network is through the use of V2G technology. This is where electricity stored in the battery of an EV can be supplied back into the network through a two-way V2G enabled charger. This process is likely to be managed by an aggregator triggering response from a large portfolio of vehicles contracted to deliver this capability, they would likely offer financial incentives to consumers to facilitate this. Individuals and businesses could also use this to take advantage of variable rate tariffs without the third-party involvement. There are a range of pilot projects developing this technology; in 2017 the UK's innovation agency, Innovate UK, committed £25 million in support to eight real world V2G demonstrator projects undertaken by a range of organisations including energy suppliers, network operators and small and medium-sized enterprises (SMEs) (17).

Battery lifetimes are typically measured in the number of discharge cycles they can undergo without battery capacity falling below a certain threshold. The measurable impact of V2G on battery health is still at the research stage, with recent papers providing seemingly contradictory conclusions. Dubarry *et al*., 2017 (18) showed that additional battery cycling due to V2G would shorten battery life; while Uddin *et al*., 2017 (19) indicated that battery degradation could be avoided. These authors have since published a joint study in which they "jointly reconcile their previous conclusions by providing clarity on how methodologies to manage battery degradation can reliably extend battery life" (20). It is clear, however, that further research in this area is necessary to determine the effects of V2G and ensure it is an attractive proposition for both electricity networks and consumers.

Our FES 2019 scenarios consider how engaged vehicle owners are likely to be with smart technology and V2G and build these assumptions into our modelling of peak demand. We classify a consumer as participating in smart charging if they actively choose not to charge their EVs at peak times, wherever possible. We assume that only 2% of vehicle owners engage in V2G through to 2030 as the technology is still at an early stage, however that number then steadily increases to 2050, with the highest levels in the Community Renewables scenario. These participation rates are shown in **Table III**.

Table III Smart Charging and Vehicle to Grid Participation Rates in 2050

	Smart charging participation, %	V2G participation, %
Community Renewables	78	14
Two Degrees	65	11
Consumer Evolution	73	13
Steady Progression	61	10

3.4.1 Impact on Peak Demand

Figure 7 shows a typical weekly residential EV charging profile. This shows the peaks in weekday demand as consumers plug in after work and the troughs overnight which occur once consumers have finished charging. The average load per vehicle is around 0.4 kW per EV, this suggests that only a proportion of total EVs are plugged into charge, with typical domestic charge rates varying between 3 kW and 7 kW. At weekends the demand profile is spread more broadly throughout the day with a far smaller evening peak. Average energy delivered to vehicles each day varies between 2.5 kWh and 5 kWh per day across the year, indicating average daily miles driven are below 25 miles per day. This level of energy demand could be met through software to automatically stagger charging times to start later, reducing peak load significantly for the 61–78% assumed to participate in smart charging.

Adding V2G technology would enable a further reduction in peak demand as some EVs plugged in at peak times would be able to feed energy back into the grid to offset existing peak demands. Cars that are also charged at their workplace during the day would also have more energy in their battery when plugging in at home and therefore be better able to participate in V2G.

Figure 8 shows the potential impact on peak demands with and without smart charging and V2G in the Community Renewables scenario. This scenario has rapid uptake of EVs, with 11.5 million EVs by 2030 and 31.3 million EVs by 2050. This compares to the slower rate of EV take-up in Steady Progression where there are only 2.2 million EVs in 2030, rising to 33.6 million EVs in 2050. The high number of EVs owned by highly engaged consumers demonstrate significant impacts on peak demand, with unconstrained charging potentially resulting in 24 GW of additional peak electricity demand in 2050 compared to only 12 GW if smart charging

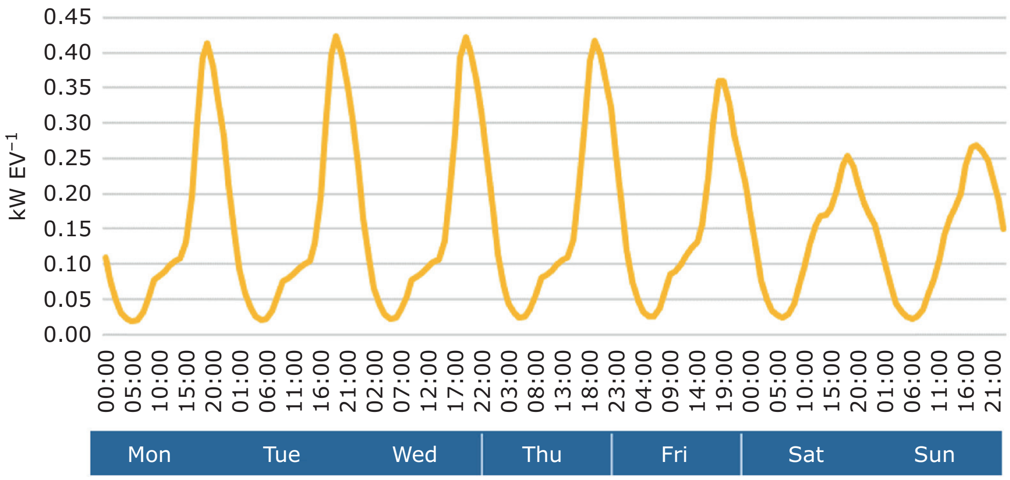

Fig. 7. Weekly demand profile, averaged over full year, for residential charging for an average EV (15)

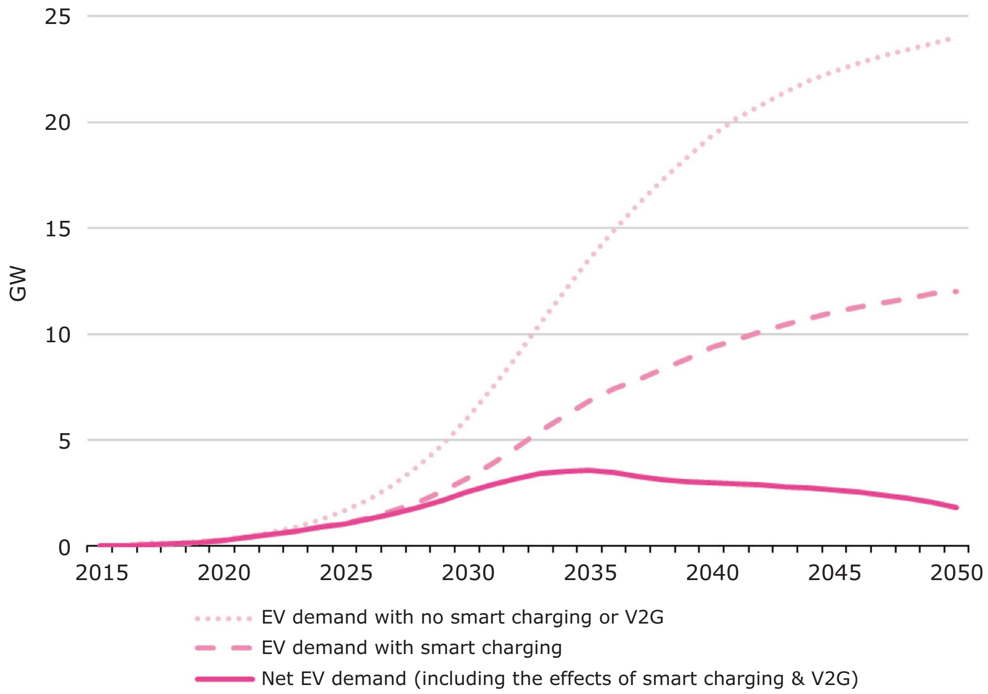

Fig. 8. FES 2019 Community Renewables EV charging behaviour at system peak (1)

is undertaken by engaged consumers or less than 2 GW of additional peak load if some vehicles are participating in V2G.

This behaviour is valuable as it reduces future peak load growth substantially, avoiding potentially costly electricity network reinforcements. The potential reduction in peak load of 22 GW is equivalent to nearly seven Hinkley Point C reactors (the 3.2 GW nuclear power station currently under construction in Somerset). This represents a potential large cost saving compared to the unconstrained charging case and indicates that smart charging and V2G can provide significant value to the electricity system.

3.4.2 Impact on Oversupply of Renewable Generation

As highlighted in Section 3.3, as installed levels of renewable generation increase there will be an increase in times when generation exceeds demand and excess renewable generation must be curtailed. We have carried out further analysis of the potential for EVs to support the energy system through smart charging to absorb some of this excess generation. The FES 2019 demand and generation dispatch projections were assessed for 2030 using the Community Renewables scenario. EV charging profiles for residential and workplace charging were load shifted away from peak times, with a 47% reduction in peak demand (1) shifted to charge overnight between midnight and 6 am, unless there was oversupply at peak. This resulted in a 7.3% reduction in renewable generation curtailment in 2030. **Figure 9** shows an example week in January where curtailment is reduced by EV load shifting.

The potential reduction in curtailment due to EV smart charging is likely to increase post-2030 as renewable generation capacity increases, and these periods of oversupply become more frequent and EV charging peaks grow; the number of EVs in Community Renewables is forecast to increase from nearly 12 million in 2030 to over 30 million in 2050.

4. Conclusion

EVs can help decarbonise both transport and electricity supply for Great Britain. This is both *via* reduced tailpipe emissions and due to the flexibility that EV batteries can offer to the electricity system. They offer a source of untapped flexibility that can provide significant benefits to Great Britain's energy system.

The challenge of meeting a net zero carbon emissions target for the UK is substantial and will require transformation across the economy.

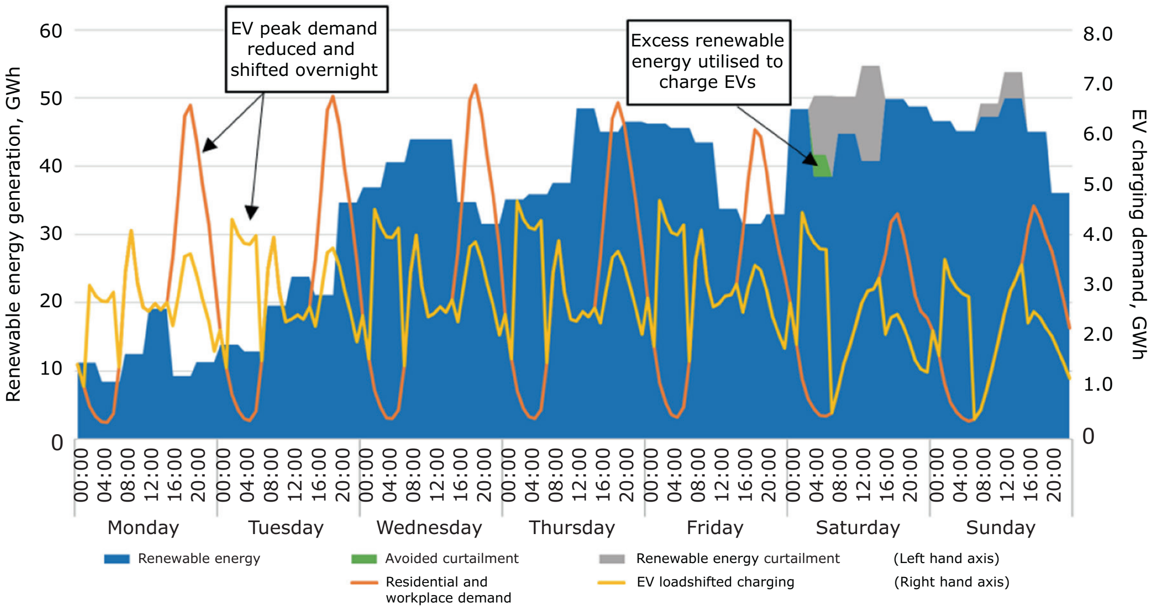

Fig. 9. Example week in January 2030 showing the potential for EV charging load shifting to reduce curtailment of renewable generation at times of oversupply. Generation output is modelled in 4 h blocks, so generation variability may result in lower utilisation of oversupply unless this is smoothed out by short-duration storage

Within the energy sector the growth in renewable generation and decline in traditional dispatchable generation such as coal and gas plants represents a significant change. This may lead to times of oversupply of renewable generation at times of low demand and challenges in meeting peak demands when renewable generation output is low as the power sector decarbonises. There will therefore be greater need for flexibility services that can help manage the variability of generation on the system.

Beyond this, demand is also likely to change as the transport sector is electrified. This has the potential to add significant additional load to the electricity network as consumers switch to EVs to replace petrol and diesel vehicles. If all consumers charge at times of existing peak demand this will require significant and costly reinforcement of the electricity networks to facilitate this. However, the use of smart charging and V2G technology means EVs can instead provide flexibility and help to integrate a higher level of renewable generation on the network through load shifting to times of oversupply. This amplifies the positive impact of EVs on decarbonisation.

As higher capacities of renewable generation are required to meet the same annual demand as thermal generation like gas or coal, if wind and solar output is high at periods of low demand there is a risk of oversupply. ESO modelling shows that excess electricity could rise to around 6% of total annual output after 2040. This power cannot be exported, as other countries that have decarbonised are likely to be facing similar issues, and it cannot be stored as available storage will already be full.

FES 2019 modelling suggests that EVs being charged with smart technology or responding to V2G could reduce additional network peak demand from EVs by over 90% in 2050 in our Community Renewables scenario. They could also enable the storage of roughly one fifth of Great Britain’s solar generation for when this energy is needed. In 2030, smart charging to shift demand from evening peaks to times of renewable oversupply could result in a 7.3% reduction in renewable generation curtailment, this could increase further by 2050.

National Grid ESO are well placed to understand these potential changes through our management of the electricity system and our annual FES publication. Our ambition is that, by 2025, we will have transformed the operation of the electricity system such that we can operate it safely and securely at zero carbon whenever there is sufficient renewable generation online and available to meet the total national load.

Acknowledgements

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Future Regulatory, Market and Technology Trends in the Global Passenger Car and Commercial Vehicle Sectors

Key challenges to achieving net zero emissions for road vehicles

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The world is at the start of an energy revolution: the biggest energy transformation since the Industrial Revolution. The growing recognition that the carbon dioxide emissions associated with the combustion of fossil fuels leads to a dramatic increase in global temperatures is driving the need to implement strategies to reduce the carbon footprint across power- and energy-hungry sectors such as power generation, domestic heating, industrial processes and transportation. This article looks at the moves that the global passenger car and commercial vehicle segments will need to make to minimise the CO_2 and greenhouse gas (GHG) emissions of the sector, which is one of the largest contributors to the global CO_2 inventory today. A number of countries have already pledged to meet net zero GHG emissions by 2050, and more are set to follow, so this article also considers what is necessary for the ground transportation sector to hit net zero.

1. Introduction

Global car and truck manufacturers, along with their supply chains, have made huge steps to minimise vehicular emissions since the advent of the internal combustion engine (ICE). Of particular note are the criteria pollutant emissions regulations, which have focused on reducing the tailpipe carbon monoxide, hydrocarbons, nitrogen oxides (NOx) and particulate matter (PM) emissions from the global vehicle fleet. For example, since the first European regulations were introduced in the early 1990s, the permitted NOx emissions of cars have dropped by almost a factor of 15, which has been enabled by close collaboration between the car manufacturers and the substrate and catalyst suppliers. More recently, the focus has shifted to CO_2 emissions, as governments and regulators work towards the implementation of measures to enable the Paris Agreement climate change commitments to be met (1). Indeed, the latest view of the Intergovernmental Panel on Climate Change (IPCC) is that there are significant benefits in targeting a maximum temperature increase of 1.5°C over pre-industrial levels, rather than the 2°C Paris Agreement target, and this 1.5°C target essentially means that CO_2 emissions need to reduce to net zero globally by 2050 (2). This is an extremely challenging target, with massive implications for all energy-hungry sectors such as transportation, which currently accounts for around 24% of global CO_2 emissions (3). Moving the transport segment to net zero by 2050 means that only vehicles with zero CO_2 emissions can be sold from 2040 or earlier, to avoid legacy fleet emissions, since cars, buses and trucks typically stay in use for 10 years or more. Indeed, the recommendation of the Committee on Climate Change (CCC), the UK Government's independent advisor on climate change, is that introduction date of the ban on vehicles powered by ICE should be brought forward from 2040 (which was the original plan) to 2035 "at the latest" or, more preferably, 2030 (4). Currently, around 1% of new passenger car sales globally do not have any tailpipe CO_2 emissions (that is, they are regarded as zero emission vehicles (ZEVs)) with almost all of these being battery electric vehicles (BEVs). There are far fewer zero emission commercial vehicle sales, so the automotive industry has a long way to go on its journey to net zero.

The two principal ZEV ground transportation options are the BEV and the fuel cell electric vehicle (FCEV). BEVs use electricity to charge the battery to provide motive power, while FCEVs use an electrochemical cell to convert the chemical energy of hydrogen (supplied from an on-board tank) and oxygen (from the air) into electricity. There are several types of fuel cell, but the one most applicable to transport applications is the polymer or proton electrolyte membrane (PEM) fuel cell (also called proton exchange membrane fuel cell), which starts up rapidly, operates at low temperature, and delivers high power density at low weight or volume compared to other fuel cells.

In some geographies there are discussions on whether biofuels or power-to-liquids, also known as e-fuels, can play a major role in the decarbonisation of the transport sector. In this context, a biofuel is a liquid or gaseous fuel produced from biomass or waste, and an e-fuel is a fuel generated through the use of renewable electricity to generate hydrogen which is then attached to carbon from CO_2 for subsequent conversion into hydrocarbon fuels similar to those used today.

Biofuels can be ethanol, methanol, fatty acid methyl ester (FAME), hydrotreated vegetable oil (HVO), biomethane (either compressed or liquefied) or advanced biofuel such as biodiesel or bio jet fuel. These biofuels can be split into generations of biofuels:

- first generation (or conventional) being produced from sugars, starch crops or vegetable oils and
- advanced biofuels from lignocellulosic biomass or woody crops, agricultural residues or waste, as well as dedicated non-food energy crops grown on marginal land unsuitable for food production or novel feedstocks such as algae.

Biofuels were first introduced in the hope of reducing carbon intensity of fuel, since in a simplistic sense the CO_2 generated by combustion is absorbed by the regeneration of the crops used to make it, and because they can be blended into fossil fuels without the need to modify engine technology.

First generation biofuels do not represent good decarbonisation options since when both direct and indirect emissions are taken into account (for example, from changes in land use), such biofuels are often only a marginal GHG emission improvement over fossil fuels, and in some cases actually have higher emissions (5). Sustainable advanced biofuels are based on wastes and residues, so their potential contribution to fuel requirements is finite. The industries that typically contribute the most to advanced biofuels are agriculture and the food industry (through residues such as organic waste sludges, manure or straw) and forestry industries, especially in the Nordics (from saw and pulp mills). Biomass resources are also already well utilised, so if the current consumption in other areas (for example, paper production) is assumed to continue, the maximum biofuel production would be able to supply around 8.5% of all road transport in the EU (5). However, the aviation and marine sectors are already making their case to use these biofuels, so while they may make a contribution to reducing road transport CO_2 in the short term (*via* blending into current hydrocarbon fuels), it is not expected that they will make a major contribution in the medium term and beyond.

For e-fuels, the first step in their production is to generate hydrogen *via* water electrolysis using renewable electricity. Hydrogen is then combined with CO_2 to form hydrocarbon fuels, with the CO_2 coming from, for example, industrial or biogenic sources, or from the direct capture of CO_2 from the air (direct air capture (DAC)). At the present time, industrial CO_2 emissions are regarded as 'waste', but capturing this CO_2, converting it into a hydrocarbon fuel, and then combusting it still leads to its release into the environment, and in the medium to long term it is expected that the CO_2 sources will either need to be from DAC or from 'green' sources such as biomass combustion.

The technologies to convert CO_2 and H_2 into both synthetic natural gas (SNG) and methanol at scale are known, and it can be expected that processes at early technology readiness level (TRL) currently under development (for example, direct electrochemical synthesis) will get more attention should there be a market. To produce e-fuels the SNG and methanol can undergo further conversion, for example to dimethyl ether or *via* the methanol-to-gasoline process to gasoline. However, not all pathways to the higher value e-fuels are commercially viable, and indeed the most attractive product to make, kerosene, is not accessible today as there is no large scale implementation of the reverse water gas shift reaction, which converts CO_2 into CO, which is the active carbon species in the Fischer-Tropsch reaction. Today the process is used to convert gas and coal to liquid fuels, but there are several projects focusing on the conversion of biomass and waste to liquid fuels.

The attraction of e-fuels in the form of the hydrocarbon fuels used today is that they can be a direct drop-in for current fuels, using the same distribution network and being burned in the same kind of engines that we have today. In some applications, such as aviation and marine, their use seems likely, as discussed elsewhere in this edition of *Johnson Matthey Technology Review*, since liquid fuels are expected to be required for a substantial period of time in these areas due to challenges with the use of battery or hydrogen fuel cells in such applications. For ground transportation, however, their widespread use seems less likely for several reasons, including:

- cost – such fuels will be more expensive than renewable-derived hydrogen (which itself will be more expensive than the renewable electricity used to generate it), since they will use such hydrogen as a feedstock and then process it further. So the lowest cost 'fuel' for future ground transport vehicles will be renewable electricity for BEVs, followed by H_2 for FCEVs, and then e-fuels for ICEs
- energy efficiency – a recent publication from Shell (6) concluded that the efficiency of e-fuel production (starting from renewable energy generation and using DAC as the source of CO_2), combined with the relatively low efficiency of the use of such fuel in an ICE, leads to an overall 'well-to-wheels' energy efficiency of around 12%. In comparison, the same study quoted the well-to-wheels efficiency of a BEV to be around 72%, and that of a FCEV around 37%
- local emissions – despite the great strides made by the vehicle makers and emission control catalyst companies, burning hydrocarbon fuels in an ICE leads to tailpipe emissions of CO, unburned hydrocarbons, NOx and PM; all of which can be avoided by the electrification of the powertrain using either electricity or hydrogen.

So, while it is expected that biofuels and e-fuels will play a significant role in the aviation and marine areas, the focus of this article is on ground transportation, where BEVs and FCEVs are expected to be the major technologies. This is consistent with, for example, the views of Martin Daum, Member of the Board of Management of Daimler AG, responsible for trucks and buses:

> "Truly CO_2-neutral transport only works with battery-electric or hydrogen-based drive" (7).

2. Tailpipe Emission Regulations

The regulations in the passenger car and commercial vehicle sectors focus on emissions from the tailpipe, and historically the main focus has been on criteria pollutants, which have enabled major improvements in urban air quality to be made. The focus is now shifting to CO_2, and **Figure 1** shows the current and incoming CO_2 regulations for cars in various countries and regions around the world (8), illustrating the substantial reductions required going forward.

The European regulations for 2025 and 2030 require reductions of 15% and 37.5% respectively over the 2021 legislation. These regulations are intended to continue to drive the decarbonisation of the automotive industry, and the fleet average

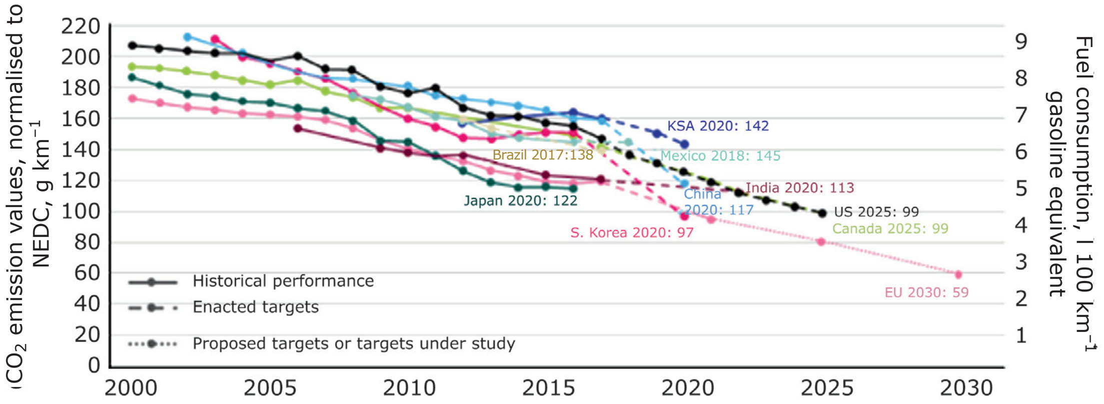


Fig. 1. Historical and future global CO_2 passenger car regulations. Values normalised to the New European Driving Cycle (NEDC) (8)

CO_2 emissions required in 2030 will require extensive electrification of the fleet. Indeed, Herbert Diess, CEO of the VW Group, has stated that these 2030 regulations will require at least 40% of VW's European sales to be electric vehicles (BEV and plug-in hybrid electric vehicles (PHEV)) in 2030 (9).

Legislation on CO_2 and GHG is also tightening in the commercial vehicle sector, with the next set of European regulations requiring a 15% drop in CO_2 emissions from today by 2025, and a 30% reduction from today in 2030. This 2030 target is expected to lead to significant hybridisation of the commercial vehicle fleet, along with some completely electrified vehicle sales. Trucks, buses and coaches are responsible for about a quarter of CO_2 emissions from road transport in the EU and for some 6% of total EU emissions (10), so introducing low and zero emission vehicles in this sector is critical to support global moves towards net zero.

The electrification of the bus market is already underway, with over 400,000 battery electric buses in use in China today (out of around 425,000 BEV buses worldwide). Some Chinese cities, such as Shenzhen, have completely transitioned to battery-powered buses, with around 16,500 such vehicles on the road. Many other cities worldwide are committed to moving away from diesel and towards zero emission buses in the coming years. For example, 13 cities have signed the C40 Fossil Fuel-Free Streets Declaration (11), and will procure only zero emission buses from 2025. These are: Auckland, Barcelona, Cape Town, Copenhagen, London, Los Angeles, Mexico City, Milan, Paris, Quito, Rome, Seattle and Vancouver. London has committed to increase its BEV fleet from 120 to 300 by 2020, and in Paris 80% of the fleet will be e-buses by 2025. Oslo has gone further, and will have fossil fuel-free public transport by 2020, while in the Netherlands all new buses will be zero emission by 2025, with the whole fleet being all-electric by 2030. These commitments will lead to improved urban air quality and a reduced CO_2 footprint, as long as the electricity used to charge the buses is from low carbon sources, as discussed later.

California often takes a mandate-based approach to regulations, in order to drive the development and initial implementation of new technologies. Within the commercial vehicle sector they are proposing an Advanced Clean Trucks mandate, which will require original equipment manufacturers (OEMs) with more than 500 truck sales in California to sell an increasing proportion of zero emission trucks, starting in 2024, per the schedule outlined in **Table I**. The intention of the California Air Resources Board (CARB) is to accelerate the first wave of zero-emission trucks, which are seen as essential if net zero targets are to be met, particularly since the commercial vehicle market is widely regarded as being significantly more difficult to decarbonise than the passenger car fleet. The schedule outlined in **Table I** will lead to a ZEV truck fleet of around 100,000 vehicles on California's roads in 2030, rising to around 300,000 in 2035.

Table I Proposed ZEV Percentage Schedule: Overview of the Proposed Californian Advanced Clean Trucks Regulation

Model year	Class 2B-3 8501–14,000 lbs	Class 4–8 Vocational 14,001 lbs and greater	Class 7–8 Tractor 26,001 lbs and greater
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	45%	65%	40%
2034	50%	70%	40%
2035	55%	75%	40%

3. Life Cycle Carbon Dioxide Emissions

Of course, tailpipe emissions are only part of the CO_2 story, since the emissions associated with the manufacture of the vehicle and the fuel also need to be considered in any holistic analysis. For BEVs the manufacture of the battery generates significant levels of CO_2, estimated to be around 175 kg CO_2 kWh^{-1} of battery capacity (12), and with vehicle batteries typically having between 30 kWh and 100 kWh of stored energy, this leads to upstream emissions of 5–17.5 tonnes of CO_2 per battery pack. In addition, the electricity used to charge the battery has associated CO_2 emissions, unless it is generated from renewable sources such as wind or solar power. For example, UK electricity currently has a carbon intensity of around 200 g CO_2 kWh^{-1} (13), which is below the average of European Union countries, while Norway (extensive use of renewable hydroelectric power) and France (predominantly nuclear power) have much lower carbon signatures.

The hydrogen used to power FCEVs is typically generated in one of two ways: either through electrolysis (in which an electric current is used to split water into hydrogen and oxygen) or the steam reforming of methane. The former route is, therefore, subject to the same CO_2 emission challenges (and opportunities) as the BEV, while the latter route generates relatively high levels of CO_2 which in future will need to be abated using carbon capture utilisation and storage (CCUS) technology, in which the CO_2 generated by the process is captured with high efficiency (which can be around 95%) and then either stored (for example, in depleted oil and gas fields) or used for other purposes (for example, to make chemicals).

Therefore, a full CO_2 life cycle analysis (LCA) of BEVs and FCEVs is required to paint a true picture of the carbon intensity of these vehicles. Some LCA studies are now being published and one of the most thorough is the one carried out by the International Council on Clean Transportation (12) who calculated the g km^{-1} CO_2 emissions over the life of the Nissan Leaf BEV (with 30 kWh battery pack, lasting for the life of the vehicle), which they assumed would cover 150,000 km in its lifetime, and compared it to the average and the lowest emitting European cars powered by ICEs. In addition, Toyota have analysed the LCA of a FCEV (14), and these values have been updated for this paper based on Johnson Matthey's knowledge of the CO_2 emissions when making hydrogen from CH_4 (with and without carbon capture and storage (CCS)).

Figure 2 shows the LCA CO_2 from the European car with average CO_2 emissions in 2017, along with the most fuel efficient ICE-based car in that year (which was in fact a hybrid), together with a BEV being operated on electricity with the EU average CO_2 footprint (the UK's level is a little

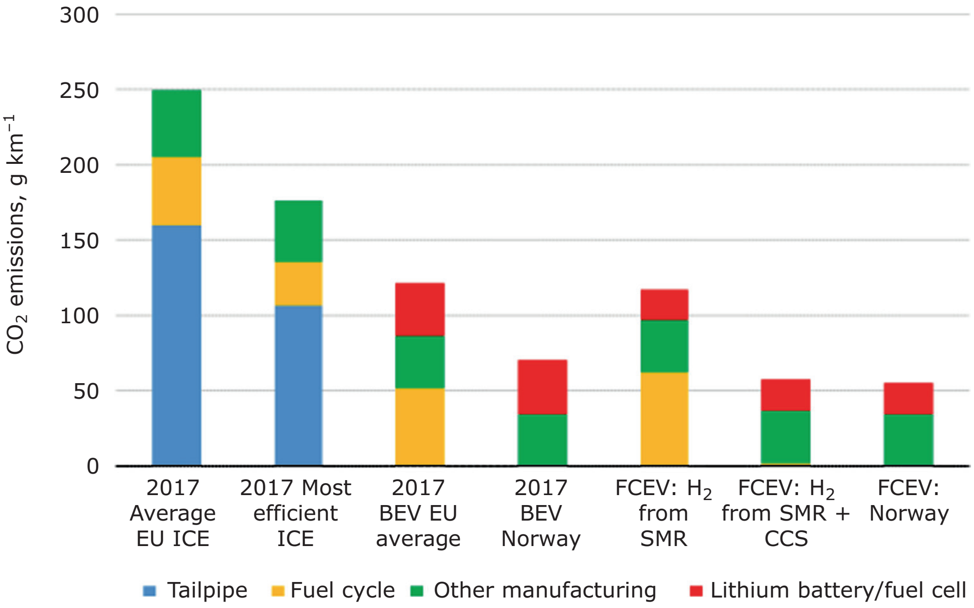


Fig. 2. Life cycle CO_2 emissions from ICE, BEV and FCEV cars, showing the impact of the CO_2 footprint of the electricity and hydrogen generation processes (12)

lower than this average), and that in Norway, whose extensive use of hydroelectric power reduces the CO_2 emissions during electricity generation to zero. The FCEV LCA is also shown, based on hydrogen generated from steam methane reforming (SMR) with and without CCUS, and based on electrolysis using Norwegian electricity. It is clear that BEVs and FCEVs have significantly lower CO_2 LCA than ICE-based cars today, and this gap will increase further as the carbon footprint of electricity generation continues to drop (see Section 4). (Note that this analysis does not include the recycling or disposal of the vehicles and their components).

A very recent BEV *vs.* ICE life cycle analysis subdivided passenger car GHG emissions into use-phase emissions (from driving the car), and production of all components (including, for example, emissions during mining of raw materials) and end-of-life emissions (15). This study concluded that driving a BEV is already lower in life cycle CO_2 emissions than petrol cars in 95% of the world. The only exceptions are countries such as Poland, where the electricity network is still mostly based on coal-fired power generation. In countries with a heavily decarbonised power system, such as Sweden and France which have large amounts of renewable and nuclear generating capacity, the average lifetime emissions from BEVs are up to 70% lower than petrol cars. In the UK, which is rapidly phasing out coal but still has a reasonable amount of gas-fired power plants, emissions are around 30% lower. The authors also point out that the advantages of BEVs will continue to grow, as power systems around the world become less carbon-intensive. The study projected that by 2050 half of the cars on the roads could be BEVs, leading to a reduction in global CO_2 emissions of up to 1.5 billion tonnes per year, which is the same as the total current CO_2 emissions of Russia.

This focus on LCA is already having a profound impact in the automotive sector. For example, the incoming VW ID.3 BEV is the first vehicle in the company's history to be built with a CO_2 neutral balance sheet, covering the supply chain (for example, only green energy is used in the production of the battery cells), production (using only green energy at the Zwickau, Germany, manufacturing plant), use phase and recycling, with any currently unavoidable CO_2 emissions being offset by investments in climate protection projects (16).

4. Net Zero Carbon Dioxide and Greenhouse Gas Commitments and Their Implications

Governments, states and regions are proposing, and in some cases (such as the UK) committing to, net zero GHG or CO_2 emission targets over the coming years. Indeed, at the time of writing two countries (Bhutan and Suriname) are already carbon neutral, 15 countries have set defined dates to become net zero, and other countries and regions, such as Germany and the EU, are discussing when to implement such a target. Within Europe, Norway plans to become net zero by 2030, Sweden by 2045 and Denmark, France and the UK by 2050. The implications of this are clear: road transport needs to decarbonise rapidly. As outlined above, a 2050 net zero target means that sales of new ICE powered vehicles need to stop by 2040 at the very latest, and preferably at some point during the 2030s, since cars and trucks are often on the road for 10–15 years or more before being scrapped.

This will be a substantial undertaking, requiring all new cars, trucks and buses to be powered by either batteries or hydrogen fuel cells on this timescale. As discussed above, this move to zero (tailpipe) CO_2 or GHG vehicles is only part of the challenge. The electricity used to charge the batteries, and the hydrogen used in the fuel cell vehicles, must also be generated in a very low or zero carbon manner, such as through renewable electricity or advanced CH_4 reforming with CCUS.

Many countries are driving down the CO_2 emissions from power generation. For example, the UK almost halved the carbon footprint of its electricity generation between 2013 and 2017, and one future projected UK pathway to 2050 is shown in **Figure 3**, from analysis for the National Grid's Future Energy Scenarios 2019 document (17). This "Two Degrees" scenario foresees significant increases in renewable use, along with a large reduction in natural gas use and the cessation of coal-fired power generation, leading to a reduction in carbon intensity from 120 g CO_2 kWh^{-1} in 2019, to just 14 g CO_2 kWh^{-1} in 2050. This scenario is consistent with the UK achieving the 2050 decarbonisation target with large-scale centralised solutions.

Net zero targets will demand the decarbonisation of road transport (and other forms of transport), and will require strong governmental and regional policies to drive and support the uptake of zero

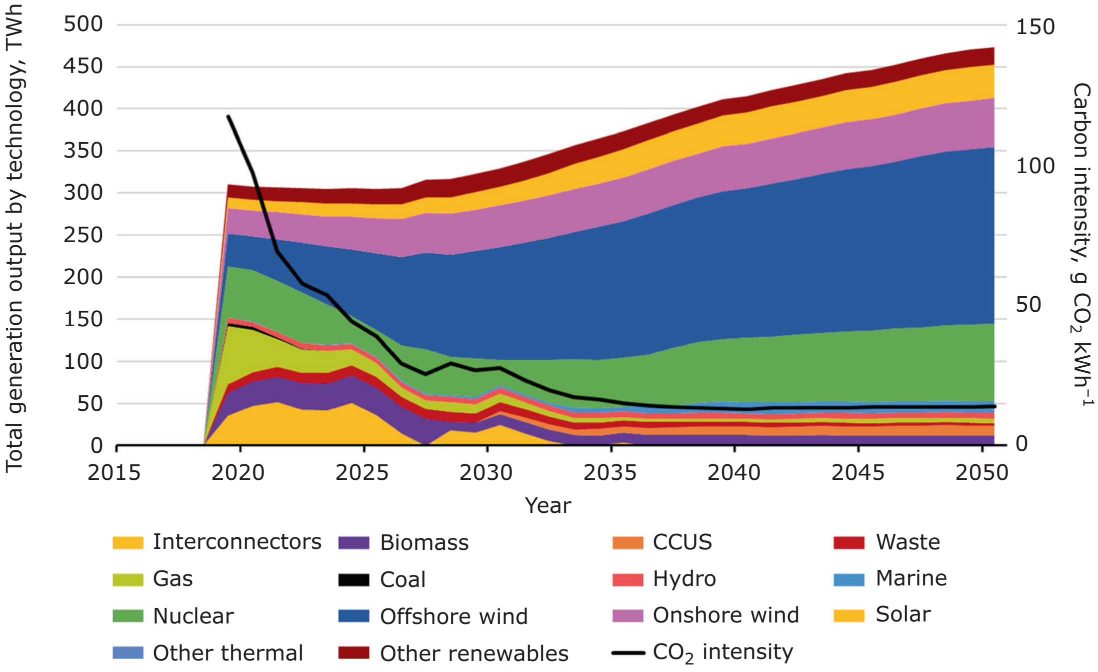


Fig. 3. Electricity output and carbon intensity of electricity in the UK National Grid's Community Renewables scenario. Reproduced with permission from (17)

emission vehicles. Extensive public charging and hydrogen refuelling infrastructure will be necessary, and the vehicles must be attractive and affordable options, with features that suit today's and tomorrow's lifestyles and transport needs.

The passenger car sector is largely driven by price, convenience and lifestyle: will my vehicle get me comfortably from A to B; can it carry the things I need to take with me; is it a sensible financial choice, in terms of purchase price, fuel price and overall cost of ownership (including likely resale value); and can I easily and conveniently refuel the car after driving the kind of distances that matter to me?

The main questions asked in the commercial vehicle market relate to how this purchase will help the business. The total cost of ownership (TCO) is a critical make-or-break calculation in this sector, as is the requirement for a very high level of vehicle uptime; so a long driving range and rapid refuelling are important here, as is the total load that can be carried by the vehicle.

Given the very different requirements in the two segments, they are considered separately in the subsequent analysis of critical drivers.

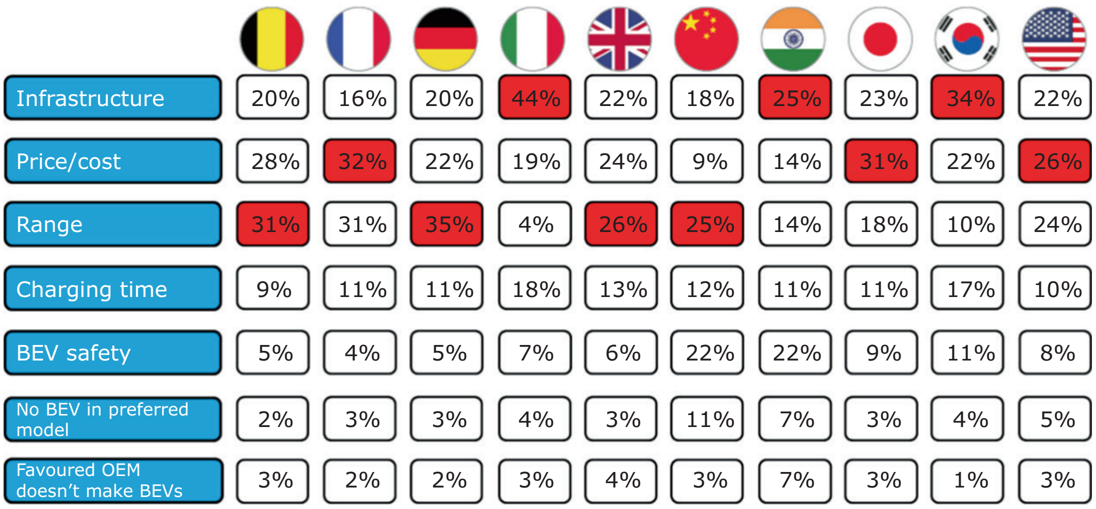
5. Passenger Car Market

5.1 Customer Pull

Deloitte recently carried out a survey (18) looking to identify and rank the key consumer concerns that prevent people buying BEVs today. The results are shown in **Figure 4**, and highlight the critical importance of vehicle price, driving range and access to charging infrastructure. Recent research in the USA shows that, among those who have considered buying an electric vehicle, but have not, the lack of charging stations is the main reason why (19). This work also found that private charging stations are just as important: in the USA nearly 80% of electric vehicle owners charge their vehicles at home, and almost 15% at work, with the rest at public stations.

5.2 Vehicle Price, Ownership Cost, Range and Fuelling Infrastructure

Vehicle range and fuelling infrastructure can be considered together, since, particularly for BEVs, the further the driving range between recharging, the less concern there is about not being able to find a suitable charge point. However, Mark Reuss,



Infrastructure	20%	16%	20%	44%	22%	18%	25%	23%	34%	22%
Price/cost	28%	32%	22%	19%	24%	9%	14%	31%	22%	26%
Range	31%	31%	35%	4%	26%	25%	14%	18%	10%	24%
Charging time	9%	11%	11%	18%	13%	12%	11%	11%	17%	10%
BEV safety	5%	4%	5%	7%	6%	22%	22%	9%	11%	8%
No BEV in preferred model	2%	3%	3%	4%	3%	11%	7%	3%	4%	5%
Favoured OEM doesn't make BEVs	3%	2%	2%	3%	4%	3%	7%	3%	1%	3%

Fig. 4. Perceived concerns related to the purchase of BEVs by country (Adapted from (13))

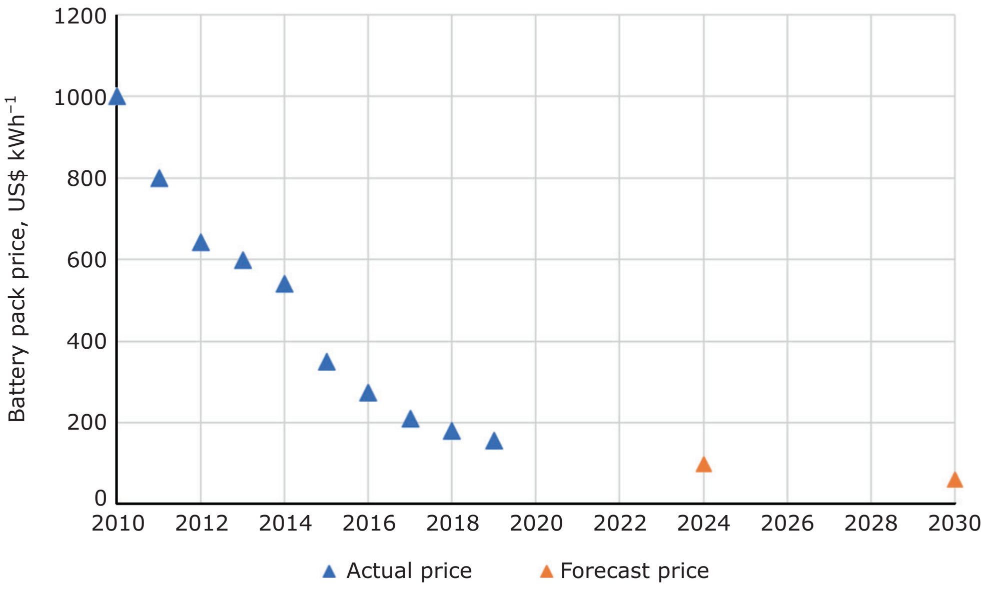


Fig. 5. Battery pack price reductions and forecast future trend (20)

GM President, believes that: "Just as demand for gas mileage doesn't go down when there are more gas stations, demand for better range won't ease even as charging infrastructure improves. People will still want to drive as long as possible between charges" (19). The BEV price is also strongly linked to its range, since, for a given battery chemistry, the vehicle range depends upon the size (capacity) of the battery (amongst other things), which impacts its cost.

5.2.1 Vehicle Price and Ownership Cost

Starting with the vehicle price and operating cost, Bloomberg New Energy Finance have looked at the trend in battery pack pricing, which shows a strong rate of reduction from around US$1000 kWh^{-1} in 2010 to US$200 kWh^{-1} in 2017 (20) and then US$156 kWh^{-1} in 2019, as shown in **Figure 5**.

There is a rule of thumb in the BEV industry that when battery pack prices reach around US\$100 kWh^{-1}, which BNEF forecast will be around 2024, the price of a BEV will be approximately the same as a similar ICE-powered vehicle. Therefore, the price of BEVs is going in the right direction, and at a good rate. FCEVs are relatively expensive at present (for example, the Toyota Mirai retails for around US\$58,500) since only a few thousand FCEVs are sold annually, so mass production practices and supply chain economies of scale have not yet been brought to bear. It is clear that the prices of both BEVs and FCEVs will reduce significantly going forward, as more of them are made and sold.

The operating costs of ZEVs are also important, and here there is more data for BEVs than for FCEVs. A study in the USA found that most BEV owners report their average cost of operation to be about one-third of that paid by the owners of gasoline-powered cars (19). And while most private owners tend to pay more attention to the initial vehicle purchase price, fleet owners focus strongly on lifetime costs (maintenance, fuel and ancillaries) because they want to know exactly how much they will be spending over the time they own the vehicle. BEVs, because of their low fuel (electricity) costs and relative simplicity (uncomplicated motors, fewer moving parts) are cheaper to own and maintain than their conventional, ICE-powered counterparts. A recent report from New York City's fleet management agency analysed fuel and maintenance costs for 1893 vehicles of its 9196 light-passenger vehicles. It found servicing costs with all-electric vehicle models were significantly lower than for gasoline, hybrid, and plug-in hybrid models (21). **Figure 6** summarises the nine year TCO of a typical BEV, hybrid and gasoline car from their fleet, which contains 149 Nissan Leaf, 1131 Toyota Prius and 62 Ford Fusion vehicles. The study found that, despite the higher initial purchase price of the BEV and its associated charger, its TCO was slightly lower than the hybrid electric vehicles (HEV) and significantly below that of the gasoline vehicle, due to its much lower fuel and maintenance costs. In fact, in this study, the operating costs of the BEV were just 22% those of the gasoline car.

There are fewer studies on FCEV operating costs, but the expectation is that the maintenance costs will be similar to those of BEVs, since the electric drivetrains are very similar. One critical parameter in the TCO calculation for BEVs and FCEVs is the cost of the electricity and the hydrogen. Electricity costs vary significantly around the world, and even across Europe, where, for example, domestic electricity costs €0.17 kWh^{-1} in the UK and €0.30 kWh^{-1} in Germany. These differences significantly impact the operating cost of BEVs as a function of geographical location.

Hydrogen is relatively expensive today, around US\$10 kg^{-1} at the pump in the US and €10 kg^{-1} in Europe, with 1 kg being typically enough for around 70–80 miles of driving. **Figure 7** shows the current production cost of hydrogen *via* various routes, with the cost from steam reforming of natural gas with carbon capture and storage (to ensure the hydrogen is low carbon) falling in the range US\$1.50–2.80 kg^{-1}, with the production cost of hydrogen from renewables being much higher, from US\$3.00–7.50 kg^{-1} (22). A recent report from Bloomberg New Energy Finance projects that renewable hydrogen costs in advantaged areas (for example those with plentiful sunshine for solar power generation) may fall to as low as US\$1.40 kg^{-1} by

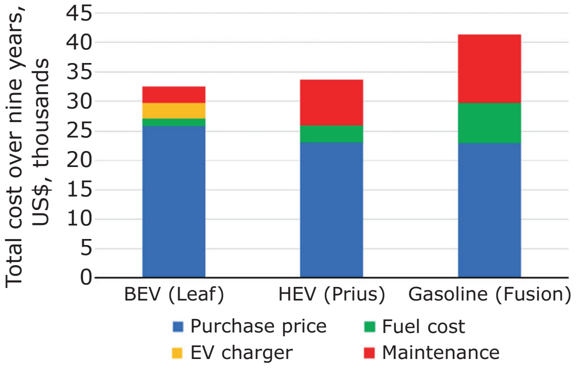


Fig. 6. Total cost of ownership of BEVs, HEVs and gasoline cars operated by New York City's fleet management agency over nine years (21)

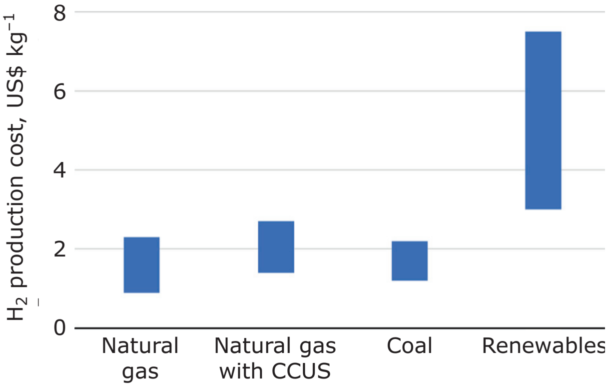


Fig. 7. Production cost of hydrogen *via* various routes (22)

2030 (23). While the ultimate net zero compliant target is to make 'green', zero carbon hydrogen, i.e. using electrolysis powered by renewable electricity, in many parts of the world 'blue' hydrogen, made using advanced CH_4 reforming with CCUS, will be significantly cheaper in the short to medium term, making it a more economically attractive option, while still having a low carbon footprint. To manage the costs associated with the energy transition it is likely that blue hydrogen will be used extensively while the cost of green hydrogen comes down to an economically acceptable level. For example, the Committee on Climate Change's Net Zero report for the UK Government forecasts that around 80% of the UK's hydrogen will be blue in 2050, with the 20% balance being green (4).

Taking an intermediate hydrogen production cost of US\$2 kg^{-1} would likely result in a price at the pump of around US\$4.50 kg^{-1} (€4.10 kg^{-1} at November 2019 exchange rates) on the 2030 timescale, once the costs of compression, storage and distribution of hydrogen at scale are added. Based on these assumptions, **Table II** shows the fuel cost of cars powered by a gasoline engine, a battery and a fuel cell travelling 10,000 miles a year in the UK and Germany, in 2020 and 2030.

Table II shows that the BEV has the lowest annual fuel cost in 2020, in both the UK and Germany, with the FCEV second and the gasoline car having the highest fuel expenditure. Indeed, the BEV has almost half the fuel cost of the gasoline car in Germany, and around 30% of the gasoline fuel cost in the UK. In 2030, the ranking of fuel cost remains the same in the UK (gasoline > FCEV > BEV), but the FCEV hydrogen cost is much closer to the BEV charging cost as a consequence of the projected reduction in hydrogen price on this timeframe. In contrast, in 2030 in Germany the FCEV has the lowest annual fuel cost, due to the anticipated reduction in hydrogen price, and because domestic electricity is significantly more expensive in Germany than in the UK. Of course, electricity prices will change in future, as the grids evolve, but this analysis gives a directional perspective based on today's prices.

It is expected that governments will tax electricity and hydrogen as the proportion of BEVs and FCEVs on the road increases, to cover the lost revenues from diesel and gasoline taxation, so projections on the future TCO of BEVs and FCEVs are complicated by this.

5.2.2 Vehicle Driving Range

In 2018 the average BEV could travel around 225 km (140 miles) between charges; as we move into the early years of the 2020s this will increase to around 400 km (250 miles) or so by a combination of higher energy density battery materials and the use of larger batteries (see for example **Figure 8**). This increased range is expected to reduce BEV range anxiety for people considering a BEV purchase.

As discussed elsewhere in this journal, one of the main development targets of ongoing battery materials research is to increase the energy density of the cathode, to increase vehicle range. Over the next few years the industry will see moves from nickel manganese cobalt (NMC) 532 (i.e. around 50% Ni, 30% Mn and 20% Co) and NMC622 to NMC811 – each new generation increases the Ni content of the cathode, which is the component principally responsible for the energy density at current voltage windows. We will also see further evolution in the nickel cobalt aluminium (NCA) battery chemistries used by Tesla and others. NMC811 also has a significantly reduced level of Co. The trend to low Co loadings is partly driven by concerns about Co availability, sustainability and future pricing, and also by the need to continue to increase the Ni content to enable higher energy density. Beyond this, the widespread introduction

Table II Estimated Annual Fuel Cost of Cars Powered by a Gasoline Engine, a Battery and a Fuel Cell in the UK and Germany, in 2020 and 2030

Application	UK 2020	UK 2030	Germany 2020	Germany 2030
Gasoline car	€1540	€1386	€1465	€1318
Battery electric car	€442	€408	€780	€720
Fuel cell car	€1250	€482	€1250	€482

Notes: Gasoline car fuel economy 45 miles per gallon (mpg) in 2020, 50 mpg in 2030; November 2019 fuel prices in both cases
BEV assumed to charge on domestic electricity, which will be cheaper than charging using the public infrastructure
Current domestic electricity prices: €0.17 kWh^{-1} in UK, €0.30 kWh^{-1} in Germany; same prices used for 2020 and 2030
H_2 price: €10 kg^{-1} in 2020; €4.10 kg^{-1} in 2030
BEV efficiency of 0.26 kWh $mile^{-1}$ in 2020, and 0.24 kWh $mile^{-1}$ in 2030
FCEV efficiency 80 miles kg^{-1} H_2 in 2020, 85 miles kg^{-1} H_2 in 2030

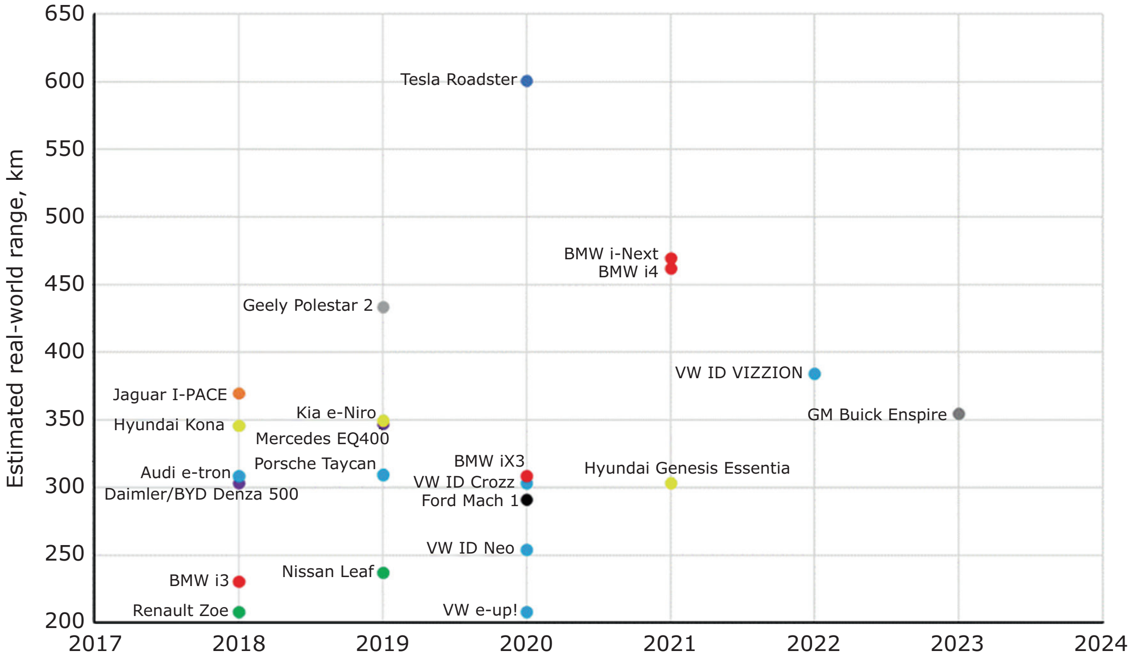


Fig. 8. Estimated real-world driving ranges of incoming BEVs. Quoted NEDC and World Harmonised Light Vehicle Test Procedure (WLTP) ranges have been converted to estimated real-world ranges using: NEDC to real-world factor 0.6; WLTP to real-world factor 0.77. Source: public disclosures and analysis by author

of solid-state battery technology is expected as we move into the 2030s, which could result in a significant further increase in vehicle range for a given battery weight and volume, as well as potentially increasing battery safety since the solid state electrolytes will not be flammable, unlike the current organic liquid based electrolytes.

FCEVs can already travel around 400 miles between refuelling (24), and this can be increased by increasing the size of the on-board hydrogen tank, and by the expected increases in vehicle and fuel cell efficiency going forward. However, the hydrogen refuelling infrastructure is less well developed than the charging infrastructure, which is one of the factors currently limiting the penetration of FCEVs.

5.2.3 Vehicle Fuelling and Charging Infrastructure

The development of the BEV charging infrastructure is already well underway, with over 175,000 public charge points in place across Europe in November 2019 (see **Figure 9**) (25) including more than 21,000 in the UK. The expectation is that most passenger car charging will occur overnight at home and at the workplace (at slow charging rate), which limits the requirement on the number of public chargepoints. The EU Alternative Fuels Infrastructure directive sets a target of one public charging point for every 10 EVs, which implies that a Net Zero Europe would need up to around 20 million public chargepoints, assuming a similar size vehicle parc as that today (for example the natural growth in the fleet from now to 2050 is balanced by an increase in shared mobility), and that 80% of EU passengers cars are powered by batteries, with the balance being FCEVs. From the 2018 number in **Figure 9** below (the last full year for which there is data), this would represent a Compound Annual Growth Rate (CAGR) of around 16.8% between 2018 and 2050. Angela Merkel, the German Chancellor, recently said that she wants to have one million public charge points in Germany by 2030, up from around 21,000 today (this would represent a CAGR of around 38%). Based on the EU Directive target, this would be enough to charge around 10 million vehicles, a significant proportion of the number of cars on Germany's roads (which is around 47 million today).

On the FCEV side, a number of governments have set formal targets for both the number of FCEVs on the road and the number of hydrogen refuelling stations (HRS) to enable this (see **Table III**). For example, China intends to have over one million FCEVs on its roads in 2030, supported by over 1000 HRSs. Last year Chinese FCEV subsidies totalled US$12.4 billion (26), and China is cutting

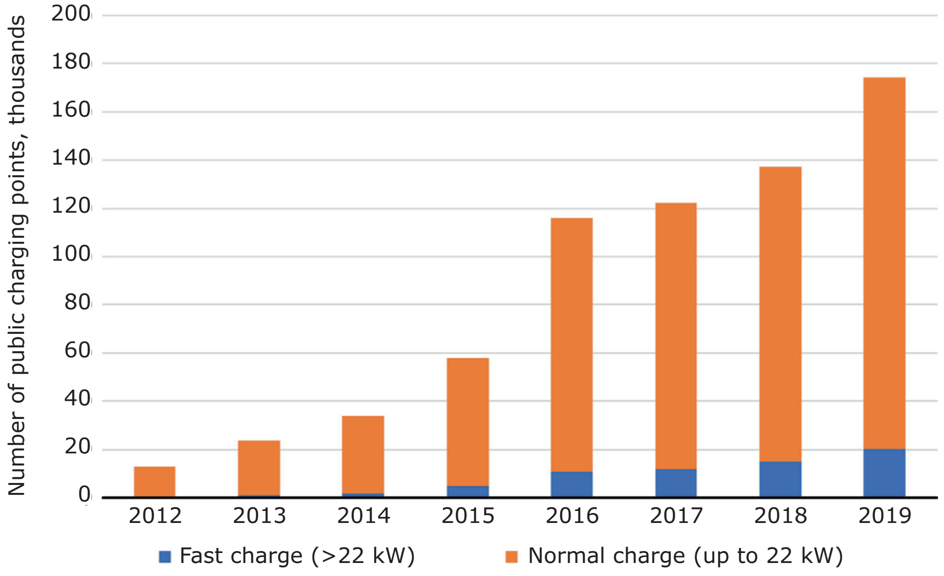


Fig. 9. Growth in the number of public charging points in Europe (25)

Table III Government and State Targets for the Size of the FCEV Fleet and Number of Hydrogen Refuelling Stations

Country or state and target count	Today	2020	2025	2030
Japan HRS	90	160	320	900
Japan FCEVs	2000	40,000	200,000	800,000
China HRS	30	>100	>300	>1000
China FCEVs	1500	5000	50,000	>1,000,000
South Korea HRS	20	310 (2022)	–	520
South Korea FCEVs	–	16,000	–	1,800,000
California HRS	35	94	200	–
California FCEVs	–	23,000 (2021)	47,200 (2024)	–
France HRS	20	–	100 (2023)	700 (2028)
France FCEVs	–	–	5200 (2023)	36,000 (2028)
Germany HRS	43	100	400 (2023)	1000
UK HRS	14	31	–	–

subsidies to BEVs and PHEVs to focus on developing other clean options such as hydrogen. In addition, China has deployed more renewable energy than any other country but its utilisation is relatively low, opening the possibility of using some of this electricity to generate hydrogen via electrolysis, to drive elements of a hydrogen-based economy, including FCEV-based transportation.

Both Japan and Korea also have broad government-driven strategies based on hydrogen, to reduce their heavy reliance on imported oil, as well as to meet their GHG reduction commitments and generate further growth opportunities for their automotive industries. The three FCEV leaders today are Toyota, Honda and Hyundai.

South Korea's Ministry of Trade, Industry, and Energy announced in June 2018 that along with private entities it would invest US$2.2 billion through public-private partnerships to speed up development of the FCEV ecosystem in the country by 2022 (27). The government plans to use subsidies to reduce the cost of FCEVs to around US$25,000 by 2025, around half the current price, and to reduce the market price of hydrogen to US$2.50 kg^{-1}. In addition, Hyundai has announced plans to invest US$6.5 billion in FCEV production facilities and related research and development activities by 2030 to produce 500,000 FCEVs in 2030 (28). The South Korean government aims to generate US$36 billion worth of added value a year and create 420,000 new jobs in the market by 2040.

6. Vehicle Refuelling Rates

Another important comparison between BEVs and FCEVs is their respective refuelling rate, as shown in **Table IV**. FCEVs can refuel in around five minutes, corresponding to an energy input per second of around 4 MW which, while slower than the 20 MW typical of gasoline and diesel fuelling, is much faster than that of BEVs, where even Tesla superchargers can only deliver a maximum rate of 0.12 MW. The introduction of ultra-fast chargers is just starting in Europe and North America, with a maximum refuelling rate of 0.35 MW, still a factor of 10 slower than fuelling a FCEV with hydrogen. These differences in fuelling rate are particularly important for some applications, for example high utilisation fleet vehicles and vehicles which do a lot of long distance driving (and heavy commercial vehicles).

7. Raw Material Use and Recycling

There are challenges in both the BEV and FCEV supply chains. For BEVs there are some concerns around Co availability and the ethics around some mines in the Democratic Republic of Congo, where around 50% of the world's Co is mined. In addition, the projected increases in BEV penetration will likely lead to supply chain pressure on commodities such as Ni (which is a key component in the battery itself) and copper (which is used to move electrons around on the vehicle, and throughout the charging infrastructure), which will put upward price pressure on BEVs. The FCEV supply chain is not well developed today because vehicle volumes are so low, so there is work to do to build the volumes required to support this technology going forward, for example around the fluoropolymer and hydrogen tank components. However, one of the most expensive fuel cell constituents, platinum, already has a highly developed supply chain, and there is plenty of Pt above ground that will be accessible *via* autocatalyst recycling.

On recycling, the importance of developing cradle-to-cradle supply chains for future technology has never been greater. There is a legal imperative for vehicle OEMs to ensure their vehicles are extensively recycled, and there are components of high value (and relative scarcity) in both FCEV membrane electrode assemblies (MEAs) and BEV batteries, so it is essential that effective recycling loops are set up going forward. Neither FCEV MEAs nor BEV batteries are recycled to a large extent today, and optimised processes do not exist for either option, but work is ongoing to develop such processes.

Table IV Comparison of Fuelling Rates of ICE, BEV and FCEV Cars

Fuel or charging technology	Fuelling rate, MW
Diesel or gasoline	20
H_2 fuel cell	4
BEV current technology (charge car in ~30 min to 6 h)	0.007–0.12
BEV incoming ultra fast charging (~80% charge in 15 min)	0.35

8. Projections of the Future Passenger Car Powertrain Mix

A number of factors will determine the proportion of BEVs and FCEVs in the future powertrain mix, with different countries, regions, OEMs and consumers making different choices. There is broad consensus, however, that BEVs are likely to dominate the passenger car ZEV sector, based on their relatively low cost and TCO, the rapidly growing charging infrastructure, the increased range of incoming BEVs and the fact that all major OEMs are bringing attractive BEVs to market over the coming years (and most OEMs also have fuel cell vehicles in small scale production (Honda, Hyundai and Toyota) or have fuel cell programmes in advanced stages of development). FCEVs are likely to play a role in the high mileage, high utilisation end of the passenger car and light commercial vehicle sectors, where their range and refuelling time advantages over BEVs are attractive.

There are many views of the rate at which the global powertrain will shift from the ICE to electrification (BEV and FCEV). LMC, an automotive global forecasting and market intelligence provider, has recently published its view of the evolution of the global passenger car powertrain out to 2050. Their base case scenario (**Figure 10(a)**) reflects their current "most likely" view of progress in technology, policy and cost, and they see BEVs with the major share in the ZEV space with over 40% of global car sales by 2050. FCEVs, helped by major growth in renewable electricity generation, become significant by 2035, exceeding 20% of global sales by 2050. Hybrids, though squeezed by

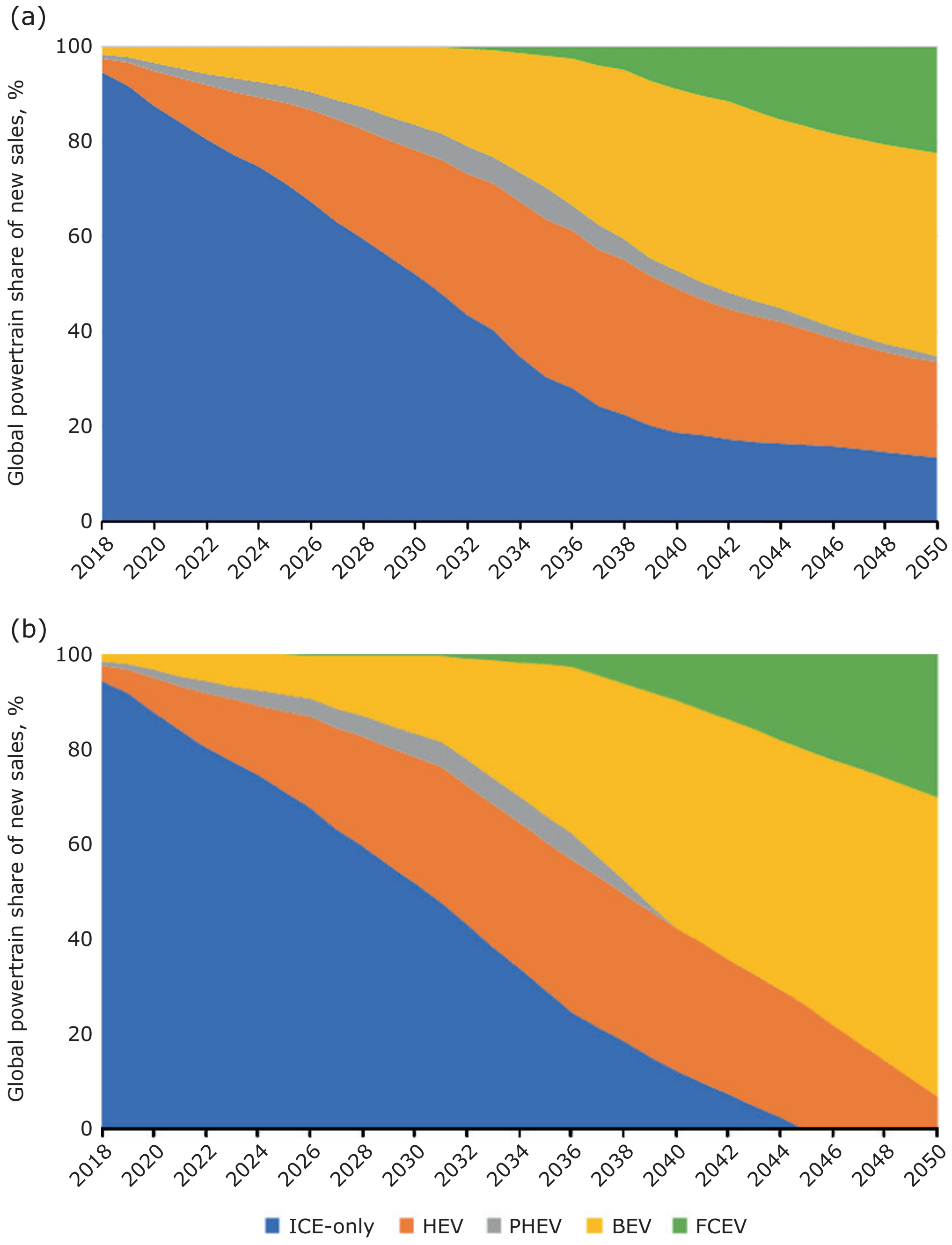


Fig. 10. LMC projected future global powertrain share of new sales out to 2050: (a) base case; (b) progressive case

ZEVs, remain important in some markets, including Japan, and make up around 20% of global vehicle sales in 2050, with the 2050 ICE sales dominated by India.

LMC's "Progressive" scenario (**Figure 10(b)**) is based on increases in public and political pressure to get the world to act more rapidly to mitigate climate change, leading to more aggressive decarbonisation policies and faster adoption of BEVs and FCEVs. Within this scenario, ICE-only sales cease in the mid-2040s and ZEV sales reach over 90% of demand by 2050, with BEVs accounting for over 60% of global sales, and FCEVs around 30%.

Even this "Progressive" case does not represent a net zero scenario globally, since this would require sales of ICEs, HEVs and PHEVs to stop before 2040, and this scenario still has ICE-containing powertrains making up over 40% of global sales in 2040. However, it could be consistent with a scenario in which Europe moves to net zero in 2050 with the rest of the world following behind and achieving net zero just after 2060.

9. Commercial Vehicle Market

As outlined above, CO_2 legislation for commercial vehicles is becoming stricter in all the major economies, and on top of the CO_2 regulations, California is planning to introduce a zero emission vehicle mandate as part of its Advanced Clean Trucks regulatory package. By 2030, this will require 15% of Class 7 and 8 trucks (i.e. vehicles over 11.8 tonnes) sold in the state to be zero emission. While batteries are expected to be the technology of choice in the lighter segments, fuel cells are becoming seen as the most likely solution to decarbonise the larger trucks. As in the passenger car sector, governments planning net zero commitments will need to transition their commercial vehicle fleets from diesel to electricity and hydrogen as they move through the 2030s, to ensure a zero emission fleet by 2050.

OEMs are beginning to position themselves for this new reality; for example, Daimler Trucks recently announced that they plan for all new trucks and buses in the triad markets of Europe, Japan and the North American Free Trade Agreement (NAFTA) to be CO_2-neutral when driving by 2039 (i.e. tank to wheels) (29). They plan to achieve this using a combination of BEV and FCEV, with battery electrics in series production by 2022 in all core regions and hydrogen fuel cell-based series production vehicles by the end of the 2020s. Daimler Truck AG and the Volvo Group, two leading companies in the commercial vehicle industry, have signed a preliminary non-binding agreement to establish a new joint venture to develop, produce and commercialise fuel cell systems for heavy-duty vehicle applications and other use cases in the second half of the 2020s. Daimler will consolidate its current fuel cell activities in the joint venture and the Volvo Group will acquire 50% in the joint venture for approximately €600 million (30).

Cummins are also investing in both battery-based powertrain technology and hydrogen and fuel cells, including acquiring a US$290 million controlling stake in Hydrogenics, a leading fuel cell and hydrogen production technologies provider (31). CNH Industrial have entered into a US$250 million strategic and exclusive heavy-duty truck partnership with Nikola Corporation (32), pioneers in the introduction of zero emission heavy duty trucks powered by hydrogen fuel cell and battery technology. The deal with CNH gives Nikola access to the European commercial vehicle market, as well as to IVECO's global manufacturing and sales network. In addition, Nikola now has Nel (electrolysis) and Hanwha (solar energy) on board to develop a clean H_2 infrastructure to power these fuel cell vehicles, where conditions allow, supporting the moves towards net zero.

TCO is the critical factor in the long-haul truck sector. Recent analyses by Cummins (33) and AVL (34) have shown that BEV trucks are not viable for this sector due to the high cost, size and weight of batteries for the required range (their weight would reduce payload) and the relatively long recharging time for such large batteries (which would reduce vehicle utilisation significantly). These studies show that the FCEV solution is strongly preferred due to the long range, rapid refueling times and overall TCO. A hydrogen price of €3.50–5.00 kg^{-1} is estimated to lead to TCO parity even with today's diesel-based trucks once such FC trucks are made in significant volumes (100,000 or so); as outlined earlier, the hydrogen price is expected to drop to around €4 kg^{-1} by 2030.

In the medium duty distribution truck sector, where driving ranges are lower than in the long-haul space, BEVs are expected to play a significant role, and for some such distribution applications BEVs already have a lower TCO than current diesel trucks. CARB estimates that the TCO of battery trucks will be lower than diesel trucks by 2024 for many local truck applications (35). They also project that FCEVs will approach the TCO of diesel by 2030.

The development of the fuelling infrastructure for zero emission commercial vehicles is generally regarded as an easier proposition than that for passenger cars, since many commercial vehicles (especially buses and distribution trucks) return to a depot overnight. For BEV-based vehicles this requires charging infrastructure at their home depots and along the parts of the strategic road network along which they operate, for cases where top-up charging away from the depot is required.

For longer distance buses, coaches, and medium and heavy commercial vehicles, the fuel cell powertrain is expected to be widely employed, requiring HRSs at home depots and along the strategic road network. Depot-based HRSs for centralised refuelling have the advantage of increased utilisation, reducing the cost of the hydrogen delivered. A recent report from the Hydrogen Council projects that the cost of hydrogen refuelling infrastructure per vehicle should ultimately drop to below the cost of the BEV recharging infrastructure due to the significant economies of scale available from increasing the size of the distribution network and the introduction of larger retail stations (36). Their analysis led them to conclude that the cost of investment per kilogram of pumping capacity from a HRS will decline roughly 70% over the next 10 years, from about US$6000 for a small station in 2020 to an estimated US$2000 for a large station in 2030. Such a cost trajectory further increases the attractiveness of the hydrogen fuel cell solution for large and longer distance commercial vehicles, since it significantly reduces the TCO of these vehicles.

There are far fewer projections of the future uptake of zero emission commercial vehicles than there are for passenger cars, but it is clear that the commercial vehicle sector needs to develop and implement zero emission vehicles rapidly to support broader decarbonisation initiatives and, particularly, moves to net zero. KGP, a consultancy that provides services to the automotive and related industries worldwide, has developed a "2°C Scenario" for the commercial vehicle market (**Figure 11**) (37), projecting that the sales of "Electric" commercial vehicles, i.e. those powered by BEV and FCEV, would need to increase from around 87,000 in 2019 to over one million per year by 2030, to be on a trajectory to enable the GHG emissions from the commercial vehicle sector to be aligned with the Paris Agreement's aim of limiting the global temperature increase due to GHG emissions to 2°C above pre-industrial levels. This level would correspond to around 25% of new sales of commercial vehicles globally.

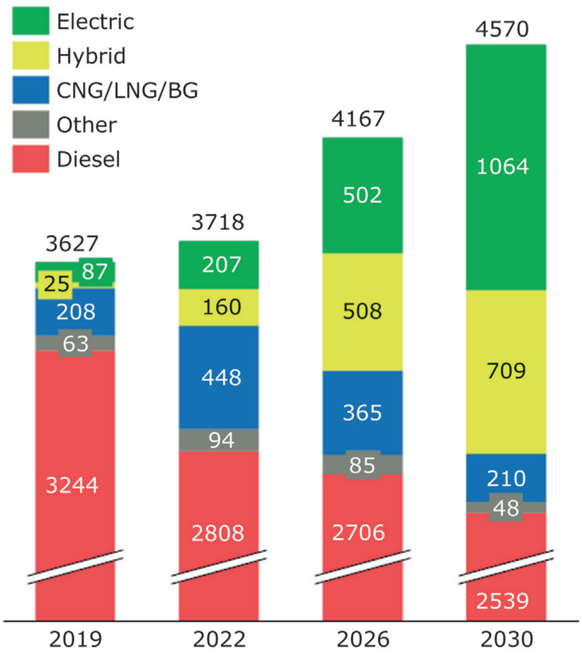


Fig. 11. KGP projected future global powertrain share of new commercial vehicle sales in the IPCC 2°C scenario, thousands. CNG = compressed natural gas; LNG = liquified natural gas; BG = biogas. Reproduced with permission from (37)

The recent report from the IPCC (2) recommends that the target temperature increase should be at or below 1.5°C, implying that a faster rate of uptake of zero emission commercial vehicles will be required. Approaches to increase ZEV penetration include increasing the stringency of CO_2 tailpipe regulations, and introducing mandates for ZEV fleet levels (such as those proposed within the Advanced Clean Trucks rule by CARB). Interestingly, 30 businesses including Nestle and Unilever recently signed a letter to the new European Commission president Ursula von der Leyen and new EU climate chief Frans Timmermans, calling for legally binding zero-emission truck and van sales targets for 2025 and 2030 (38). They pointed out that these sales targets need to be ambitious, to drive a huge increase in the supply of zero-emission vehicles compared to a business-as-usual scenario, and to put Europe on track to meeting its 2030 climate targets. The businesses believe that binding sales targets will accelerate the uptake of zero-emission vehicles, make air in cities cleaner, put European vehicle-makers at the forefront of innovation while at the same time making Europe less dependent on oil imports. The signatories also say that the EU's 2030 emissions reduction target must be increased to 55% and the bloc should go climate-neutral by 2050; the latter is the target already proposed by the European Commission.

Overall, therefore, the commercial vehicle sector is becoming increasingly aware of its need to develop zero emission vehicles to play a major role in the decarbonisation of road transport, and extensive work is underway to develop and bring such vehicles to market. Governments and regulators have a significant role to play in creating the right policy framework to drive the initial introduction of such vehicles into the marketplace, and then to encourage their further uptake to enable net zero and air quality targets to be achieved.

10. Summary

The demand for cleaner urban air and massive reductions in CO_2 and other GHG emissions is increasing both from the public and from regulators and governments in many countries and regions. Net zero GHG targets have been set and legislated in several geographies, and more are clearly going to follow in the coming months and years. Transportation is currently a major emitter of criteria pollutants (including CO, hydrocarbons, NOx and PM) and of CO_2, and the decarbonisation of this sector requires the transition from ICE-powered vehicles to battery electric and fuel cell electric zero emission powertrains. Of course, the minimisation of the carbon footprint of such vehicles is contingent on the electricity and hydrogen used to fuel them being low or zero carbon. In the case of BEVs this means the electricity grid needs to be decarbonised, and this is occurring at good pace in many countries, accelerated by the ongoing reductions in the cost of renewable energy derived from, for example, solar and wind. For FCEVs it means decarbonised electricity to generate green hydrogen by the electrolysis of water, and the addition of CCUS technology to advanced reforming plants, to convert CH_4 into blue (low carbon) hydrogen. The low carbon hydrogen infrastructure and distribution network will constitute part of the transition towards a broader hydrogen economy in many countries, supporting moves to net zero across industry, power generation (including seasonal energy storage to enable increased renewable power generation) and heating for buildings, as well as transportation.

The decarbonisation of the passenger car sector will be driven by rapid uptake of BEVs, which will occur as their purchase costs continue to fall, their driving range continues to increase, and the required charging infrastructure is rolled out worldwide. BEVs are also expected to play a significant role in urban bus and distribution truck applications. FCEVs are expected to dominate the long haul trucking segment as it decarbonises, due to their cost, weight, range and charging time advantages over battery-based technology. They will also likely play a role in inter-city buses and distribution trucks, and in larger passenger cars and sport utility vehicles (SUVs) for applications and customers requiring a long driving range and rapid refuelling.

There is no doubt that net zero targets at the state, country and regional level will be challenging to meet on the 2050 timeframe recommended by the IPCC, but the surface transportation sector is developing and introducing the technologies to enable this. As long as governments and regulators put in place an appropriate set of policy measures and incentives to encourage the early implementation and subsequent mass uptake of zero emission vehicles, the car, van, bus and truck segments will make a huge contribution to global moves towards decarbonisation and the development of net zero economies worldwide.

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East Asian Transportation

Icebreaking into a low carbon future

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The energy transition paradigm consists in a substitution of fossil energy for renewable resources, and low carbon transportation is one of the most important issues within this process. The oil century introduced modern mobility to society and since then petroleum supply has been a key to control transportation services. Energy security and environmental issues, as well as business aspects of implementing innovative technological chains at national and international levels, are major drivers for decarbonisation of transportation services for East Asian economies. Policy, institutions and technological patterns toward lower carbon footprints for the transportation sector are overviewed in this article. The emphasis is on hydrogen technologies, the corresponding drivers and the ambitions of industrialised East Asian economies to establish hydrogen infrastructure at a national level. The major factors for hydrogen technologies and hydrogen infrastructure developments in China, Japan, South Korea and Taiwan are briefly discussed. The role of road transportation systems in such development is highlighted. Current energy consumption for transportation is described, some official documents are reviewed and a snapshot of recent developments is provided for each of these economies.

1. Introduction

Decarbonisation of transport relates to the structure of energy consumption in the transport sector, unless vehicle-mounted carbon capturing devices are considered. The structure of primary energy consumption in the world and final energy demand for transportation services in 2016 are shown in **Figure 1**. Obviously, the main pattern for transport decarbonisation is associated with substitution of petroleum for other energy carriers with lower carbon footprints. Such energy carriers are gas (primarily methane), electricity and hydrogen. Vehicles utilising the last two types of energy as input, provided that hydrogen is used as fuel for fuel cells (FCs), are called zero emission vehicles (ZEVs). However, it is necessary to take into account the origin of these energy carriers, since their source could be coal, oil or natural gas. The ultimate solution to the issue of transport decarbonisation is complete electrification of transport, including the use of so-called 'green' electricity and hydrogen, i.e. those originated from

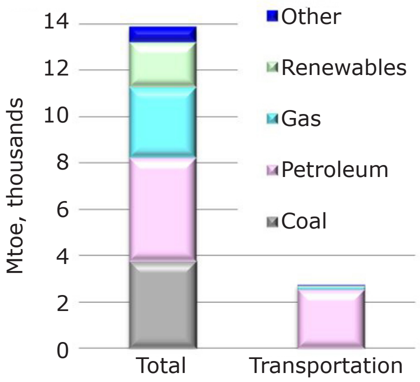

Fig. 1. World energy consumption in 2016. Mtoe = millions of tonnes of oil equivalent (1). IEA, All rights reserved

renewable or nuclear energy. The fact that water vapour has global warming potential is beyond the scope of the topic under discussion.

Transport decarbonisation patterns have several aspects: social, economic, technological and institutional. The social aspect is affected by fears of future crude oil supply exhaustion and anthropogenic impact on the environment. The economic drivers are profit-making for vehicle manufacturing and energy supply businesses and value-added ambitions for national governments, including substitution of energy import by establishing domestic innovative energy technology chains. The technological aspect relates to maturing and commercialisation of technologies for more effective utilisation of traditional fuels and the 'green' production, transportation and storage of electricity and hydrogen. The institutional factor refers to the regulatory mechanisms to reduce greenhouse gas (GHG) emissions associated with passenger and cargo traffic by all transportation modes, both at national and international levels. Other issues of technological and comparative socio-economic assessments of transport systems involving the shift from petroleum to gas fuel, improvements in vehicles' energy efficiency, introduction of biofuels, carbon capturing systems and rationalisation of transport services remain outside the scope of this article. Aspects of transport decarbonisation, related to the creation and development of hydrogen technologies in the industrialised economies of East Asia in recent years, will be considered further.

2. East Asian Economies as Forerunners

The East Asian economies of Japan, South Korea, China and Taiwan are among the global leaders in a number high-technology industries. More than half of cars, buses, trucks and more than 90% of newbuild ships in the world are produced in these economies (**Figure 2** and **Figure 3**), and they hold significant share of the world's electric vehicles stock and sales, including infrastructure for charging battery electric vehicles (BEVs), see **Table I** and **Table II**. The industrial might of East Asian countries combined with energy resource shortage has led to their overwhelming dependence on coal, oil and gas imports. Taiwan, Japan and South Korea are characterised by extreme dependency on energy imports (**Figure 4**), while China is the world's largest energy importer (**Figure 5**).

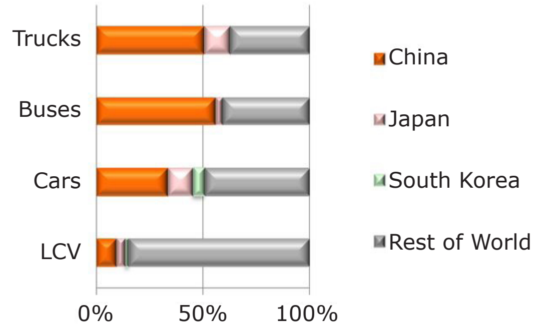

Fig. 2. World's vehicle production by major type and country of manufacturing, 2018 (2)

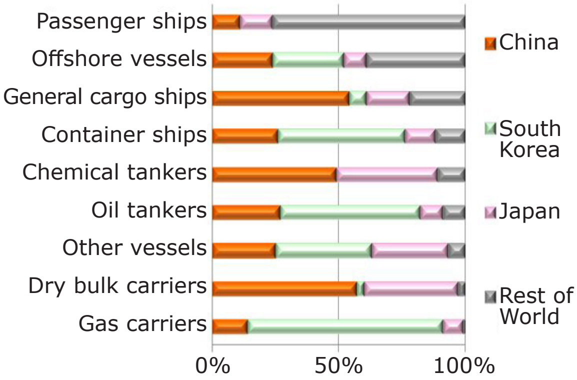

Fig. 3. Deliveries of new ships by major vessel type and countries of construction, 2017 (3)

The carbon footprint of transportation systems is usually measured from 'tank to wheel', i.e. GHG emissions from fuel and energy stored on-board the vehicle. Following this approach a BEV is considered a ZEV even in cases where the electricity stored in its battery is produced from coal or gas. However, 'tank-to-wheel' GHG emission is an important metric when strictly defined common transportation systems like roads, aviation, water and railways are considered. The respective share of these modes within the total final energy consumption for transport in four East Asian economies in 2016 and their share by energy consumed are shown in **Table III**.

The per capita GHG emissions from domestic transportation, and particularly those of road vehicles in South Korea, Taiwan and Japan are significantly higher than the world's average GHG emissions (**Figure 6**). As the International Energy Agency (IEA)'s report shows (7), the GHG emissions due to international bunkering are relatively small in comparison to domestic transportation emissions. However, it seems that a significant part of such emissions, induced by international marine and aviation traffic originated

Table I Electric Car Stock and Sales in 2018 (4)[a]

	World	China	Japan	South Korea	Share of China, Japan and South Korea in the world
	millions				%
Electric car stock (BEV and plug-in hybrid electric vehicle (PHEV))	5122	2306	255	60	51
Electric light commercial vehicle (LCV) stock (BEV and PHEV)	244	138	8	–	60
New electric car sales (BEV and PHEV)	1975	1079	50	34	59
New electric LCV sales (BEV and PHEV)	80	54	0	–	68

[a] IEA, All rights reserved

Table II Electric Vehicle Supply Equipment Stock in 2018 (4)[a]

	World	China	Japan	South Korea	Share of China, Japan and South Korea in the world
	Units				%
Publicly accessible chargers (slow and fast)	538,609	275,000	29,971	9303	58
Publicly accessible slow chargers	395,107	163,667	22,287	5394	48
Publicly accessible fast chargers	143,502	111,333	7684	3910	86

[a] IEA, All rights reserved

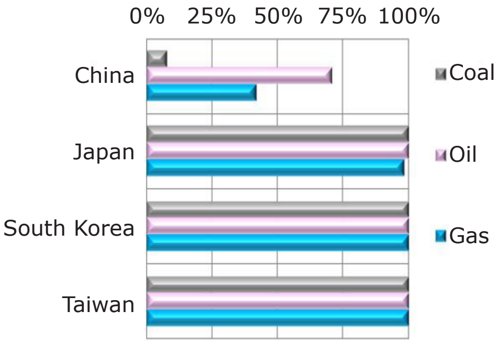

Fig. 4. Energy import dependency of East Asian economies in 2018 (5)

in East Asia, is attributed to the countries proportionally to the traffic within their economic zones, not by the site of actual fuel bunkering. This shows a strong link between international initiatives for GHG emissions reduction and energy policy drivers for the development of low-carbon technologies for mobile energy systems in East Asian economies.

It is clear that shifting from petroleum to natural gas and electricity will lead to lower carbon footprints. Electrification eventually will end up in zero 'tank-to-wheel' GHG emissions.

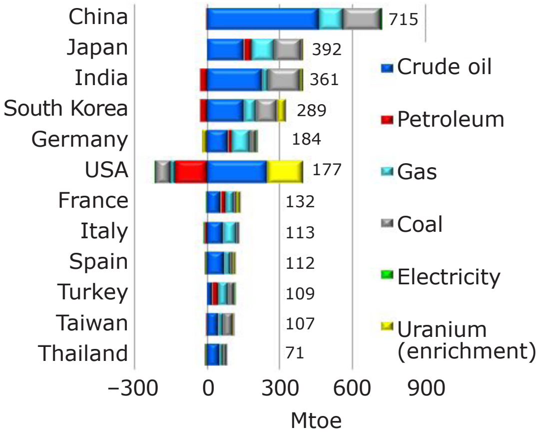

Fig. 5. Top 12 net energy importers in 2018 (5)

Importantly, vehicle electrification could be based on two approaches: (a) electricity generated outside the vehicle; and (b) electricity generated on board. The latter implies existence of fuel storage, electricity generator and power transmission within a single vehicle. If such a transport vehicle (ship, aircraft, locomotive, road or off-road vehicle) is fuelled by 'green' hydrogen or electricity, it is a true ZEV under the 'well-to-wheel' terms.

Table III The Structure of Energy Consumption in East Asia[a] by Transportation Modes in 2016 (6)

Indicator	Petroleum, Mtoe	Gas, Mtoe	Electricity, Mtoe	Total, Mtoe	Share by mode, %
All modes	397	29	13	439	100
Road	293	29	5	326	74
Air[b]	51	–	–	51	12
Water[b]	50	–	–	50	11
Rail	4	–	8	12	3
Share by energy, %	90	7	3	100	–

[a] Includes China, Japan, South Korea and Taiwan
[b] Includes international bunkering for aircraft and ships

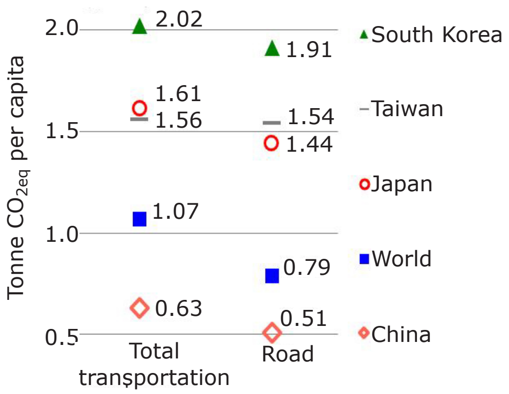

Fig. 6. The intensity of GHG emissions in East Asia in 2017 (7). Data sources: UN and IEA

East Asia is already a leader in FC electric vehicle (FCEV) production. Currently, there are more than 11,000 FCEVs in the world, and while most FCEVs are used in the USA, up to 85% of them have been produced in East Asia (8). East Asian economies are characterised by the widespread use of light vehicles for individual movement, such as mono-, bi- and tricycles, mopeds and motorcycles, thus different types of battery and FC scooters are under development (9).

Despite extensive railway electrification in East Asia, FC locomotives are being designed in Japan and South Korea. International aviation will not be a priority for the implementation of hydrogen technologies, while electric propeller aircrafts and drones could be powered by FC. Recent advances in liquefied natural gas (LNG) fuelled ships and its combination with FC technologies will bring new impetus to low-carbon powertrain development for water transport systems.

Electrification is the main option for ultimate decarbonisation for all types of transportation systems. The trends of transport electrification are determined by advances in storage of electricity and hydrogen, and by improvements in onboard powertrain (the efficiency of the transformation of stored energy into mechanical work) for these types of energy carriers.

The *Johnson Matthey Technology Review* provides significant contribution to the FC and car batteries technologies development, which is recorded in the issue on the occasion of the 200th anniversary of the journal (10, 11).

Road vehicles are ideal for the development of hydrogen and electric battery technologies because:

- the lifespan of such vehicles is relatively short
- the vehicle cost is relatively low
- the share of the powertrain cost in total vehicle cost is higher
- requirements for weight compactness are much tighter than for ships, locomotives and aircraft
- learning experience is quickly gained for technologies and safety procedures due to the car fleet's long operating hours
- the availability of hydrogen infrastructure for general use (shared with buildings and industry).

The main advantages of hydrogen technologies over those based on batteries are higher gravimetric density of onboard energy storage and the speed of vehicle refuelling (**Table IV**). Similar to battery-based transportation systems, progress in FC technologies needs intensive hydrogen infrastructure development.

The commercialisation of FCEVs and introduction of hydrogen infrastructure will lead to the creation of hydrogen mobility energy systems, the ultimate stage for all carbonless non-catenary electrified transportation modes. It is the start of the process of transitioning energy systems to full independence from fossil fuels.

The most worked out concept for a sustainable circular society within East Asian economies has

Table IV Comparison of Fuel Cell Electric Vehicle and Battery Electric Vehicle Technologies in Terms of Mobility (12–14)

Indicator	Tesla Roadster (BEV)	Toyota Mirai (FCEV)
Weight	Electric battery, 450 kg	2 tanks (~5 kg of H_2 @ 70 Mpa) = 128 kg; FC 114 kW = 56 kg
Energy stored on board	53 kWh	167 kWh
Energy efficiency (at the wheel)	96%	43% (LHV[a])
Gravimetric energy density of the energy delivered	113 Wh kg^{-1}	390 Wh kg^{-1}
Refuelling time	Hours (tens of minutes for urgent charging)	3–5 min (routine procedure)

[a] LHV = lower heating value

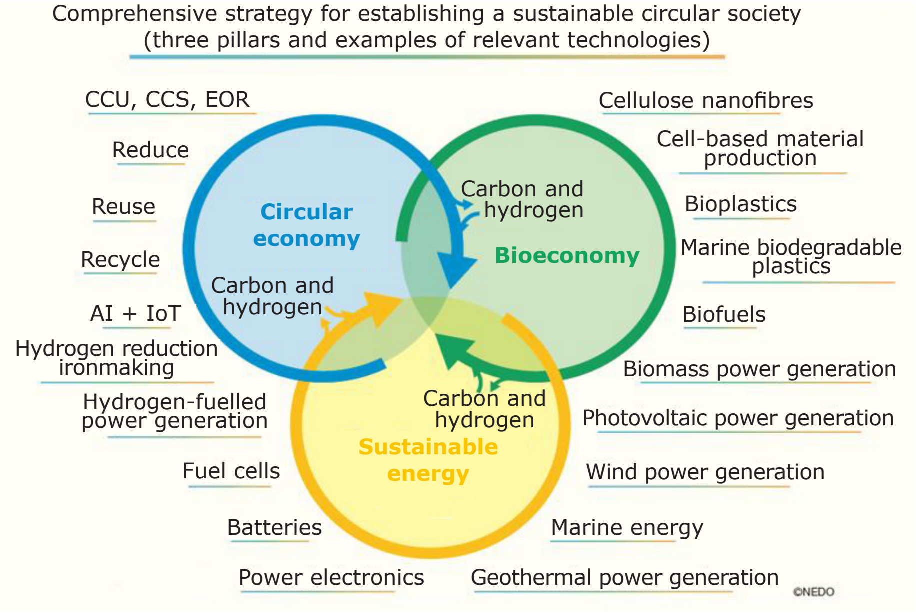

Fig. 7. The concept for a sustainable circular society in Japan, where hydrogen is instrumental as new energy carrier. CCU = CO_2 capture and utilisation; CCS = CO_2 capture and storage; EOR = enhanced oil recovery (injection of CO_2 to enhance oil production combined with CCS); AI = artificial intelligence; IoT = internet of things (15). Copyright NEDO

been developed in Japan (**Figure 7**) (15). Hydrogen technologies are an integral part of this concept, which introduces hydrogen as a new energy carrier 'electrofuel' (8), fungible to electricity.

Japan acts as an international icebreaker, capturing leadership positions in hydrogen energy systems development at a national level. This East Asian economy provides an example of energy institutions' reformation to decarbonise transportation by substituting petroleum for hydrogen. At the summit of the G20 leaders in Osaka in June 2019, the report "The Future of Hydrogen: Seizing Today's Opportunities" was presented (8). The report was prepared by the IEA on behalf of the Government of Japan.

The energy supply framework and policy drivers to reduce carbon intensity in the transport sector for China, Japan, South Korea and Taiwan will now be reviewed. Since the topic for discussion on technological and institutional options to reduce carbon footprints of transport services in East Asia is very broad, the study will focus on programmes for hydrogen technologies and related institutional developments.

3. China

3.1 Energy Consumption and Transportation Sector

Coal and crude oil occupied 66% and 20%, respectively, of China's total primary energy supply in 2016. The share of natural gas was only 6%, and the same niche was occupied by renewables. In 2016 the country imported 68% of crude oil and 36% of natural gas consumed (6). According to China's energy strategy, by 2030 at least 20% of primary energy supply should be provided by renewables, and GHG intensity of gross domestic product (GDP) should be 60–65% lower than the 2005 level (16).

China's road transport leads fuel consumption within the transportation sector, followed by aviation and water transport (**Table V**). The transport sector consumed 10% of the country's total primary energy supply (6) and produced 844 million tonnes of GHG emissions in 2016 (9% of total anthropogenic GHG emissions in China in that year), including 698 million tonnes from road transportation. International marine and aviation traffic added another 31 million tonnes and 26 million tonnes of GHG emissions, respectively (7).

Diesel, gasoline and natural gas are the main types of fuel for road transport in China. Noteworthy, the role of vehicles using natural gas, the most carbon-efficient fossil fuel, is visible in the structure of fuel consumption and the structure of vehicle park by fuel type (**Table VI**). A good potential for fuel switching and decarbonisation exists in rail transport, such as railway electrification and introduction of LNG and hydrogen locomotives. However, the role of coal in electricity generation should be taken into consideration if 'well-to-wheel' carbon emissions for transportation are accounted, as the share of this carbon-intensive fuel in power plants energy mix is more than two-thirds (6).

3.2 Institutions

The National Development and Reform Commission under the State Council is a government institution responsible for energy strategy and the development of five year energy plans. The policy of promoting transport decarbonisation is conducted on a national level by The Ministry of Industry and Information Technology, Ministry of Commerce, Ministry of Ecology and Environment and the National Energy Administration. Provincial and municipality governments have similar bodies in charge of developing and conducting decarbonisation policy at their levels. In 2018 the China Hydrogen Alliance was established by state-owned China Energy Investment Corporation and 18 other sponsors. The aim is to enhance the development of China's hydrogen sector by providing policy advice and serving as a platform to coordinate efforts for the development and commercialisation of hydrogen technologies. The alliance is supported and supervised by the Ministry of Science and Technology and other government bodies (18). The Society of Automotive Engineers of China, a national academic organisation founded in 1963, facilitates scientific and technical progress in the automotive industry. The society organises conferences, seminars and in-service training,

Table V The Energy Consumption in Transportation Sector of China in 2016 (6)

Indicator	Gasoline, Mtoe	Diesel, Mtoe	Kerosene, Mtoe	Fuel oil, Mtoe	Gas, Mtoe	Electricity, Mtoe	Total, Mtoe
National transportation	89.8	122.5	20.2	3.7	22.7	10.8	269.7
Domestic air transport	0.9	0.4	20.2	0.7	0.0	–	22.2
Road	87.2	102.4	–	0.0	22.7	4.8	217.1
Rail	0.1	3.2	–	0.0	0.0	6.0	9.3
Inland waterways	1.7	16.6	–	2.9	0.0	–	21.2
International bunkering	–	0.4	9	9	–	–	18.3
Marine	–	0.4	–	9.3	–	–	9.7
Aviation	–	–	8.6	–	–	–	8.6
Share, %							
National demand	33	45	8	1	8	4	100
International bunkering to national consumption	–	–	43	253	–	–	7

Table VI Stock of Road Vehicles in China in 2017 (17)

Fuel type	Gasoline	Diesel	Compressed natural gas	LNG
Vehicles, million	185.26	19.57	5.73	0.35

establishes relationships with foreign societies of automotive engineers and represents China in IEA's Electric Vehicles Initiative, IEA's Technology Collaboration Program on Advanced Fuel Cells and in other activities connected with 'new energy vehicles' technologies (19).

The energy development strategy action plan for the period 2014–2020, adopted by the State Council in 2014, declares fuel substitution and a robust development of electric vehicles, hybrid and natural gas vehicles and ships. The development of clean vehicle production, strengthening fuel consumption standards and environmental security standards on transport are also highlighted. The document also included hydrogen FCs in the 20 key technologies to be developed (20).

China's decarbonisation policy under consideration within Central Government is to ban sales and even production of internal combustion engine cars in the foreseeable future (21).

3.3 Major Recent Developments

China is a world leader in BEV stock (4) and sales (21) as well as in electric vehicle supply equipment stock (**Table II**). To date the FCEV technologies are mostly at the development stage. However, the characteristics of SAIC Motor's (a Chinese state-owned automobile manufacturer) newest FCEV model Roewe 950 are close to those of Toyota (Japan), Honda (Japan) and Hyundai (South Korea) (22). FCEVs in China are now at the early commercialisation stage, as their stock in the country accounts for just 63 units by the end of 2018 (23).

In 2013 China developed its first FC locomotive. In 2015 Tsinghua University, China, and Chinese state-owned rolling stock manufacturer CRRC Corporation Limited produced a FC tram. In 2016 CRRC's subsidiary produced a hybrid tram powered by hydrogen cells and a supercapacitor, which has been run on Tangxu Railway from October 2017 (22, 24). The same year CRRC awarded a contract to supply eight hydrogen FC trams for a new light rail line in Foshan (25). Luzhou, Taizhou and other cities are also planning to put into operation hydrogen-powered trams (22).

The Chinese hydrogen FC roadmap began to take shape in the late 1990s, however, research and development (R&D) activities had been carried out before (26). In 2015 the Chinese government prepared a strategy plan "Made in China 2025", where key strategic high-technology industries were pointed out. The plan highlights the importance of BEVs and FCEVs and urges the development of a full value chain within the country's automobile industry (27). Currently, the supportive measures to promote FCEVs include:

- R&D financing, through national research projects and grants
- Financial incentives: central and local governments provide subsidies for FCEVs as well as hydrogen refuelling stations (HRSs) (28)
- Demonstrations have been organised to familiarise the public with FCEVs and to promote them since the Olympic Games in Beijing in 2008. Demonstrations have been organised on a daily basis in some cities (29)
- Themed industrial parks for hydrogen value chains, based on the cooperation between research institutes (private and government) and businesses, have been created in Handan (Hebei), Yunfu (Guangdong), Rufu (Jiangsu), Taizhou (Fujian), Chengdu (Sichuan) and Datong (Shanxi), while more intentions are stated in other areas (30, 31).

According to the roadmap, prepared by the Society of Automotive Engineers of China in 2016 (32), the cost of hydrogen commercial vehicles and passenger cars will decrease significantly (by 2.5 and 1.7 times, respectively) in the coming decade, FCEV stock will reach 5000 by 2020, 50,000 by 2025 and 1 million by 2030; there will be 100, 350 and 1000 HRS nationwide, respectively. Similar scope is defined in the "White Paper on China's Hydrogen Energy and Fuel Cell Industry", issued by China Hydrogen Alliance in 2019: the number of FCEVs will rise from 2000 in 2019 to 50,000 by 2025, to 1.3 million by 2035 and to 5 million by 2050. The number of HRS will grow from 23 in 2019 to 200 by 2025, to 1500 by 2035 and to 10,000 by 2050 (22).

Some features of transport decarbonisation in China:

- The transport decarbonisation drivers include not only environmental and energy security issues, but also capturing leading positions in the emerging global 'clean vehicles' market. ("Made in China initiative" (27))
- The effects of transport electrification and the use of hydrogen vehicles on carbon emissions are limited by the prevalence of coal in electricity generation and the dominance of coal gasification in hydrogen production (33).

4. Japan

4.1 Energy Consumption and Transportation Sector

Japan is crucially dependent on energy imports, and more than 80% of electricity in Japan is produced by thermal power plants (6). Almost 20% of anthropogenic GHG emissions in Japan is attributed to transport, including 17% due to road transportation services (7).

The fuel consumption in the Japanese transport sector is dominated by road vehicles, followed by aviation and sea traffic (**Table VII**). The fuel consumption of the international sector (international bunkering) significantly exceeds that of the national transport system. Rail transport in Japan is almost entirely electrified, which results in the lowest carbon intensity of all transportation modes.

At the end of May 2019 Japan had 82 million vehicles, including 62 million cars (of which 42 million are small and light), 14.4 million trucks (including 11.6 million LCVs)), 0.23 million buses, 1.8 million special application vehicles and 3.7 million motorcycles. Sales of new BEV and PHEV, shared almost equally, reached some 50,000 in 2017–2018.

Japan is the third largest vehicle producer in the world after China and the USA. In 2018 11.9 million cars, more than 90,000 buses, 1.3 million trucks and 0.3 million LCV were manufactured in Japan. The share of hybrid cars production in 2014 to 2018 was between 17% and 20% (2, 4, 34–36).

4.2 Institutions

On 8th November, 2016, Japan adopted The Paris Agreement within the United Nations (UN) Framework Convention on Climate Change (37). The Government of Japan plans to reduce GHG emissions by 26% by 2030 and by 80% by 2050 (38, 39).The concept for a sustainable circular society in Japan, where hydrogen is instrumental as a new energy carrier, is at the core of the Japanese energy strategy (15). The action plan for the implementation of hydrogen society was elaborated in Japan after the 2011 Fukushima disaster (40).

Japan currently acts as an international icebreaker, capturing leadership positions in the hydrogen energy systems development at a national level. This East Asian economy provides an example of energy institutions reformation to introduce a 'new' energy carrier: hydrogen. The energy strategy for Japan is driven by necessity to secure the country's energy supply, to reduce imports of fossil fuels, to ensure compliance with the Paris Agreement and to catch the opportunity for development of a high-technology energy-related industrial sector, including powertrains and auxiliary equipment for mobility applications. The amended Strategic Energy Plan (41) with a vision to 2050 was adopted by the Government of Japan in July 2018. The document emphasises the challenges of energy transition and decarbonisation for "Japan's electric power, thermal, and transportation systems". In regard to transport sector policy the Government of

Table VII The Energy Consumption in Transportation Sector of Japan in 2016 (6)

Indicator	Gasoline, Mtoe	Diesel, Mtoe	Kerosene, Mtoe	Fuel oil, Mtoe	Gas, Mtoe	Electricity, Mtoe	Total, Mtoe
National transportation	39.6	24.5	4.4	1.0	0.8	2.0	72.4
Domestic air transport	–	–	4.4	–	–	–	4.4
Road	39.6	23.3	–	–	0.8	–	63.8
Rail	–	0.2	–	–	–	2.0	2.2
Inland waterways	–	1.1	–	1.0	–	–	2.1
International bunkering	–	–	7	4	–	–	11
Marine	–	–	0.1	4.5	–	–	4.6
Aviation	–	–	6.6	–	–	–	6.6
Share, %							
National demand	55	34	6	1	1	3	100
International bunkering to national consumption	–	–	152	438	–	–	15

Japan states it will apply the potential of technology innovations in electrification and hydrogenation.

The issue is that in order to introduce hydrogen as a new commercial energy carrier a complicated and extensive infrastructure along the whole hydrogen supply chain must be established, and many institutional and technical regulations should be introduced. Pointing out the importance of a holistic approach to complex energy issues at the consumer end:

> "The [Government of Japan] will increase the possibility of efficient, stable and decarbonizing distributed energy systems that consolidate in a compact manner electricity, thermal, and transportation systems being established locally under demand-side leadership by effectively combining the downsizing and efficiency improvements in renewable energy, technological innovations in storage batteries and fuel cell systems, and progress in digitalization technology and smart grid technology that make supply-demand control at the local level possible."

The Strategic Energy Plan does not exclude future introduction of biodiesel fuel "taking into consideration international trends", while natural gas is expected to be increasingly used as fuel in the transportation sector, including ships. However, the strategic goal is to increase the ratio of next-generation vehicles in production by 50–70% by 2030. Under next-generation technologies advanced batteries, FCs and hydrogen high-pressure tanks are considered. The Strategic Energy Plan incorporates the Basic Hydrogen Strategy, adopted in December 2017 (42). Pursuant to the latter, Japan will accelerate an expansion of demand for hydrogen in transportation, concentrating on FCEV for cars, buses and trucks. In the spring of 2016 the national-scale showcase for hydrogen driven transportation systems was declared for the Tokyo Olympics in 2020. It is considered as a landmark for the country: "The 1964 Tokyo Olympics left the Shinkansen high-speed train system as its legacy. The upcoming Olympics will leave a hydrogen society as its legacy", Yoichi Masuzoe, Tokyo Governor (43).

In March 2019 a hydrogen and fuel cell action plan was developed by the Government of Japan. It will coordinate and facilitate actions by industry, academia and government for hydrogen-related technology and infrastructure development up to 2030 (40, 44). While the primary object for hydrogen technologies in the transportation sector are road vehicles, the next step is expected in developing shipping applications (40).

The New Energy and Industrial Technology Development Organisation (NEDO) is a major actor, responsible for design and implementation of the national hydrogen programme under guidance of the Ministry of Economy, Trade and Industry (METI). The Council for Electrified Vehicle Society was inaugurated in July 2019, "aiming to establish a society in which low carbonization, dispersed energy sources, robust vehicles and energy are integrated" to proactively engage the Government of Japan, METI, car manufacturers, energy companies and municipalities "in efforts for taking advantage of xEVs" (45).

4.3 Major Recent Developments

At the beginning of 2018 there were 2926 FCEVs in Japan, including 18 commercial buses in Tokyo. The next milestones are 40,000 FCEV in 2020, 200,000 in 2025 and some 0.8 million in 2030. Projections for FCEV stock in 2050 vary between 8 million vehicles for the reference scenario, to an optimistic 16 million. The number of city buses and fork-lifts should grow to 1200 and 10,000 in 2020 and 2030, respectively. Japan had 108 HRS nationwide as of June 2019; the number of HRS is expected to reach 160 in 2020, and double in the next five years (40).

Toyota planned to roll out 100 hydrogen FC buses to shuttle visitors between venues at the 2020 Tokyo Olympic Games. Then, for the Beijing Winter Olympics in 2022, "more than 1,000 buses are planned in partnership with Beiqi Foton Motor Co which aims to make the most of a push by China to start adopting the zero-emissions technology". To date, "Toyota has sold fewer than 10,000 of the Mirai", a reflection of "insufficient refuelling stations [network], consumer worries about resale values and concerns over the risk of hydrogen explosions". However, the Japanese government "sees hydrogen as a key way to reduce its reliance on oil" (46). Japan's Toyota is expanding semi-truck manufacturing in the USA in cooperation with Kenworth, utilising an upscaled version of the hydrogen powertrain in Toyota's Mirai FC passenger car (47). The East Japan Railway Company tested its own version of a FC locomotive for the first time in 2017. In 2019, repeated tests were carried out with an improved version of the electric motor (48, 49).

5. South Korea

5.1 Energy Consumption and the Transportation Sector

While the energy supply of the transport sector in South Korea is 85% based on the consumption of petroleum products (**Table VIII**) (50), the passenger rail network is characterised by a high degree of electrification (51). Due to international bunkering activity in South Korea and the share of South Korea in global shipbuilding, implementation of low carbon technologies in marine transportation is an important driver for the country's energy policy.

South Korea's road fleet includes more than 23 million vehicles: 19.5 million cars and vans, 3.6 million trucks and 91,000 special vehicles. There are 53,071 EVs, 5890 PHEVs and 900 FCEVs in South Korea (4, 23, 52). Currently 18 HRS are operational in South Korea (53).

5.2 Institutions

As a technologically advanced economy and one of the world leaders in several energy-intensive industries, South Korea is facing the need to improve energy and environmental safety. Since 2008, the South Korean government has implemented a 'green society' policy.

In January 2019 the government announced the setting up of the development plan "Roadmap to Become the World Leader in the Hydrogen Economy" (54, 55). South Korean decarbonisation measures for the road transportation sector include several major options:

- significantly tighten the efficiency requirements for vehicles (the standards of fuel consumption for new car models in 2020 is raised to 24 km l^{-1})
- stimulating demand for environmentally friendly cars by subsidising the purchase of electric cars
- development of the public transportation network and shifting the bus fleet structure in favour of electric and hydrogen systems
- increase the number of charging stations for electric cars (56).

The plan includes such goals as:

- to adopt the national law on hydrogen energy in 2019
- to reach a cumulative fleet of 6.2 million FCEVs by 2040
- to increase the number of HRS to 1200 by 2040
- to develop a network of hydrogen taxis in 10 major cities, starting from a pilot project in 2019 with the aim to reach 80,000 cars by 2040.

5.3 Major Recent Developments

New partnership H2KOREA was established to improve coordination between government agencies and private business. Members of H2KOREA are governmental and administrative authorities (Ministry of Trade, Industry and Energy, town councils of Ulsan, Incheon and Daegu), research institutions (Institute for Advanced Engineering and Korea Research Institute of Standards and Science) and industrial companies (Hyundai, Hyosung and Doosan Fuel Cell Co Ltd). The main goals for H2KOREA are state support and participation in the formation of legislation in the field of hydrogen technologies (57).

Table VIII The Energy Consumption in Transportation Sector of South Korea in 2016 (6, 50)

Indicator	Gasoline, Mtoe	Diesel, Mtoe	Kerosene, Mtoe	Fuel oil, Mtoe	Gas, Mtoe	Electricity, Mtoe	Total, Mtoe
National transportation	9.9	17.9	1.2	0.2	5.0	0.2	34.4
Domestic air transport	–	–	1.2	–	–	–	1.2
Road	9.9	17.5	–	–	5.0	–	34.4
Rail	–	0.1	–	–	–	0.2	0.3
Inland waterways	–	0.3	–	0.2	–	–	0.5
International bunkering	–	1.2	4.9	9.3	–	–	15
Marine	–	1.2	–	9.3	–	–	10.6
Aviation	–	–	4.9	–	–	–	4.9
Share, %							
National demand	28	51	4	–	14	1	100
International bunkering to national consumption	–	7	400	5426	–	–	45

The sales of Hyundai's NEXO FCEV accelerated in 2019. While less than 1000 hydrogen cars had been sold annually since 2013, by May 2019 the cumulative number of sold vehicles since the start of 2019 had already exceeded this level (58).

In order to meet the government plans to purchase a total of 802 hydrogen buses for the police force by 2028, Hyundai Motor unveiled an upgraded version of a FC electric bus. A test-run of the vehicles will be conducted during 2020, and production will commence in 2021 (59).

Hydrogen powered drones are available for purchase in South Korea. It is announced that the drone's flight time is up to 110 min and the payload is up to 3 kg (60).

Samsung Heavy Industries became the first shipbuilder to develop a crude oil tanker powered by FCs. The oil-based power generators in the tanker are replaced by solid oxide fuel cell (SOFC) using LNG as fuel. "Being the first shipbuilder to secure this marine FC technology illustrates that Samsung Heavy is highly likely to lead the market," said Kyunghee KIM, Vice President of SHI International Corp, USA (61).

Hyundai announced key investments into three hydrogen companies to strengthen its leadership position in the global hydrogen FC ecosystem (62). South Korean Hyundai Motor Group is conducting research to create a hydrogen train; the completion of the project was announced for late 2020 (63).

6. Taiwan

6.1 Energy Consumption and the Transportation Sector

Taiwan has over 21 million vehicles, including 35,000 buses, 1.1 million trucks, 7 million cars and about 13.5 million motorcycles and scooters (64). The main fuel for road transport is petroleum products, and international bunkering for air and sea traffic overwhelmingly exceeded that of the national transport system (**Table IX**). Despite an almost complete absence of domestic shipbuilding, road vehicle and aviation manufacturing, there is plenty of room for efforts to shift energy demand in transportation from petroleum to natural gas, electricity and hydrogen, both for national and international transport systems.

6.2 Institutions

A new Taiwan government, formed in 2016, announced a course to strengthen the development of renewable energy and decarbonisation of transport with the widespread use of green technologies, including FC. There is no officially published energy strategy regarding renewable energy, with the exception of establishing the Taiwan Energy and Carbon Reduction Office in 2016. The main organisations responsible for shaping Taiwan's carbon-free transport policy are the Bureau of Energy, Ministry of Economic Affairs,

Table IX The Energy Consumption in Transportation Sector of Taiwan in 2016 (6)

Indicator	Gasoline, Mtoe	Diesel, Mtoe	Kerosene, Mtoe	Fuel oil, Mtoe	Gas, Mtoe	Electricity, Mtoe	Total, Mtoe
National transportation	8.1	4.0	0.1	0.1	–	0.1	12.5
Domestic air transport	–	–	0.1	–	–	–	0.1
Road	8.1	3.9	–	–	–	–	12.1
Rail	–	–	–	–	–	0.1	0.1
Inland waterways	–	0.1	–	0.1	–	–	0.2
International bunkering	–	0.1	3	1	–	–	4
Marine	–	0.1	–	1.2	–	–	1.3
Aviation	–	–	2.7	–	–	–	2.7
Share, %							
National demand	65	32	1	1	–	1	100
International bunkering to national consumption	–	2	2861	1281	–	–	32

Environmental Protection Administration, Taiwan Hydrogen Industrial Development Alliance and the Taiwan Power Company. However, the proposed plans for the development of carbon-free transport face serious bureaucratic obstacles, caused by the national monopoly's unwillingness to deal with new participants in the electricity market (65).

In 2017 a governmental programme to reduce transport taxes for low-carbon vehicles was adopted, focusing on private cars and scooters. According to this programme, a significant increase in ZEV by 2025 should be achieved by introducing 6000 vehicles and 150,000 motorcycles and mopeds running on lithium-ion batteries. The subsidy mechanism is under discussion to motivate domestic companies working in the sphere of carbon-free transport.

Given the high density of the urban population and the number of agglomerations, the authorities of large municipalities are inclined to road extension, rather than infrastructure development for electric and hydrogen vehicles.

In 2015 the Environmental Protection Administration presented a plan for the development of a comfortable and safe urban environment. In 2018, there were already 1800 electric charging stations, and the plan is to increase their number to 5000 units over the next 5–7 years (66). A choice of scooters as a main target of carbon-free technology development looks justified by its convenience for transportation in the warm climate, as well as Taiwan's dependency on imported road vehicles.

7. Conclusions

Improving energy security and reducing anthropogenic environmental impacts are strategic issues for the energy policies of industrial economies in East Asia: China, Japan, South Korea and Taiwan. The transport sector is of particular importance, since it is pivotal in efforts to relieve peaking oil demand, and is instrumental in decarbonising final energy consumers.

The East Asian economies' thirst for energy security is the most important driver for transport decarbonisation. The next driver is a commitment to combat climate change, as a number of binding regulations and government programmes aimed at reducing GHG emissions have been adopted. Additional policy drivers are the role of China, Japan and South Korea in the world's vehicle manufacturing and shipbuilding; as well as the size of the international ship and aircraft bunkering business in East Asia for passenger and cargo traffic.

There are considerable efforts within East Asian economies to develop policy towards low carbon energy supply infrastructure in general, and low carbon transportation systems in particular. The general trend is fuel substitution (petroleum to gas, internal combustion engine to more energy-efficient combinations of motor and powertrain) and electrification of transport vehicles, including advances in mobile energy systems, like hybrid and FC powertrains. The 'hydrogen society' concept combines renewable energy for green hydrogen production and its utilisation as the ultimate non-carbon fuel. While key hydrogen technologies have a wide range of applications in transportation, from tankers, locomotives and aircraft to hydrogen-driven monocycles, road transport applications are important at the commercialisation stage for a number of economic and technological reasons.

A scramble for capturing leading positions in the global ZEV market has become a distinctive feature of BEV, FCEV and hydrogen technologies development in the East Asian economies. They are at the forefront of the course to introduce hydrogen as new energy carrier, and it can be seen as the starting (icebreaking) position for transition of a petroleum-based transportation system into one ultimately independent from fossil energy. Japan, China and South Korea are already implementing regulation, energy institute transformation and transition from the pilot stage to the practical development of carbon-free mobility systems at a national level. Currently, the fundamentals for the competitive development of all low-carbon technologies have been created in East Asian economies in order to reduce the transport system's carbon footprint.

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"Graphene-Based Nanotechnologies for Energy and Environmental Applications"

Edited by Mohammad Jawaid (Universiti Putra Malaysia), Akil Ahmad (University of KwaZulu-Natal, South Africa) and David Lokhat (University of KwaZulu-Natal, South Africa), Micro and Nano Technologies Series, Elsevier, The Netherlands, 2019, 446 pages, ISBN: 9780128158111, £131.75, €159.16, US$170.00

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Introduction

The book titled "Graphene-Based Nanotechnologies for Energy and Environmental Applications", edited by Mohammad Jawaid, Akil Ahmad and David Lokhat, focuses on recent developments in graphene-based materials, composites and devices for a variety of applications in storage devices, supercapacitors, water treatment, ion-separation, photocatalysts and antimicrobial applications. It is part of the series Micro and Nano Technologies published by Elsevier. The first editor of the book, Mohammad Jawaid from the Universiti Putra Malaysia, has expertise in nanomaterials (particularly graphene materials) and their composites and has significant research output with a h-index of 53. The second editor, Akil Ahmad, currently a postdoctoral researcher at the University of KwaZulu-Natal, South Africa, has worked on nanomaterials synthesis and applications of nanomaterials in wastewater treatment. David Lokhat, the third editor of the book from the University of KwaZulu-Natal, has been working on reactor and extraction technologies.

The book is divided into three major parts: Introduction, Energy and Environment. Each category has many chapters written by diverse authors. A total of 59 authors from different affiliations contributed to the different chapters. Firstly, the introduction covers basic terminologies and definitions of nanotechnology, nanomaterials and provides specific literature background on graphene-based materials and their composites for energy and environmental applications. Ahmad *et al.* collected literature on graphene-based nanotechnologies, which covers the latest developments in graphene research around the world, and David Lokhat contributed towards energy and environmental applications leveraged by graphene derivatives along with publication statistics. Production methods, characterisation methods and properties of graphene and its applications in different areas are covered. The literature and data were collected and compiled from over 350 publications. Every chapter has a conclusion or concise summary with potential prospects for the future in each research or subject area.

Energy

Mamvura *et al*. (University of South Africa) have written a chapter on renewable energy systems using graphene derivatives. The chapter covers applications of graphene in battery-powered vehicles, fuel cells, solar cells and energy storage devices. Mohamed I. Fadlalla and Sundaram Ganesh Babu (University of Cape Town, South Africa) presented a chapter on graphene materials in photocatalytic water splitting for hydrogen production. Topics such as mono- or bi-semiconducting catalyst and metal and non-metal doped graphene-based photocatalysts for water splitting applications are covered. Umar *et al.* (Universiti Sains Malaysia) included topics on metal decorated graphene nanocomposites for energy storage applications. Their chapter is mainly focused on metal-based composites, solar and fuel cells, supercapacitors and lithium-ion batteries and mechanisms of energy conversions are covered in detail. A chapter on graphene oxide (GO) for hydrogen storage applications was written by Azim *et al*. (University of KwaZulu-Natal). Composites of GO and reduced GO with metal oxides, carbon nanotubes and organic materials and relevant fabrication methods are well elaborated in this chapter. Professor Mohammad *et al*. (King Saud University, Saudi Arabia) have contributed a chapter towards graphene-derived nanocomposites as supercapacitors and electrochemical cells. This chapter includes the synthesis (**Figure 1**) and physical properties of graphene nanosheets, a section on biosensors and a short note on supercapacitors produced from graphene nanocomposites. Jean Mulopo and Jibril Abdulsalam (University of the Witwatersrand, South Africa) have provided a chapter on graphene-based energy storage applications (capacitors, batteries, fuel cells and solar cells) with an emphasis on electrical and thermal conductivity, specific surface area and specific heat properties.

Overall, this section of the book with six chapters covers a wide range of electronic devices incorporating graphene and its derivatives. In-depth analysis and data have been included from a significant number of publications and research works. Topics on graphene composite as air filters, gas sensors, volatile sensors, liquid sensors, radiation sensors and pollutant sensors are adequately discussed in these chapters.

Environmental Applications

The section of the book begins with a chapter on graphene-based sensors for the detection of volatile organic compounds (VOCs) written by Ansari *et al*. (Aligarh Muslim University, India). Graphene with metal additives as sensors and their functioning mechanisms have been well discussed in this chapter. Haseen *et al*. (Aligarh Muslim University) concentrated on the application of magnetite-GO composite for wastewater treatment. This chapter covers magnetite-GO for specific dispersive solid-phase extraction. Mohamma Laskar and Sana Siddiqui (Jazan University, Saudi Arabia) focused on GO-based filters for solid-phase extractions, including nascent GO, chelates adsorbed GO, functionalised GO with external molecules and specific GO nanocomposites. GO functionalised with magnetic molecules and their composites with polymer or metal matrices have been extensively studied. Reduced GO (rGO) derivatives for such applications are also included.

A chapter by Kumar *et al*. (King Abdulaziz University, Saudi Arabia) covers graphene-metal oxide composite photocatalyst for degrading water pollution. Structure and property (chemical and physical) relationships and the effect of graphene's bandgap on photocatalytic decomposition are interpreted. The mechanism of photocatalysis for relevant graphene materials and metal-GO and rGO composites are included. Hussain *et al*.

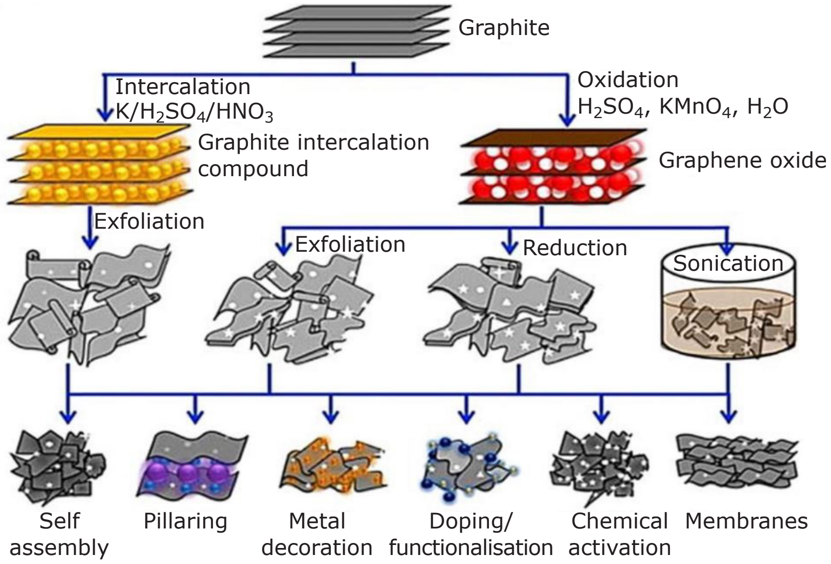


Fig. 1. Synthesis of graphene derivatives. Copyright (2019). Reprinted with permission from Elsevier

(Jubail Industrial College, Saudi Arabia) collated information on a new generation of GO for removal of polycyclic aromatic hydrocarbons from a wide range of literature and new results. The chapter covers several properties of graphene, such as mechanical, electrical and thermal properties and their influence on the interaction of polycyclic aromatic hydrocarbons as well as the role of GO as an adsorbent for such hydrocarbons. A chapter by Ng *et al*. (UCSI University, Malaysia) is dedicated to graphene-based membranes for separating hazardous contaminants in wastewater. This is probably the only chapter that gives importance to both polymer-based and metal-based graphene composites for the targeted application. Traditional thermoplastics (polystyrene, polyvinylidene fluoride, polyamide-imide, polyacrylonitrile and polyethersulfone) composites and conducting polymer (polyaniline)-based graphene composites are organised with their fabrication process and efficiency as a membrane in a descriptive manner.

Hossain *et al*. (Universiti Sains Malaysia) focused on antimicrobial activity of graphene-based materials. The antimicrobial mechanism of major graphene derivatives (GO, rGO and graphene) are discussed along with the performances of their composites with hydrogel and polymer dispersions. The effect of toxicity of graphene materials on antimicrobial activity adds to the value of this chapter. Graphene-metal oxide hybrid composites for treating textile dyes are discussed in a chapter by Shahadat *et al*. (Indian Institute of Technology, Delhi). This short chapter attempts to add to the knowledge of graphene-metal synthesis for removal of industrial dyes and provides details of the effects of functional groups (hydroxyl, carboxyl and oxygen) present in the composite systems on their performance. Reddy (Universiti Teknologi PETRONAS, Malaysia) and co-authors emphasised graphene nanomaterials for removal of pharmaceutical compounds in drinking water. The impacts of surface functional groups, sorption kinetics, pH and temperature on absorption stability of graphene-based materials and nanocomposites are discussed in detail. Research data on polymer-based, ceramics-based and metal-based composites are also covered in this chapter. Two chapters, by Yadav *et al*. (Shree Velagapudi Ramakrishna Memorial College, India) and Abbas *et al*. (Universiti Sains Malaysia), focus on the application of graphene composites in air quality and wastewater treatment. **Figure 2** depicts different applications in which graphene nanocomposites can be utilised.

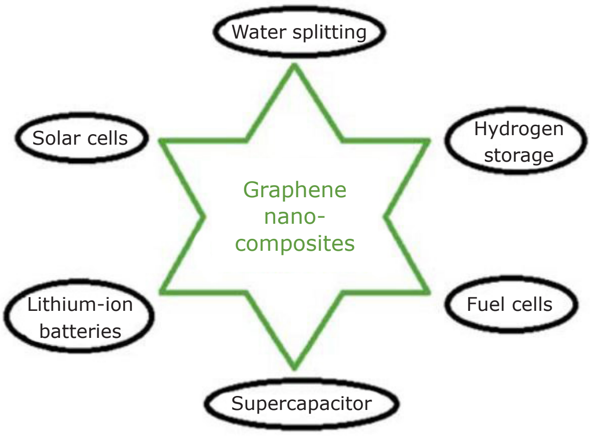
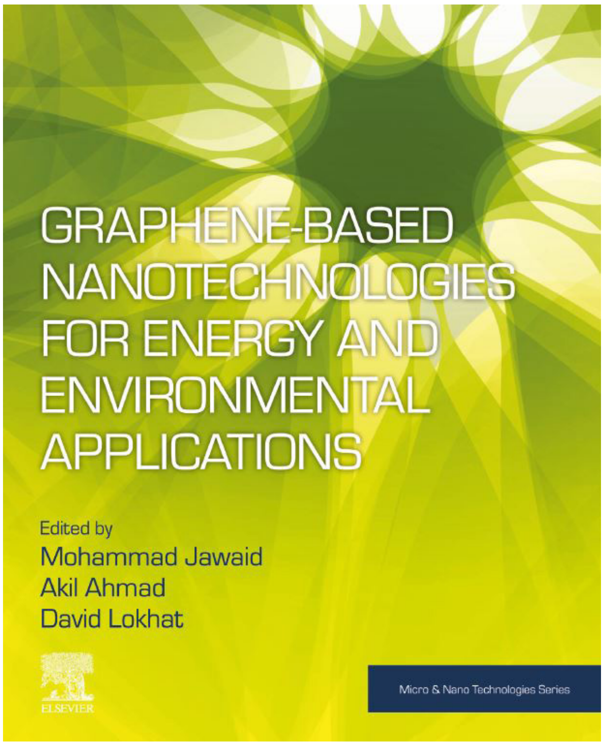


Fig. 2. Applications of graphene nanocomposites. Copyright (2019). Reprinted with permission from Elsevier

Conclusions

Each chapter provides solid knowledge in its prescribed subject matter, and they read and flow well. However, looking collectively, there are several duplications and repetitions found in the book, especially the synthesis of graphene and applications such as storage devices and water treatment. These chapters are written using different language, and the knowledge is not very diverse. Another major flaw of the book is that it has missed out on the latest developments in graphene-based polymer composites and their multifunctional applications in energy and environment, which is a significant subject area that is expected to be covered in a book like this. There is only one chapter (Chapter 15) that covers sufficient polymer-graphene composites in the removal of hazardous contaminants from wastewater. Other application areas related to energy and environment are completely neglected. Furthermore, while most chapters have excellent illustrative figures, a few chapters do not have a single figure. It is always better and more attractive to have figures to effectively convey scientific concepts and processes. The summary in each chapter is concise, and future prospects are given appropriately. The front cover, preface, table of contents, index and back cover are suitable and sufficient.

Summing up, this book provides useful knowledge predominantly in graphene-based materials for storage cells, sensory and wastewater treatment applications.



"Graphene-Based Nanotechnologies for Energy and Environmental Applications"

The Reviewer

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The Role of Zero and Low Carbon Hydrogen in Enabling the Energy Transition and the Path to Net Zero Greenhouse Gas Emissions

With global policies and demonstration projects hydrogen can play a role in a net zero future

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As public pressure to limit global warming continues to rise, governments, policy makers and regulators are looking for the most effective ways to achieve the target set by the Intergovernmental Panel on Climate Change (IPCC) to keep the global temperature increase to below 1.5°C above pre-industrial levels. This will require the world to move to net zero greenhouse gas (GHG) emissions by 2050, and numerous governments have committed to reach net zero by this date, or even earlier. It is widely recognised that achieving net zero at the state, country and regional levels will necessitate a systems-wide approach across all the major sources of GHG emissions, which include power generation, transport, industrial processes and heating. Land use is also critical with billions of trees needing to be planted and a change in the amount of meat eaten. There is a growing realisation that hydrogen has a vital role to play, particularly to decarbonise sectors and applications that are otherwise extremely difficult to abate, such as industrial processes, heavy duty freight movement, dispatchable power generation and heating applications. Hydrogen will also provide long-term (for instance seasonal) energy storage, enabling much greater uptake of renewable power generation, which itself is a key prerequisite of the clean energy transition. Hydrogen can play a role in the decarbonisation of all major segments, and this means it can facilitate cross-sector coupling, enabling the exploitation of synergies between different key parts of the economy. This article discusses the different production routes to low and zero carbon hydrogen, and its uses across numerous applications to minimise and eliminate carbon dioxide and GHG emissions, building a picture of the key role that hydrogen will play in the energy transition and the broader global move towards decarbonisation and climate stabilisation. An overview of some of the ongoing and planned demonstration projects will be presented, outlining the importance of such activities in providing confidence that the hydrogen approach is the right one for multiple geographies around the world and that there are technologies that are ready to be deployed today.

1. Introduction

The use of hydrogen is not new. Fuel cells were invented over 150 years ago and have been providing on-board power to space missions for over 50 years. Industry makes millions of tonnes of hydrogen every year, with its main uses (in pure and mixed forms) being: oil refining (33%), ammonia production (27%), methanol production (11%) and steel production *via* the direct reduction of iron ore (3%). Hydrogen is manufactured primarily from the conversion of natural gas (~75%) and coal (~20%), with 2% from electrolysis. The associated CO_2 emissions are of the same magnitude as those of the UK and Indonesia combined (1).

The urgent need to minimise and then eliminate CO_2 and other GHG emissions to avoid a climate catastrophe is driving new dialogue around ways to achieve this, and hydrogen is moving to the centre in many of these discussions. For example, the Committee on Climate Change (CCC), the UK Government's independent advisor on climate change, said in its net zero policy document that moving from the previous target of 80% GHG emissions reduction to the net zero target "changes hydrogen from being an option to an integral part of the strategy" (2).

This article will present an overview of some ongoing and planned demonstration projects, outlining the importance of such activities in providing confidence that the hydrogen approach is the right one for multiple geographies around the world and that there are technologies that are ready to be deployed today.

2. Net Zero Policies and Their Implications

The IPCC reported in November 2018 that global warming should be limited to 1.5°C (3), and they showed that this requires net CO_2 and GHG emissions to become zero by 2050. Achieving net zero by 2050 is going to be very challenging, both at the country and the worldwide level. While CO_2 emissions in the developed economies have generally either stabilised or started to drop, those in rapidly developing countries such as China and India are increasing significantly, as shown in **Figure 1**.

The global requirement for energy to drive industry, transportation, heating and cooking is also rising, placing further stress on efforts to limit global warming (5). Nevertheless, several national governments have set net zero targets, and some have already enshrined them in legislation (6, 7, 8). In the UK, the Department of Business, Energy and Industrial Strategy (BEIS) responded to the IPCC report by commissioning the CCC to review the implications of a net zero target, and to assess whether there was a credible pathway to achieve zero GHG emissions. The CCC's ground-breaking work outlined a bottom up approach to a total energy system decarbonisation, achieving net zero. On the back of this, the UK was the first of the G20 major global economies to legislate a net zero emissions target by 2050 when it updated the Climate Change Act early in 2020 (6). 15 other countries have now set net zero targets, including Sweden (2045), Denmark, France and New Zealand (all 2050) and several others (including Chile, Spain and the EU27, through the European Commission) are discussing the target and its timeline (9).

The implications of net zero are marked. In the past, those emissions most costly and difficult to abate could be left. However, net zero means that most sectors will have to become completely emission free. Furthermore, processes which offer negative emissions will become extremely important to offset areas such as aviation where a zero emission pathway will be extremely challenging for the foreseeable future. For example, the combustion of biomass with the capture and storage of the CO_2 generated is one route to negative emissions, as is the more well-known example of planting trees.

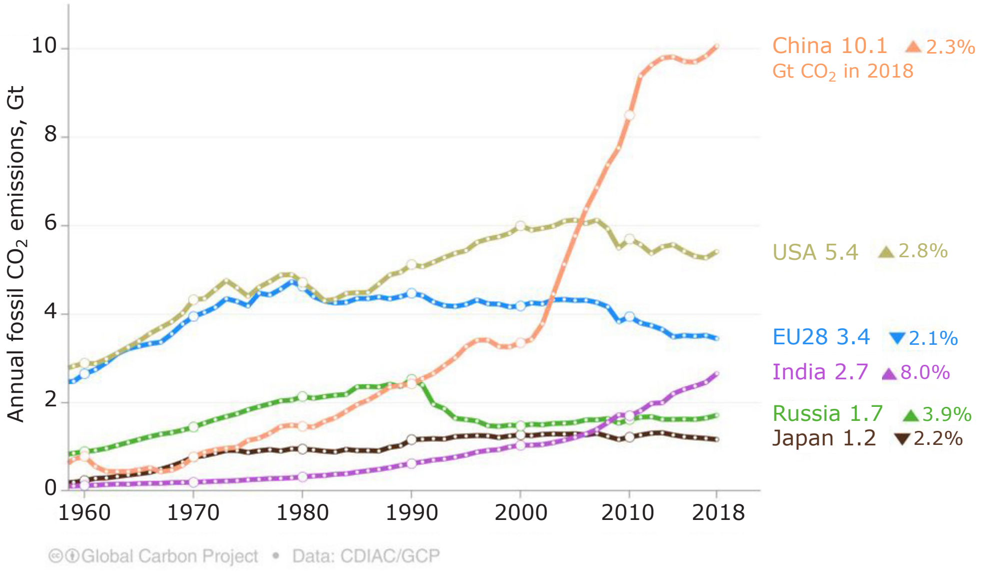

Fig. 1 Historical and projected annual CO_2 emissions from major countries and regions. Reprinted from (4) under a Creative Commons Attribution 4.0 International license

3. The Role of Hydrogen in Enabling Global Decarbonisation and Net Zero

Hydrogen is regarded as a flexible energy vector, and this section discusses its potential application in a number of key sectors: power generation (including energy storage), transportation, industrial and chemical processes and heating buildings (10). There are many divergent forecasts, as the appreciation of the role that hydrogen could play in reducing global emissions develops (2, 10, 11). However, many proposals require at least a tenfold increase in production of low carbon hydrogen over the fossil fuelled production today. As an example in 2017 the Hydrogen Council produced a report which described the scaling up of hydrogen out to 2050. The analysis showed a requirement for 78 exajoules (EJ) of low carbon hydrogen *versus* 10 EJ of fossil derived hydrogen today. The split proposed between different sectors was 9 EJ for power generation, 22 EJ for surface transport, 16 EJ for industrial energy, 11 EJ for building heat and power, 9 EJ of new process feedstocks and 10 EJ to convert existing feedstocks (10) to low carbon hydrogen.

3.1 Power Generation

One reason that hydrogen did not take off previously as part of global decarbonisation efforts was that there were other sectors with high CO_2 emissions that could be reduced more cost effectively. From a policy perspective it was easier and cheaper to focus on the power sector where large reductions in emissions have been achieved. For example, in the UK the carbon intensity of electricity generation was almost halved between 2013 and 2017 (12) by the removal of coal from the system and the deployment of high levels of renewables such as solar and wind as well as conversion of some coal to biomass. The relative return has been high as there was an existing infrastructure to plug these new generation sources into, which to date has been largely able to cope with the move from large centralised generation facilities to more distributed power generation (such as wind and solar). However, the existing system may struggle to run stably as the proportion of renewables increases further. For example, there was a major loss of power across several regions in the UK in August 2019 when the system lost stability, partially caused by loss of a large off-shore wind farm (13).

Increasing the renewable content in the power generation sector is a key lever in moves towards net zero across many sectors, and renewable energy now accounts for a third of global power capacity (2). In the UK, up to 40% of electricity generation comes from renewables today, including 20% from wind, 12% from biomass and 6% from solar (14, 15). This increasing trend will clearly continue, driven both by the needs to decarbonise the power generation sector, and by the continued reductions in the cost of wind and solar power installations. **Figure 2** shows the dramatic drop in the cost of utility scale solar, on-shore and off-shore wind power between 2012 and 2023 (17), showing how competitive renewables have become with fossil fuel power generation. A recent report from Bloomberg New Energy Finance (BNEF), USA, (18) states that from 2010 to the present day, there has

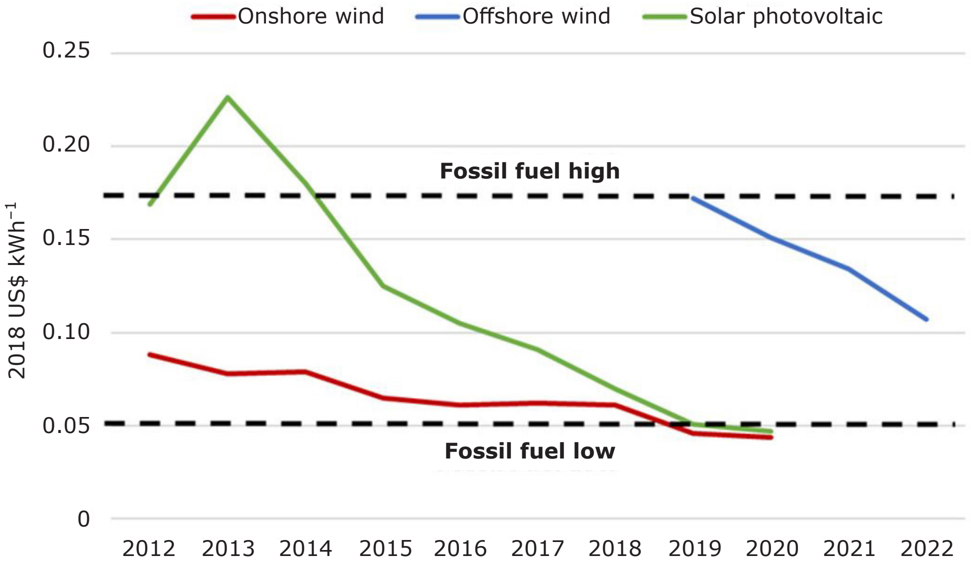

Fig. 2. Cost of generation for utility scale renewables and fossil fuels from 2012 to 2022 (16)

been an 85% reduction in the cost of solar power and a 49% reduction in the cost of wind power. Indeed, the BNEF report goes on to say that more than two thirds of the global population today live in countries where solar or wind, if not both, are the cheapest form of new electricity generation. By 2030, new wind and solar are forecast to get cheaper than running existing coal and gas plants almost everywhere, if the transmission system costs are ignored.

As well as the system stability challenges mentioned above, another concern with increased future reliance on renewables is how to maintain supply when the sun isn't shining and the wind isn't blowing. This introduces the need for large scale energy storage, with different storage and release timescales depending on location. For example, California and the UK have economies of comparable sizes, and have a similar total electricity demand, but the seasonal variation in energy demand is lower in California than in the UK, due to its more stable climate. In California, therefore, the main requirement is for short-term energy storage, storing excess solar energy during the day for use in the evening and overnight, so battery-based solutions make sense here. In the UK (and in large parts of Europe) there are massive seasonal demand fluctuations, so very large amounts of excess energy must be stored for much longer periods of time. In fact, as the proportion of renewables increases there will be a need for even more seasonal energy storage as the fossil fuel baseload has been reduced, which lends itself to a gas-based solution. Hydrogen will play a key role here since it can be generated from water through electrolysis using excess renewable energy (to make zero carbon hydrogen), as well as by advanced gas reforming with carbon capture utilisation and storage (CCUS) (to make low carbon hydrogen), as discussed later. Crucially, hydrogen is able to provide underground storage of a zero-carbon fuel at the multi-Terawatt hour (TWh) scale required for inter-seasonal energy storage. This underground hydrogen storage can be in depleted gas fields or salt caverns, depending on local geological conditions (19).

Turbine manufacturers are already turning their attention to hydrogen gas turbines. Most have a turbine capable of taking a blend of hydrogen and natural gas today and are working on 100% hydrogen turbines. In this way, hydrogen provides the required flexible, dispatchable power to compliment the growth in variable renewable generation.

3.2 Transportation

There is no doubt that many countries have made significant steps to decarbonise the power sector, but this is not the case for other sectors such as transport where emissions have increased over the past 10 years (20, 21). Even in Europe, where tailpipe CO_2 levels are regulated and where there is a strong drive to improve fuel efficiency (and reduce CO_2) to minimise fuel and vehicle taxation costs, the last two years have seen an increase in the average CO_2 emissions of new cars in the European fleet (see **Figure 3**). This has been partly driven by the reduction in sales of diesel vehicles (which are more fuel efficient than comparable

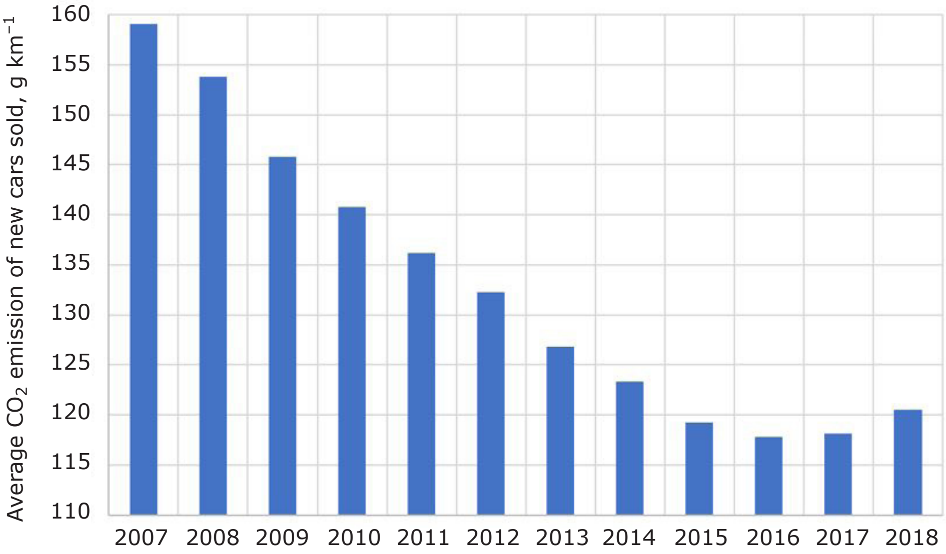

Fig. 3. Average CO_2 emission of new cars sold in Europe (22)

gasoline vehicles) and by the increase in sales of larger cars, such as sport utility vehicles (SUVs). Nevertheless, this trend is going in the wrong direction and needs to be reversed rapidly.

The two main routes towards net zero ground transportation are based on uptake of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). BEVs are already being sold in significant numbers and in the passenger car sector these will make up a large proportion of sales in a future, decarbonised world (22). However, there are transport applications where hydrogen fuel cells constitute a more suitable zero emission powertrain, such as in long haul trucking. Hydrogen (when pressurised in storage tanks) can have a much higher energy density than batteries and refuelling with hydrogen can be carried out in a similar timeframe to filling current fuel tanks, while the batteries required to meet the needs of long haul trucks would need to be very large, and therefore expensive and heavy, and require a long time to charge (23). Fuel cells also match the needs of cars covering large annual distances, where the long range and fast refuelling advantages make a compelling combination. In addition, fuel cell powered locomotives are starting to be introduced, and these could provide a cheaper route than electrification to decarbonise rail transport for branch lines (24).

Many governments (25) have developed strategies around the future use of hydrogen in transportation and have set targets on the uptake of FCEVs and the number of installed hydrogen refuelling stations (HRS) to provide their fuel. For example, the uptake of FCEVs is projected to increase massively in China, on the back of strong government policy and incentives. The government is planning to have over one million FCEVs in the vehicle fleet by 2030. Japan and South Korea are also strongly focused on developing into hydrogen economies, and part of this involves increased uptake of FCEVs in the transport sector, with concomitant HRS infrastructure development. As well as being driven by energy security considerations, this government focus on hydrogen also provides support and stimulus for large domestic original equipment manufacturers who are the leaders in global FCEV introduction: Toyota, Japan, and Hyundai, South Korea.

So fuel cells will work alongside batteries to play an important role in reducing the CO_2 footprint of ground transportation. Furthermore, FCEVs also have a battery, so there are some very direct synergies between the two technology approaches.

3.3 Industrial Heat and Feedstock for Chemical Processes

The main historical use of hydrogen has been in refineries to process crude fuels into refined fuels, to remove sulfur and as a feedstock for ammonia and methanol production (26). In future, these processes will need to be decarbonised further by moving to a low carbon hydrogen feedstock, but it is not a simple process as plant sizes are large and are heavily integrated. Retrofit opportunities are available, but they will often not decarbonise the processes in line with net zero targets.

New processes are being considered such as the use of electrolysis to provide hydrogen for ammonia production. Currently these are small prototypes and it is unclear at what point the economics of such a route could be considered competitive. Among others, ENGIE, France, and Yara International ASA, Norway, have announced a project in Western Australia (27) based on using solar power, however there are challenges in storing electricity or hydrogen to buffer for night-time as chemical plants do not like to be started up and shut down repeatedly.

With the move to net zero there has been a focus on heavy industry. Under the previous GHG reduction targets of 80%, it was recognised that heavy industry is hard to decarbonise and it would be likely that residual emissions would be left in certain sectors. However, net zero means that nearly all emissions need to be removed from the industrial sector as there are other areas that are even harder to decarbonise, such as aviation. The challenge for industry is it has few routes to decarbonisation since high temperature processes have historically used fossil fuels and conversion to electrification is not deemed technically or commercially feasible in many cases. Hydrogen is viewed as the most viable technical alternative and given the correct support to value the low carbon product could be the most economical solution.

The other major issue with industrial processes is the scale. Today a world scale methanol plant can produce 5000 tonnes per day (tpd) from fossil fuels, primarily natural gas and coal. To convert a single plant of this scale to using hydrogen produced by electrolysis would require power from more than 500 of the world's largest wind turbines (28). There are examples of plants (29) that can use renewable energy to generate hydrogen for production of methanol when combined with captured CO_2, but these are currently at much smaller scale than required for a world market of greater than 75 million tonnes per annum (30).

3.4 Heating Buildings

Recently heating is an area in focus particularly in the UK where currently 85% of domestic houses use natural gas. With a net zero ambition all heating must be fully decarbonised. Whilst electric heat pumps can be an efficient route and will play a part to low carbon heating (particularly in new housing stock), the uptake of this technology is low, so alternative solutions will be required and again hydrogen offers a number of advantages as it can be retrofitted into existing systems in the home (31).

The challenge posed by heating in the UK (and a number of countries worldwide) is that there is a marked seasonal variation in energy requirement through the year. An often-cited graph (**Figure 4**) demonstrates this well, showing the energy demand in the UK between 2015 and 2018 split between the different fuels. What is clear is that the UK relies heavily on gas to provide a secure and resilient energy system. Gas provides on average around three times more energy than electricity and at peak demand this can increase to more than five times more energy. The other stark feature of the graph is how constant the demand for electricity and transportation fuel are, whilst the demand for gas is very seasonal. The ability to store gas in large volumes and the infrastructure in place to deliver gas to the end user allows for the rapid response to changes in demand profile.

The proposal from the CCC for net zero requires the capacity of the electricity grid to double, both in terms of generation and transmission, to accommodate the large increase in BEVs. To date the UK has made great strides in decarbonising power, but realistically three to four times more renewable generating capacity is needed and network infrastructure to meet the new requirement before considering using large amounts of renewable electricity for heat or to make hydrogen to be used for heating. Therefore, it has widely been proposed to use low carbon hydrogen, manufactured from natural gas at large scale, to provide decarbonised heating. Initially this would be by blending hydrogen into the grid. In the future when the safety case has been proven there could be the move to 100% hydrogen in the UK's gas transmission and distribution system.

Again in the UK, the H21 report (32) has been instrumental in setting out a clear, rational plan to cover all requirements for a transition from natural gas to hydrogen, using Leeds as a test case. The proposal had four steam methane reformers produce hydrogen coupled with CCUS. The hydrogen is then distributed through the polyethylene piping that is rolling out across the gas distribution network. The domestic side would require burners to be changed (for example gas

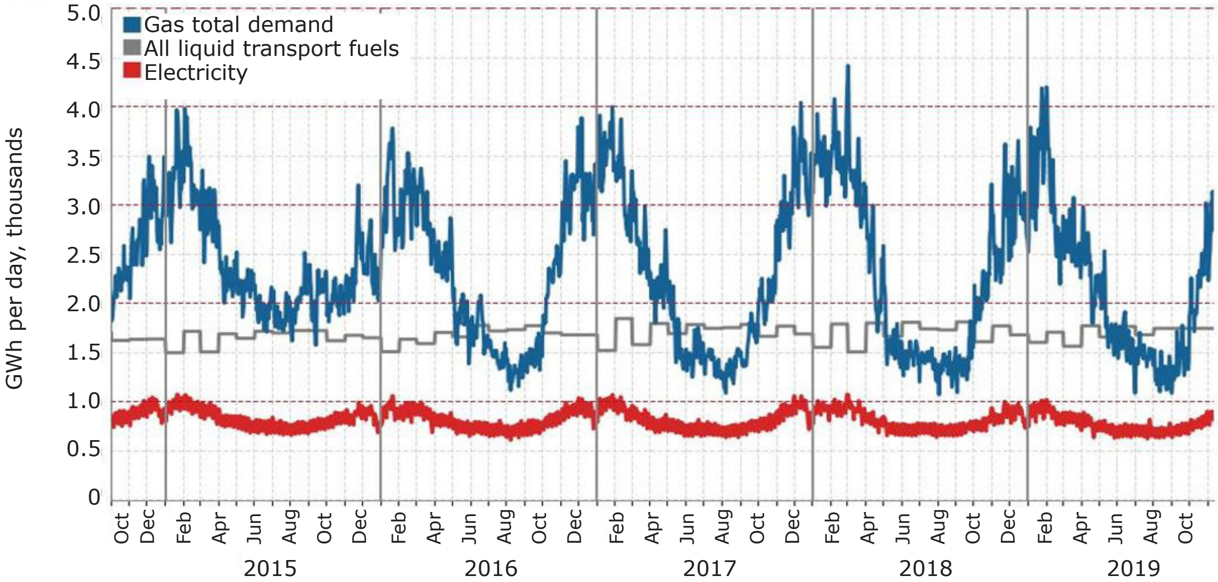

Fig. 4. Annual trends in the UK's daily use of energy for electricity, transport and gas. Data are from the National Grid, Elexon and BEIS. Charts are licensed under an Attribution-No Derivatives 4.0 International license. By Grant Wilson, University of Sheffield, UK

boilers, cooking hobs and ovens), but this was done in the 1960s when the UK transitioned from town gas (which contained around 50% hydrogen) to natural gas (which contains essentially no hydrogen) (33). A lot of attention has been paid to the H21 work as it gave a fully costed route using existing technology blocks with a scheme to roll it out across a real network by domain. The work was recently extended to cover the North East of England.

Trials are taking place in the UK at Keele University where an ITM Power electrolyser (ITM Power, UK) is blending hydrogen into the private university gas network. The project (34) is led by Cadent, UK, and it is funded by the Office of Gas and Electricity Markets (Ofgem) (£6.8 million). To cover the domestic use case BEIS has awarded (35) £25 million to a project managed by Arup, UK, called Hy4Heat. The UK is well placed as an iron gas main replacement programme (36) has been running for a number of years converting piping to polyethylene, which is a much better material for transporting hydrogen. Iron piping has issues with embrittlement when in contact with hydrogen, which would lead to safety issues. Other trials looking at 100% hydrogen in the gas grid under the H21 programme are being led by Northern Gas Networks, UK, which include research and development (R&D) as well as operational and maintenance considerations of conversion.

As mentioned above, one of the key considerations for heating is to be able to store large volumes of energy and distribute it across the country. In the next section we will consider how hydrogen can be made, stored and distributed.

4. Low and Zero Carbon Hydrogen Production, Storage and Distribution

While hydrogen can be produced through the electrolysis of water, most of the hydrogen produced today is manufactured by steam methane reforming (SMR), in which, at high temperatures, natural gas is converted to hydrogen and CO_2. As identified by the CCC, production of bulk low-cost, low carbon hydrogen from fossil resources is an integral part of meeting the UK's net zero obligations (and net zero targets around the world). It can also make a significant and important contribution to the UK's pressing 4th and 5th carbon budget shortfalls. The low cost aspect is important: at present the cost of manufacturing hydrogen by advanced gas reforming incorporating downstream CCUS (to ensure the hydrogen has a low carbon footprint) is around US\$1.50–2.80 kg^{-1}, while the cost of hydrogen from renewables is much higher, falling between US\$3.00–7.50 kg^{-1} (1). Hydrogen made from electrolysis using renewable electricity is regarded as zero carbon and is referred to as 'green' hydrogen, while that made *via* methane reforming with CCUS is regarded as low carbon and referred to as 'blue' hydrogen. While the end-point in a fully decarbonised ecosystem will be green hydrogen, the most cost effective way to integrate hydrogen broadly into a wide range of applications today (and for the foreseeable future in many parts of the world) is to use blue hydrogen. For example, the CCC's Net Zero report and roadmap predicts that the UK will require approximately 270 TWh of hydrogen in 2050 (up from around 15 TWh today), and they estimate that around 80% of this will be blue hydrogen, with the remaining 20% being green, as shown in **Figure 5** (2).

Before we discuss the routes to blue hydrogen, electrolysis will be outlined. Electrolysis uses electricity to split water into hydrogen and oxygen. This reaction takes place in an electrolyser, which like fuel cells consists of an anode and a cathode separated by an electrolyte. There are two commercially available technologies:

- Alkaline technology has been commercially available for many years. The electrolyte is a liquid alkaline solution of potassium hydroxide and materials like nickel, carbon-platinum, cobalt and iron are used for the electrodes. Alkaline is considered a well-known, lower risk technology, and generally has a lower capital cost than proton exchange membrane (PEM) but a higher operating cost (37)
- PEM technology is more recently commercialised. The electrolyte is a PEM, which allows diffusion of H^+ from one electrode to the other. One electrode is Pt and the other is iridium/iridium oxide. Ir/IrO_x is necessary because it can withstand the acidic conditions of the cell (many metals dissolve under these conditions) (38).

There are two other types of electrolyser at earlier technology readiness levels:

- Anion exchange membrane (AEM) is similar to PEM but anions diffuse through the electrolyte. AEM is expected to be as efficient and dynamic as PEM but membrane development is required for it to withstand the alkaline conditions (39)
- Solid oxide electrolysers run at high temperature (600–800°C) and could make use of waste heat or steam in industrial processes. Currently there are issues relating to the durability of the ceramic materials at high temperatures.

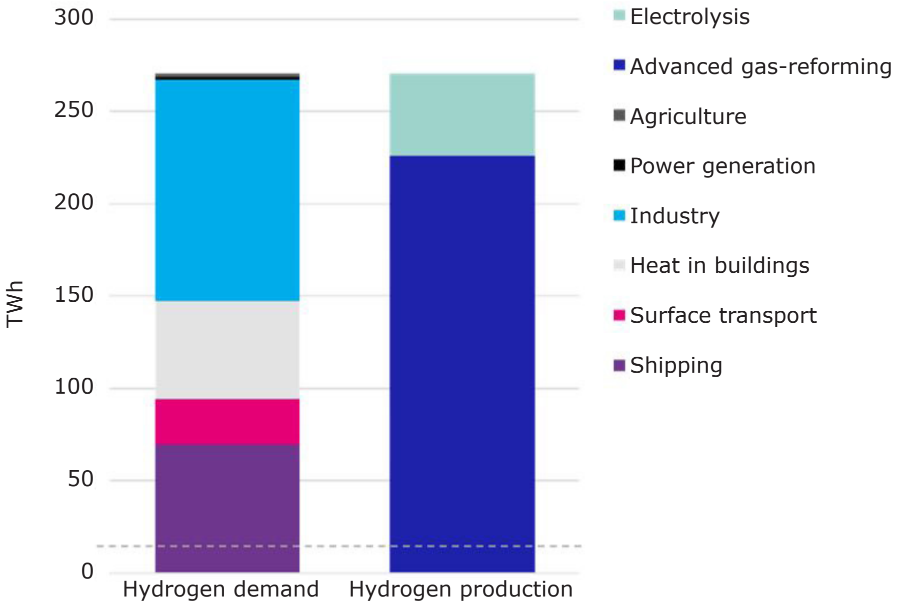

Fig. 5. Projected net zero UK demand for hydrogen in 2050, and the proportion generated by electrolysis (green hydrogen) and advanced gas reforming (blue hydrogen). Copyright (2019) Committee on Climate Change (2)

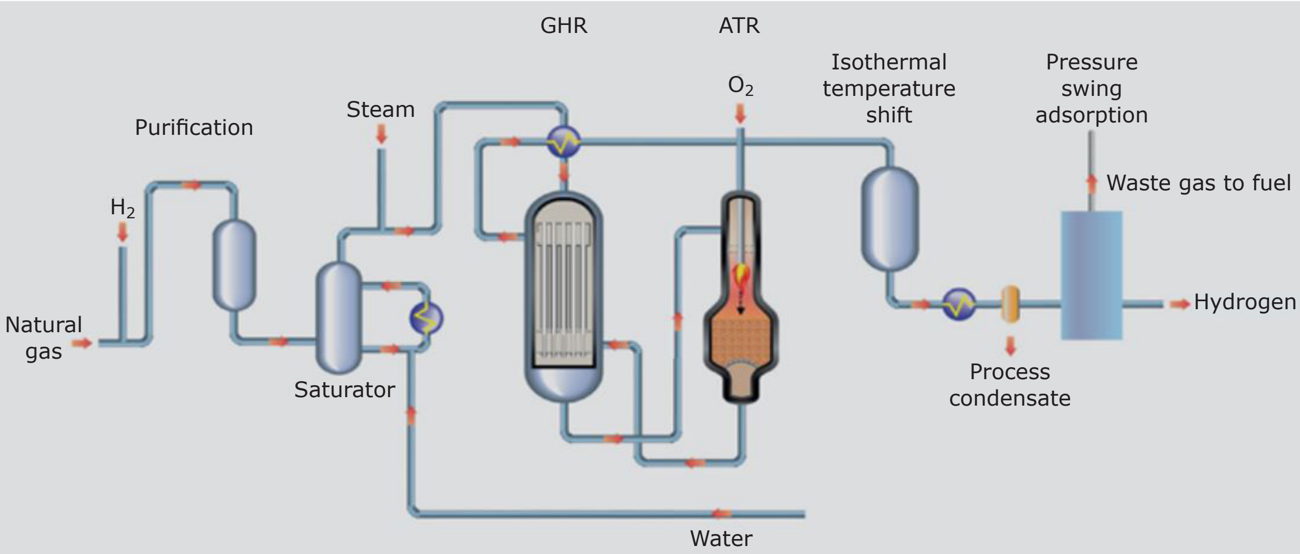

Fig. 6. The LCH^{TM} flowsheet

The topic of electrolysis will be revisited in the future as there are important advances required to enable large scale deployment. In the near term, as mentioned above, the consensus is that blue hydrogen will be key. Johnson Matthey, UK, has developed a process known as Low Carbon Hydrogen (LCH^{TM}), which has a gas heated reformer and autothermal reformer at its core to generate blue hydrogen from natural gas, shown in **Figure 6** (40). This approach gives a higher hydrogen yield and is more energy efficient than existing SMR technologies. And, crucially, this process is easier and cheaper to decarbonise through CCUS than an SMR. The process delivers a high CO_2 capture rate, high efficiency and low-cost solution, providing significant benefits compared with SMR and alternative autothermal reforming (ATR) technologies. The approach is based on established chemical process engineering, designed to operate at scale, enabling carbon reduction for industry, dispatchable power, domestic heating and transport.

The main benefits of the LCH™ technology compared to the current SMR technology with >95% CO_2 capture rates are:

- a cost-effective way of producing low carbon hydrogen with a CO_2 stream that is suitable for transport and geological storage
- the hydrogen product is of suitable quality and quantity to be used for a range of applications including domestic, industrial and, in the future, power generation and fuel cell vehicles
- high reliability and robustness in terms of the ramp rates and turndown capability which can match demand
- eliminates the cost issues associated with the SMR post-combustion CO_2 removal unit
- small plot plan allowing efficient utilisation of existing available area and option for installation of larger plants in case of increasing hydrogen demand.

A comparison of the process performance for LCH™ *versus* an SMR is shown in **Table I**, where the hydrogen production rate has been fixed and a minimum CO_2 capture rate of 95% has been required.

Overall, the LCH™ technology offers the UK and other countries a 'low regrets' way of moving towards a net zero scenario as all of the unit operations have been deployed at scale in other areas, such as in production of methanol and ammonia. Design work has confirmed that a single train is capable of producing 300 MW (lower heating value) of high purity hydrogen. Furthermore, work has been conducted that indicates that a 1.5 GW hydrogen plant could be built in a single train with a number of equipment items in parallel.

One of the major barriers to hydrogen deployment *versus* other renewable technologies has been the requirement to build new infrastructure immediately, particularly for generation and distribution to the various customers. Today much of the hydrogen market is dominated by captive supply where generation is next to use, for example hydrogen production for use at a refinery for upgrading transport fuels.

The view that hydrogen can be crucial to decarbonise multiple market sectors means that hydrogen production at scale will be required. It is envisaged that a hub and spoke model will work best, with centralised production facilities bearing the brunt of the load, supplemented by smaller production facilities operating away from large emissions centres. The clustering of existing industry, gas facilities (liquified natural gas, gas turbines), ports, major pipelines and intersections with hydrogen production and CCUS facilities represents the lowest cost route to net zero. The additional ability to reuse existing gas distribution networks in some countries will play a large role in reducing transport costs.

Before returning to examples of key UK projects it is worth discussing how energy is moved as this is one of the key infrastructure challenges to make a dramatic energy transition. Transportation and storage are costly elements of the value chain. At small scale distributed production will rely on local storage and distribution, for example tube trailers. At large scale the reuse of gas pipelines will allow

Table I Comparison of Process Performance and Total Capital Cost for a Steam Methane Reforming *versus* an LCH™ plant.

Parameter	Units	SMR flowsheet	LCH flowsheet
Natural gas as feed	$kNm^3\ h^{-1}$	39.74	38.31
Natural gas as fuel	$kNm^3\ h^{-1}$	5.36	0
Total natural gas	$kNm^3\ h^{-1}$	45.10	38.31
Natural gas energy[a]	MW	439	400
Hydrogen production	$kNm^3\ h^{-1}$	107.4	107.4
Hydrogen energy[a]	MW	322	322
Natural gas efficiency	%	73.3	80.6
CO_2 captured	$tonne\ h^{-1}$	83.7	76.3
CO_2 emitted	$tonne\ h^{-1}$	4.4	3.7
CO_2 captured	%	95.0	95.4
ISBL + OSBL[b] **CAPEX**	£, millions	261	159

[a] Energy is stated on a lower heating value basis

[b] Inside battery limits (ISBL), outside battery limits (OSBL), capital expenditure (CAPEX)

hydrogen to be moved around cost effectively and there are known and available solutions for storing hydrogen such as salt caverns. More capacity will be required to deal with the volumes of gas required, but this is not seen as a barrier for deployment.

There is another opportunity that hydrogen offers, which is to move renewable energy from where it can be generated at very low cost to where it can be monetised. There are areas of the world which have very good utilisation factors for renewables, but they are not near demand centres and the cost and practicality of a transmission system would not be viable. The focus has been on using hydrogen to transport the energy in a chemical bond. Different strategies are being considered, such as liquefication of hydrogen, synthesis of a hydrogen containing molecule (ammonia or methanol) that can be converted back to hydrogen or use of a carrier (liquid organic hydrogen carriers) where an organic molecule is hydrogenated and dehydrogenated. The main considerations are process efficiency, energy density, safety and whether there is existing infrastructure (41).

Extensive studies have been carried out and large-scale projects are now being initiated to demonstrate how low and zero carbon hydrogen can be manufactured at scale and integrated at a city-wide and regional level (42–45). In the UK, BEIS are currently engaged in supporting a number of studies covering the whole value chain to understand the current technology options and potential lowest cost solutions. The strategy is being developed as part of the Clean Growth Plan. In addition, since the announcement of the UK's Net Zero legislation there have been further funding streams announced, which are either live (Industrial Strategy Challenge Fund), under consultation (Industrial Energy Transformation Fund) or will be consulted on in 2020 (Low Carbon Hydrogen). However, this should only be considered as the tip of the iceberg. Of critical importance to the sustained roll out of low carbon hydrogen will be the business models that allow private investment, which improves the supply chain and increases scale ultimately driving down costs to the consumer.

Whilst no definitive policy changes have been made to date in the UK there has been much more focus on how the UK can lead in low carbon technologies and embed this at the heart of plans for clean growth. BEIS has responsibility for both the Clean Growth Plan and Industrial Strategy. It has recently been much more active in the hydrogen and CCUS space, considering production, transport and use. Another £33 million has been made available under the Hydrogen Supply Competition (HSC) focused on production (46).

5. Case Study: HyNet

The HyNet project comprises the development and deployment of a 100 kNm^3 h^{-1} (equivalent to 300 MW of hydrogen, lower heating value) hydrogen production and supply facility to be sited at Essar Oil's Stanlow refinery utilising Johnson Matthey's LCH^{TM} technology. It could represent one of the first deployments of a technology proven in other sectors to the production of clean hydrogen and will achieve this at scale, at higher efficiency than other reforming technologies and with a very high carbon capture rate. It therefore will deliver low cost, low carbon bulk hydrogen.

This plant is core to the North West HyNet project. It is not a theoretical plant design but one that meets the specific regional demands, delivered on a specific project site. It will provide a foundation reference design for replication through multiple lines in the North West, elsewhere in the UK and internationally. When associated with the HyNet CO_2 transport and storage infrastructure, this delivers low cost, low carbon hydrogen for key industrials alongside non-disruptive blending to over two million households as part of delivering a net zero industrial cluster in the region. A schematic of the concept is shown in **Figure 7**.

Having completed prefeasibility work under Phase 1 (47) of the BEIS HSC, the full front-end engineering design and wider operational, delivery, contracting and consenting programme is underway as part of Phase 2 of the HSC, which will deliver a shovel-ready project, providing the basis for a final investment decision. The project is being developed by a consortium of Johnson Matthey, as technology provider, SNC-Lavalin, Canada, as project delivery specialists, Essar Oil which owns the land, and led by project developer Progressive Energy, UK.

6. Case Study: Acorn

The Acorn Hydrogen Project, in North East Scotland (**Figure 8**) places advanced reforming technology at its core. The project will deliver a replicable process for cost-efficient hydrogen production based around natural gas, whilst capturing and sequestering climate changing CO_2 emissions.

By 2025, the plant could be the first operational clean hydrogen plant in Europe, enabled for early

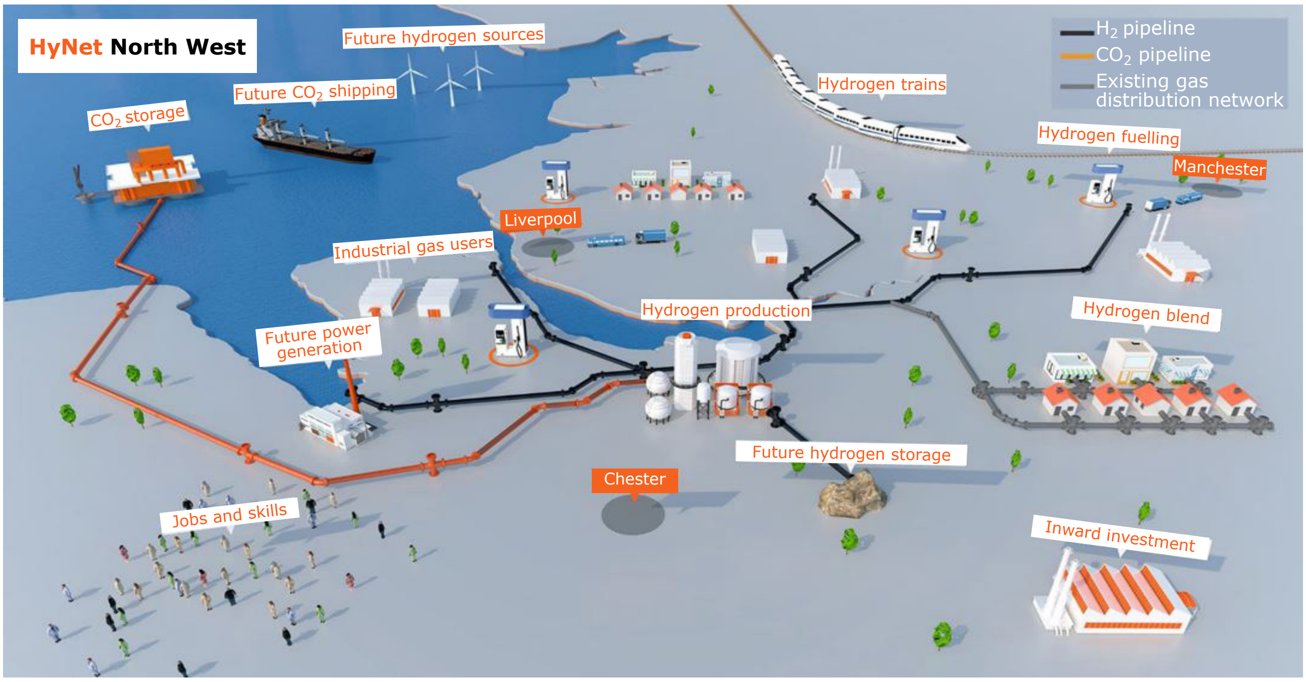

Fig. 7. A schematic of the HyNet project. Provided courtesy of HyNet

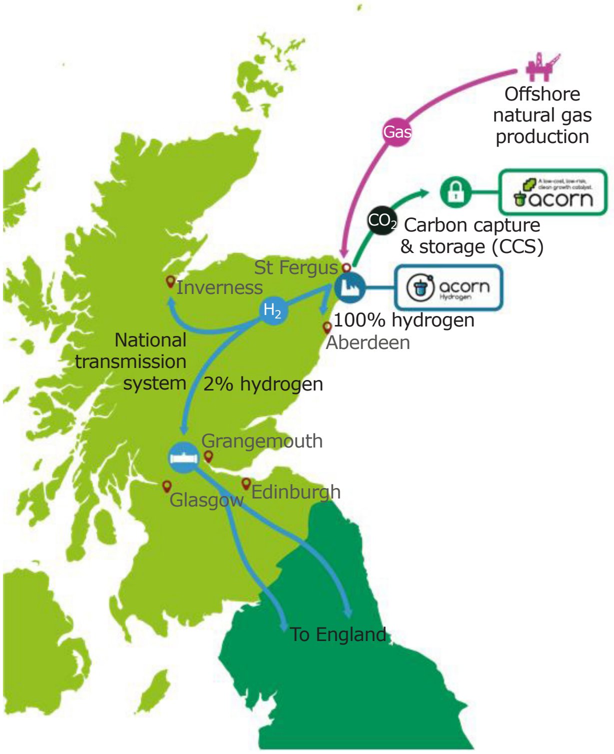

Fig. 8. A schematic of the Acorn project to be located in Scotland at St Fergus. Provided courtesy of Pale Blue Dot

development by the Acorn CCUS Project which is under development at the same location. North East Scotland is home to the oil, gas and renewables supply chain, which has the capability, capacity, technology and assets to diversify into a future hydrogen supply chain, creating economic value and jobs for the region and supporting a just transition to a low carbon economy. Clean hydrogen can be blended into the National Transmission System (NTS) and used in the region for decarbonising heat, industry and transport.

Phase 1 of the HSC delivered a feasibility study for an advanced reforming process at St Fergus (48). The basis of the study was export of hydrogen at a 2% by volume blend into the NTS. No technical issues were identified. Crucially, the work has also strengthened the partnering and route to market aspects of the Acorn Hydrogen Project.

The Acorn Hydrogen Project is led by Pale Blue Dot Energy, UK, and benefits from strong industry study partners in Shell, The Netherlands, Chrysaor, UK and Total, France, while Johnson Matthey will play a significant role in providing a hydrogen technology option for the project. Acorn Hydrogen offers Scotland and the UK the opportunity to capture up to 19 million tonnes CO_2 equivalents of CO_2 per year through the build-out, enabling the UK to reach its net zero obligations by 2050 and Scotland by 2045.

These are not the only projects that are being discussed in the UK. Recently announced, the Zero Carbon Humber (49) project brings together Equinor, Norway, Drax, UK and National Grid, UK with a vision to cut the emissions from the largest UK hotspot and again has hydrogen at the core. Johnson Matthey is also involved in a project called Cavendish (50) looking to produce low carbon hydrogen at the Isle of Grain, which would provide decarbonised dispatchable power to service London as well as providing a decarbonised gas for domestic heating.

It should be noted that this is not purely a UK opportunity as shown by the projects being discussed in The Netherlands, H-Vision project (51) at the Port of Rotterdam as well as Magnum (52), which is the conversion of a natural gas combined cycle gas turbine (CCGT) to hydrogen. The recently published US Hydrogen Roadmap (53) also discusses routes to hydrogen and sees a role for low carbon hydrogen production from natural gas.

7. Conclusions and Recommendation

Low carbon hydrogen has the potential to play a large role in supporting the journey to net zero. Projects should be deployed in the next 10 years to learn the real costs of operation and stimulate the supply chain. It will take time to build the volume of hydrogen production and the infrastructure for hydrogen use in all the sectors discussed above. There is always the question of balancing supply and demand, but with the many potential use cases building capacity will be a key starting point. Hydrogen produced by electrolysis powered by renewables is the ultimate answer and efforts need to be developed and scaled up, but it will struggle to deploy at the scale required in many locations in the near term. Both routes to low carbon hydrogen will be needed and they should be seen as complimentary with a transition happening over time.

Acknowledgements and Declaration of Interests

The author declares the following interests. Johnson Matthey is a consortium member in the HyNet project; an industry partner in Acorn Hydrogen Project; and a supporter of Cavendish project. The author represents Johnson Matthey on the Hydrogen Council Working Board, the Decarbonised Gas Alliance, the CCUS Advisory Group and is on the Advisory Board of the new cross sector publication H_2 View.

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Sam French currently works in Business Development at Johnson Matthey, leading the development of the strategy and the programme for Low Carbon Hydrogen. Previous roles at Johnson Matthey include Technology Manager for the steam reforming catalyst and technology research and development (R&D) team. After moving from R&D into Business Development, he was tasked with developing a portfolio of new opportunities for processes from new feedstocks, such as biomass, waste and renewable energy. Sam represents Johnson Matthey on the Hydrogen Council Working Board, the Decarbonised Gas Alliance, the CCUS Advisory Group and is on the Advisory Board of the new cross sector publication H_2 View.

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Johnson Matthey Highlights

A selection of recent publications by Johnson Matthey R&D staff and collaborators

Exploring Fuel Cell Cathode Materials using *ab initio* High Throughput Calculations and Validation using Carbon Supported Pt Alloy Catalysts

M. Sarwar, J. L. Gavartin, A. Martinez Bonastre, S. Garcia Lopez, D. Thompsett, S. C. Ball, A. Krzystala, G. Goldbeck and S. A. French, *Phys. Chem. Chem. Phys.*, 2020, **22**, (10), 5902

The ORR activity and stability of elements (M) and platinum alloys (Pt_3M) was determined using a combined DFT and experimental approach. Carbon-supported alloy nanoparticles were measured within MEA environments, providing validation for the calculations. The reliability of descriptors and the stability of alloy surfaces under different adsorbate environments was assessed. It was predicted that segregation of M to the surface is likely under an oxygen atmosphere. Correlation was shown between the amount of base metal leached in the C-supported catalysts and the calculation segregation energies. Good correlation was also observed between computed O adsorption energies and ORR activity.

Isotopic Studies for Tracking Biogenic Carbon during Co-processing of Biomass and Vacuum Gas Oil

C. Mukarakate, K. Orton, Y. Kim, S. Dell'Orco, C. A. Farberow, S. Kim, M. J. Watson, R. M. Baldwin and K. A. Magrini, *ACS Sustain. Chem. Eng.*, 2020, **8**, (7), 2652

With the aim of tracking biogenic carbon in FCC units, ^{13}C-labelled biomass was co-processed with vacuum gas oil (VGO) in both a Johnson Matthey zeolite catalyst (CP758) and an equilibrium catalyst (E-Cat). Biogenic C was shown to integrate into alkenes and aromatic hydrocarbons in both catalysts. It was also detected in cycloalkanes during experiments with E-Cat, however biogenic C was not observed in linear alkanes. Unexpectedly, small amounts of C from VGO were found in several partially deoxygenated biomass compounds. The work recognises the importance of utilising both biomass- and fossil-derived feeds in catalyst development. It also provides an understanding of reaction mechanisms for co-processing bio-oil and VGO.

Thermal Runaway of a Li-Ion Battery Studied by Combined ARC and Multi-Length Scale X-ray CT

D. Patel, J. B. Robinson, S. Ball, D. J. L. Brett and P. R. Shearing, *J. Electrochem. Soc.*, 2020, **167**, (9), 090511

The key characteristics of thermal failure in a commercial lithium-ion battery were identified with the use of accelerating rate calorimetry (ARC). The effects of thermal failure on the electrode materials were then analysed using X-ray CT and SEM. Gas generation at elevated temperatures (>200ºC) led to mechanical deformations in the cell architecture and the cathode particles reduced in size by a factor of two due to thermal runaway conditions. Surface deposits were detected on both cathode and anode materials. The relationship between heat generation within a cell during failure and electrode microstructure was analysed. The work has implications for the optimisation of electrode designs for safer battery materials.

Sized-Controlled ZIF-8 Nanoparticle Synthesis from Recycled Mother Liquors: Environmental Impact Assessment

M. García-Palacín, J. I. Martínez, L. Paseta, A. Deacon, T. Johnson, M. Malankowska, C. Téllez and J. Coronas, *ACS Sustain. Chem. Eng.*, 2020, **8**, (7), 2973

NaOH or NH_4OH were used to synthesise ZIF-8 nanocrystals from recycled mother liquors (**Figure 1**). Thermal stability, surface area, morphology and crystallinity were investigated. LCA was also implemented to examine the environmental effects associated with the product. The phase purity and nanometre size particles of the obtained ZIF-8 were considered when assessing the suitability of the synthesis methodology through different characterisation methods. The process was deemed sustainable, as the amount of solvent required for washing was significantly lower and phase pure ZIF-8 was obtained.

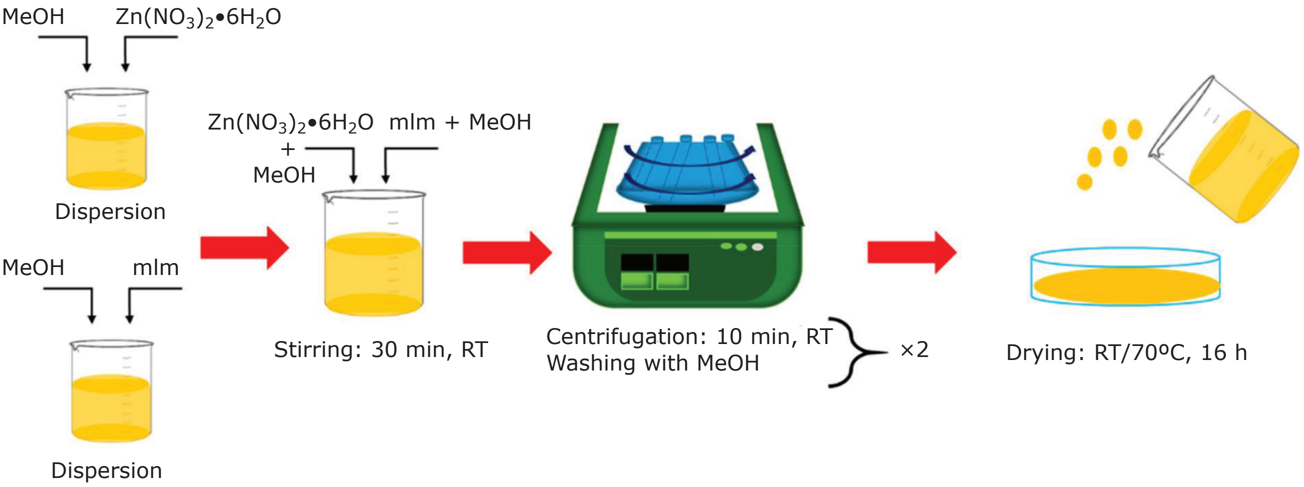

Fig. 1. Synthesis of ZIF-8. Reproduced with permission from M. García-Palacín et al., *ACS Sustain. Chem. Eng.*, 2020, **8**, (7), 2973. Further permissions related to the material should be directed to the ACS

New CCL|MPL Architecture Reducing Interfacial Gaps and Enhancing PEM Fuel Cell Performance

L. Daniel, A. Bonakdarpour, J. Sharman and D. P. Wilkinson, *Fuel Cells*, 2020, **20**, (2), 224

A novel architecture for fuel cell MEAs was presented to enable the reduction of gaps at the cathode catalyst layer (CCL) surface. This was achieved by deposition of the microporous layer (MPL) directly onto the catalyst coated membrane (CCM). Low temperature sintering of the MPL with the CCM was accomplished using a low bonding temperature Teflon. The altered structure improved electronic contact and minimised water pooling at the CCL|MPL interface, thus enhancing PEMFC performance. The water management improvements are of particular importance for thinner CCLs to achieve performance demand with low cathode catalyst loading MEAs.

Numerical and Experimental Studies of Gas Flow in a Particulate Filter

J. D. Cooper, L. Liu, N. P. Ramskill, T. C. Watling, A. P. E. York, E. H. Stitt, A. J. Sederman and L. F. Gladden, *Chem. Eng. Sci.*, 2019, **209**, 115179

Experimental measurements from MRI imaging were used to validate predicted gas flow fields in wall-flow particulate filters from one-dimensional (1D) and 3D numerical models. Through-wall and gas axial velocity were calculated at six flow rates and evaluated against predictions from a recent 1D model and an open source 3D CFD code. The 3D model outperformed the 1D model at high flow rates, however both models demonstrated good agreement at low flow rates. The 3D CFD predictions of gas velocity were validated and the calculated parameters were compared with existing literature correlations. With the correct descriptors, the 1D model velocity predictions were coincident with the 3D CFD predictions.

Investigation of the Oxygen Storage Capacity Behaviour of Three Way Catalysts Using Spatio-Temporal Analysis

C. Coney, C. Hardacre, K. Morgan, N. Artioli, A. P. E. York, P. Millington, A. Kolpin and A. Goguet, *Appl. Catal. B: Environ.*, 2019, **258**, 117918

Temperature profiles and gaseous species inside the channels of a commercial three-way monolith catalyst were investigated with *in situ* spatiotemporal mapping. This was achieved with the development of a transient lean-rich switching method alongside the spatially resolved capillary inlet MS (SpaciMS) technique. Carbon monoxide oxidation was used as a probe reaction. Reaction sequences in the monolith catalyst were clarified by the SpaciMS technique. The 3%Pd/Al_2O_3 catalyst demonstrated excess OSC-like behaviour, something previously unseen. The water gas shift reaction was shown to be insufficient to account for the excess CO conversion. It was hypothesised that, under rich conditions, a $Pd(OH)_x$ surface species was acting in the same way as an oxygen storage component.

Efficient Non-dissociative Activation of Dinitrogen to Ammonia over Lithium-Promoted Ruthenium Nanoparticles at Low Pressure

J. Zheng, F. Liao, S. Wu, G. Jones, T.-Y. Chen, J. Fellowes, T. Sudmeier, I. J. McPherson, I. Wilkinson and S. C. E. Tsang, *Angew. Chem. Int. Ed.*, 2019, **58**, (48), 17335

A suitable catalyst has yet to be developed to decentralise ammonia synthesis for energy storage or fertiliser production without carbon emissions. It is widely known that Ru catalysts are promoted by heavier alkali dopants. However in this study, and despite its poor electron donating ability, Li demonstrated the highest rate through surface polarisation. Due to this excellent promotion rate, Ru-Li catalysts were shown to be suitable for ammonia synthesis, surpassing industrial Fe counterparts by 195-fold. Further investigations revealed new insights in activating N_2 by metallic catalysts. It was demonstrated that Ru-Li catalysts hydrogenate end-on adsorbed N_2 stabilised by Li^+ on Ru terrace sites to ammonia in a stepwise manner.

Understanding the Dynamics of Fluorescence Emission during Zeolite Detemplation Using Time Resolved Photoluminescence Spectroscopy

N. Omori, A. G. Greenaway, M. Sarwar, P. Collier, G. Valentini, A. M. Beale and A. Candeo, *J. Phys. Chem. C*, 2020, **124**, (1), 531

Time resolved photoluminescence spectroscopy (TRPS) was used to characterise photoluminescence (PL) arising from synthesised chabazite framework zeolites at three separate phases of the detemplation process. Within a zeolite framework, the steric confinement effects of organic structure directing agents (OSDAs) were demonstrated using temporal resolution. A signature region for determining the presence of the template was established. Gated spectra comparisons between uncalcined and partially calcined zeolites revealed the presence of the template together with template-derived combustion products. TRPS had the capacity to track depletion of OSDA and establish a characteristic PL spectrum for a clean zeolite, and the sensitivity to show residual organic material remained in a zeolite after an extended thermal detemplation process.

Interstitial Boron Atoms in the Palladium Lattice of an Industrial Type of Nanocatalyst: Properties and Structural Modifications

T. Chen, I. Ellis, T. J. N. Hooper, E. Liberti, L. Ye, B. T. W. Lo, C. O'Leary, A. A. Sheader, G. T. Martinez, L. Jones, P.-L. Ho, P. Zhao, J. Cookson, P. T. Bishop, P. Chater, J. V. Hanna, P. Nellist and S. C. E. Tsang, *J. Am. Chem. Soc.*, 2019, **141**, (50), 19616

B atom properties, positions and structural modifications to the Pd lattice of an industrial interstitial B doped Pd nanoparticle catalyst system were studied using a combination of techniques. Short-range disorder was introduced with B incorporation into the Pd lattice, however the overall fcc lattice was maintained. Different types of structural disorder and strain were shown to be introduced into the nanoparticle history, and these distortions contributed to the appearance of local HCP structured material in localised regions. The characterisation of industrial metal nanocatalysts provides important guidance to the structure-activity relationship of the system and this was achieved by using new toolsets across length scales from macro- to microanalysis.

Electrochemical Measurement of Intrinsic Oxygen Reduction Reaction Activity at High Current Densities as a Function of Particle Size for $Pt_{4-x}Co_x/C$ ($x = 0, 1, 3$) Catalysts

C. Zalitis, A. Kucernak, X. Lin and J. Sharman, *ACS Catal.*, 2020, **10**, (7), 4361

The performance of a range of catalysts with the initial composition $Pt_{4-x}Co_x/C$ was compared using a newly developed electrochemical technique. The current densities for the Pt/C catalysts were shown to increase by up to 80-fold when moving from the typical 0.9 V to 0.65 V. As demonstrated using a kinetic model, at low current densities (~0.9 V *vs.* RHE) the dealloyed catalysts had greater mass activity while at high current densities (~0.65 V *vs.* RHE) they were no longer as active as 2.1 nm particle Pt catalysts. The study predicted that a catalyst composed of 3.8 nm $CoPt@Pt_{1ML}$ particles at 0.65 V would have optimum mass activity performance.

Spatially-Resolved Investigation of the Water Inhibition of Methane Oxidation Over Palladium

C. Coney, C. Stere, P. Millington, A. Raj, S. Wilkinson, M. Caracotsios, G. McCullough, C. Hardacre, K. Morgan, D. Thompsett and A. Goguet, *Catal. Sci. Technol.*, 2020, **10**, (6), 1858

SpaciMS and steady state furnace temperatures of 400–450ºC were used to assess the spatial effects of temperature and 0–10% H_2O feed concentrations on complete methane oxidation reactions on a $3\%Pd/Al_2O_3$ wash-coated monolith. Within a central monolith channel, 12 sets of experimental profiles were obtained and used to screen a series of postulated global kinetic models. With the aim of improving confidence in parameter estimation, a 1D heterogenous single channel reactor model was incorporated. A number of global kinetic models were hypothesised and the Akaike information criterion (AIC) was used to differentiate between them. The best statistical fit was a newly derived two site model.

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Johnson Matthey Technol. Rev., 2020, **64**, (3), 374–392

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Evolution in the Engine Room: A Review of Technologies to Deliver Decarbonised, Sustainable Shipping

Technology options for the shipping sector to meet international ship emissions limits

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One of the more evocative cases of disruptive innovation is how steam powered vessels displaced sailing ships in the 19th century. Independent of wind and currents, shipping entered a new age. Faster shipping enabled more efficient trading and easier international travel. It fuelled economic growth and wealth creation. This transition was not rapid, taking half a century to evolve, a period in which hybrid vessels, those using sails and steam generated power were a common sight. The age of steam brought a period of change which affected many aspects of shipping, not only its appearance and practices but also its environmental impact. It facilitated further disruption and the emergence of what has become the industry standard for a 'prime mover': the diesel engine. Achieving the decarbonisation of the shipping fleet as soon as possible this century will be one of the most significant disruptions the shipping sector has had to manage. Meaningful change by 2050 requires strategic development and decisive action today, made all the more complicated by the immediate demands that the sector manages both the current and longer term impact that the COVID-19 pandemic will have on the shipping industry. This paper looks briefly at the transition from wind power to carbon based fuel power to gain insight into how the shipping sector manages disruptive change. It also reviews some technology options the shipping sector could adopt to reduce its environmental impact to meet a timetable of international requirements on ship emissions limits. The paper will focus on how the engine room might evolve with changes in: (i) energy conversion, how power is generated on board, i.e. the engine; and (ii) energy storage, i.e. choice of fuel.

1. Introduction

International shipping is the lifeblood of the global economy, with over 90% of world trade carried by sea (**Figure 1**). It is the most efficient and economical (and in many cases the only practical) means of delivering goods across the world, but its sheer scale means that maritime transport is highly polluting. Powered by residual oil, shipping is responsible for a quarter of global nitrogen oxides (NOx) emissions (1, 2) and accounts for about 1 billion tonnes of combustion carbon dioxide emissions (3, 4) (greater than Germany's and more than double those attributable to the UK).

Via the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI (6), the International Maritime Organization (IMO) has established rules that limit emissions of pollutants such as NOx and sulfur oxides (SOx) (7). In recent years these have required changes to engine room design and vessel operation. It has forced operators to consider carefully their fuel requirements and whether their vessels need emissions control equipment. More recently the IMO has set medium- and longer-term goals to reduce the carbon intensity of the shipping sector (8) and this looks set to revolutionise shipping. It has already stimulated a growing interest in alternative approaches to powering the world's shipping fleet.

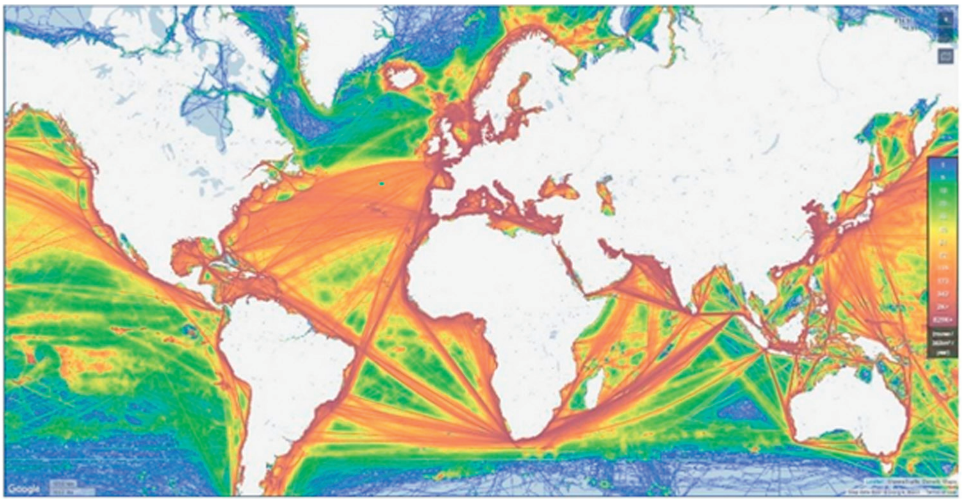

Fig. 1. Global shipping lanes (5)

To achieve improved efficiency and better environmental performance the shipping sector has a range of options and strategies to pursue. These include optimised or alternatives to some shipping fundamentals such as propeller design, vessel design (9), assisted propulsion and the use of specialist hull coatings. Their effectiveness and cost will vary, a function of the technology, the vessel type and its charter.

Two of the most effective means of controlling emissions remain the choices of engine and fuel. To allow for non-conventional technologies that are in early stages of study or deployment we will use more general terms, energy conversion for the means of energy transformation (for example, combustion engine or fuel cell) that is used to propel the vessel and energy storage for the source of this energy (for example, fuel or battery).

Shipping has entered a transition state during which many technology options will be tested on board against key metrics such as safety, technical capability, economic performance and environmental impact. With the current regulation requirement incumbent technology and its analogues will be challenged to deliver improved performance with greater versatility. In the long term meeting the demands of very low emissions is likely to require quite different technology. This is expected to take a long time, acknowledging the typical lifetime of a vessel, the maturity of low emissions technology and the fact that the sector has not witnessed such a disrupting force for over a century, when on-board steam generated power challenged the long-established wind powered sailing fleet.

2. The Development of On-Board Power

Maritime trade has developed over many thousands of years. The earliest cargo vessels were single logs with attached shipment that floated downstream. About 5000 years ago some of the earliest trade routes had been established along the Arabian Sea. The Roman empire was (in part), established and maintained though development of its shipping fleet, for conquest, transport and trade. In the medieval period, the Arab Empire established efficient trade routes through Asia, Africa and Europe, helped by significant innovation in vessel development. During this period, remarkable designs emerged that set standards and influenced shipping for centuries. The caravel vessels that crossed the Atlantic to the New World in the 15th century could trace their lineage through incremental innovations on the medieval *qarib*. During the Age of Discovery from the 15th–19th centuries, there were advances in both ship building and navigation that opened up major global trade routes.

2.1 Steam Power

In 1818, the SS *Savannah* was built with a steam engine powering paddlewheels on each side of the vessel. As an insurance the *Savannah* also had sails and in 1819, it became the first steamship to cross the North Atlantic Ocean, a voyage that took about a month (10). Sails were used for most of the voyage. The *Savannah* was a successful pioneer but there were no rapid followers in the fleet. It took a further 20 years before steam ships

Innovation Case Study: The Carbon Age of Shipping

The sailing ships' centuries of dominance were challenged by steam power in the early 19th century (**Figure 2**). Prone to breakdowns and occasional explosions, early steam vessels were deemed neither safe nor reliable enough for challenging, long distance travel such as transatlantic voyages. They found a niche application with river and lake transportation where their ability to travel independently of the wind conditions was a distinct advantage. With growing experience safety issues were addressed and reliability improved sufficiently to allow transatlantic service. Disruptive innovation (12) refers to situations where new technology is introduced to a market that offers similar capabilities to existing offerings, but with some disadvantages that make it less desirable, for example stage of development, reliability or cost; but with at least one distinctive advantage that allows it to find a niche, survive and grow. In this niche, the technology innovation can accelerate at a faster pace than the incumbent. In some cases, this eventually leads to the mass market adopting the new technology, sometimes *via* a hybrid phase where both new and incumbent technologies are on board.

As the safety and reliability of steam technology improved, early steam vessels began venturing further afield. On long haul charters they ran with sails partly as an insurance and partly as it was difficult to carry enough coal or water for these voyages. On 4th April 1838 the SS *Sirius* left Cork in Ireland and 18 days 4 hours and 22 minutes later reached New York, becoming (one of) the first vessels (13) powered by continuous steam to cross the Atlantic from Europe to North America, establishing the age of on-board combustion power (**Figure 3**).

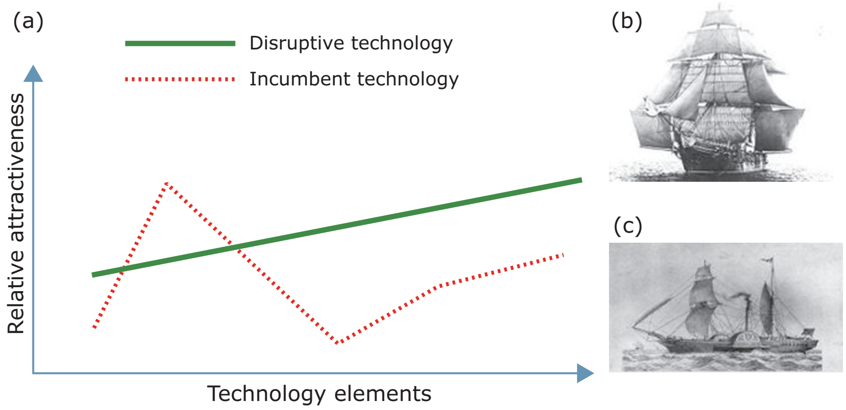

Fig. 2. (a) Relative attractiveness and technology elements of disruptive technology (steam power) *vs.* incumbent technology (sail power) in early 19th century shipping; (b) 19th century sailing vessel; (c) sidewheel steamship

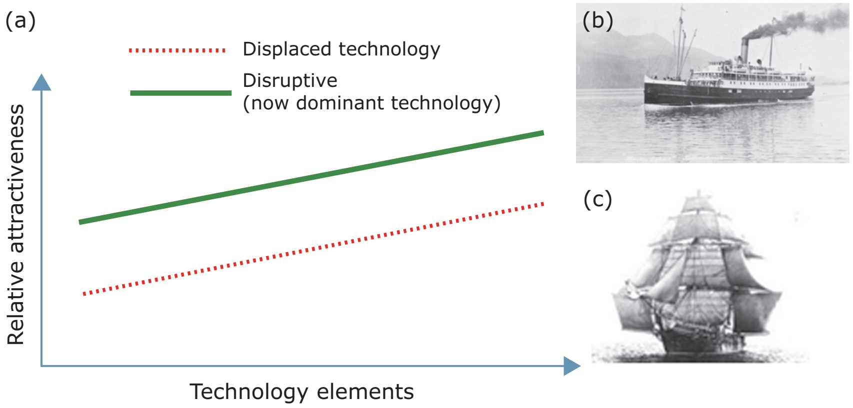

Fig. 3. (a) Relative attractiveness and technology elements when a disruptive technology (steam power) became dominant over the incumbent technology (sail power); (b) early 20th century steamship; (c) 19th century sailing vessel

made regular transatlantic crossings. Progress was slow but sure and no longer dependent on winds and ocean currents typical journey times fell significantly (by 50% or more).

Steam power evolved to use fuel oil and boilers to generate steam and finds niche application even to this day, for example in liquefied natural gas (LNG) carriers and navy vessels (using nuclear power). Early steam ships suffered their own significant problems. The coal bunkers took up precious cargo space. The operation of a furnace required significant manpower and combustible coal and coal dust meant the vessels were more vulnerable to catastrophic fires. These concerns over safety and efficiency set the challenge for further innovation and the emergence of an on-board solution that, in time, addressed many of the concerns: the diesel-fuelled internal combustion engine (ICE).

2.2 The Internal Combustion Engine

The ICE was introduced in the early 1900s, when British shipbuilding was at its peak. An early adopter of the technology was the Doxford Yard on the Wear in Sunderland. Doxford's four-cylinder engine (11) combined efficiency with simplicity of operation and soon found wide adoption. This and similar engines offered the benefit of better revenue generation through more effective use of space (as the fuel did not require the same volume storage as coal) and cost savings, for example requiring less manpower to operate. They also offered a greater range between refuelling stops. The large two stroke (2T) engine became the standard for international shipping but innovation continued generally in response to specific sector needs.

2.3 Diesel Electric

Diesel electric generators produce electricity that drives an electric motor unit that turns the propeller shaft or other propulsion devices. Diesel electric systems occupy less space than the two-stroke diesel engine equivalent and as it dispenses with the need for auxiliary power it also allows the weight in the hull to be more evenly distributed. Diesel electric technology also emerged in the early 1900s but for most of that century found niche application. Advances in alternating current drive technology have facilitated wider adoption of the central power station on board that efficiently manages both propulsion and other power requirements. It is particularly useful in applications where dynamic positioning is required and those where propulsion is one of many power demands, for example drilling vessels.

2.4 Co-Evolution of Engine with Fuel Oil

Critical to the development of on-board power was the symbiotic relationship between the diesel engine and fuel. As vessels changed and the engine room evolved, one of the critical factors in this was the way the shipping sector adapted to the availability of cheaper fuel, the heavy residual of the refinery. Ship engines were specifically designed and modified to be powered by heavy fuel oil (HFO). HFO has a tar like rheology and contains high levels of sulfur (~3%) and other residual components such as heavy metals. Its physical chemistry means that HFO must be heated to allow it to flow and it is combusted at high temperatures that produce significant levels of NOx. The fuel borne sulfur is emitted as SOx. A typical fuel intake for a large two-stroke diesel engine and its indicative emissions are illustrated in **Figure 4**.

The diesel engine brought many benefits and became the workhorse of shipping, but success had a dark side: a rapidly growing and unsustainable environmental impact. By the 1990s there was growing pressure to address this and as shipping was a global industry it needed to be addressed at a global level.

3. Limiting Emissions from Shipping: Regulatory Approach

The IMO is the United Nations specialised agency with responsibility for the prevention of marine and atmospheric pollution by ships and prefers to govern by consensus, *via* a process of discussion and agreement. In this spirt it organises meetings to gather many of the interested parties including nation state representatives, industry groups and other non-governmental organisations (NGOs) to discuss and agree how to address environmental concerns. It seeks to balance the (economic) concerns of the industry with environmental concerns. This is not an easy task and in practice can result in a protracted process taking many years to reach an outcome.

The pressure for shipping to address its expanding environmental wake has seen some progressive

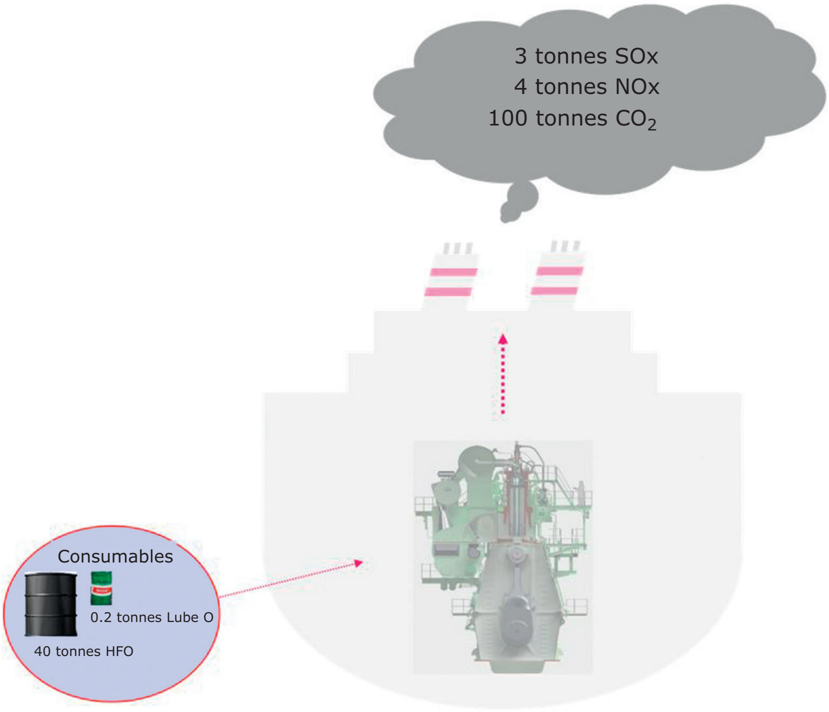

Fig. 4. Schematic of a large ship engine (MAN B&W L70MC engine) (14). Illustration courtesy: MAN Energy Solutions. A large ship engine (~10 MW) can consume up to 40 tonnes of HFO fuel and over 200 kg of lubrication oil ('lube o') per day. Typical daily emissions of CO_2 are of the order of 100 tonnes, over 3 tonnes of SOx and 4 tonnes of NOx. Emissions of CO, particulate matter and unburned fuel are also significant (of the order of 100 kg each per day)

steps taken on emissions, especially those from new build vessels. New emission rules are signalled well in advance of enforcement dates to allow the sector to plan and adjust, minimising the economic cost of the change. This can lead to unintended consequences, exemplified in the IMO III rules for NOx. Agreed in 2008 and coming into force in 2016 for new build vessels operating in NOx Emission Control Areas (NECAs), the rules were expected to reduce the NOx emissions in these areas (15). In 2019 it was reported that very few port calls used Tier III compliant vessels. Since the new rules only applied to new build vessels it allowed operators to legitimately use older (more polluting) vessels to enter NECAs. This anomaly will correct itself in time, but it will take a decade or more, many decades from the initial discussions to lower NOx emissions.

It raises questions about a process that takes many decades to take effect when both environmental NGOs and progressive member states are looking for more rapid results from policy decisions. The aspiration of the consensus model of governance, even in complex multiparty problems, is to deliver a balanced outcome that all parties support. The outcome does not satisfy every party with some disagreement recorded over the timing, applicability and availability of technology (16, 17). It can also mean that there is little appetite and limited possibility to revisit, review and revise after a brief period of 'real world' experience and evaluation (18).

After many years of discussing the sector approach to local pollutants and air pollution (chiefly NOx and SOx) the IMO focus has moved to another side effect of on-board power: greenhouse gas (GHG) and CO_2 emissions (19, 20).

3.2 Carbon Dioxide and Greenhouse Gases

In order to address emissions of CO_2 from the shipping sector the IMO developed the Energy Efficiency Design Index (EEDI) which is mandatory for new vessels and the Ship Energy Efficiency Management Plan (SEEMP) for all vessels (21). The EEDI is intended to stimulate accelerated innovation in the sector as it mandates the use of more energy efficient (less polluting) equipment to meet minimum energy efficiency standards on a per capacity distance basis (for example, tonne kilometre). In addition, it requires a progressive improvement on a five-year basis (10% in the first phase). It is a non-prescriptive, performance-based mechanism and uses a mathematical formula based on the technical design parameters for a given ship (Equation (i), (22)).

$$\mathrm{EEDI}\left(\frac{\mathrm{gCO_2}}{\mathrm{tonne^{-1}\ mile^{-1}}}\right) = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}{}^{*}\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}{}^{**}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}} \quad \text{(i)}$$

It leaves the choice of technologies in a specific ship design to the industry. The EEDI has been developed for the largest and most energy intensive segments of the merchant fleet and currently covers 72% of emissions from new ships including oil tankers, bulk carriers, gas carriers, general cargo, container ships, refrigerated cargo and combination carriers. For ship types not covered by the current formula, appropriate equations are being developed. The SEEMP establishes a mechanism to improve the energy efficiency of the existing fleet in a cost-effective manner. It allows shipping companies to manage ship and fleet efficiency over time by monitoring performance, using tools such as the Energy Efficiency Operational Indicator (EEOI). It is intended that SEEMP will incorporate best practice for fuel efficient ship operation, as well as guidelines for voluntary use of the EEOI for new and existing ships. In this way, at each stage, the ship owner or operator is encouraged to consider new technologies and practices as they optimise vessel performance.

In April 2018 the IMO took steps to clarify the intended outcome of its policy measures, announcing its GHG strategy with a vision to phase out GHG emissions as soon as possible this century. It outlined three ambitions:

a. Use the EEDI to reduce the carbon intensity of individual vessels
b. Reduce the CO_2 emissions per unit of transport work by at least 40% by 2030, targeting 70% reduction by 2050 (based on 2008 emissions)
c. Reduce annual GHG emissions by at least 50% by 2050 (2008 basis) on a pathway to CO_2 emissions reduction consistent with the Paris agreement.

This is a progressive agenda, especially given that trade and thus shipping is expected to grow significantly in the next few decades (creating a potential emissions gap) as illustrated in **Figure 5**.

The IMO recognises that delivery on this objective needs considerable support stating that: "technological innovation and the global introduction of alternative fuels and/or energy sources for international shipping will be integral to achieve the overall ambition". In so doing the sector has recognised the key elements of technology strategy required to meet these targets. Meeting the three main options for reducing GHG emissions in shipping the sector will seek:

a. To improve vessel design
b. To use more efficient on-board powertrains
c. To substitute fossil fuels either directly with low-carbon biofuels or low or zero-carbon electricity, or indirectly by using low or zero-carbon electricity to produce hydrocarbon or carbon-free fuels (power-to-X, e-fuels).

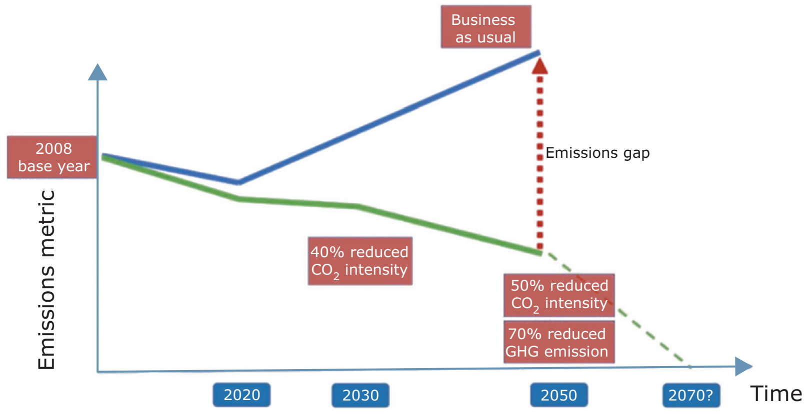

Fig. 5. Schematic summarising the IMO CO_2 and GHG strategy. Source: DNV GL

4. Meeting Emission Requirements: Industry Options

To achieve the very low emissions required by 2040 and 2050 the engine or energy converter and the energy store (fuel type) will play an important role. Improvements can be tracked and monitored in several ways. One is to focus on the vessel as a system and point source and look at the impact it has on its environment i.e. a 'tank-to-propeller' analysis (23, 24). A more complete analysis also considers the supply chain, referred to as 'well-to-wake' analysis (25). Here the more holistic approach considers emissions associated (with land based activity) with aspects such as fuel manufacturing or production, storage and use, so that the wider aspects of emissions are measured, addressed and reduced. Some regulatory approaches allow for greater operator choice and versatility in approach by placing the emphasis on reducing emissions on a fleet (rather than a vessel) basis.

The well-to-wake analysis links the drive to decarbonise shipping with that of decarbonisation of power generation and transportation on land. Some in the shipping community argue that it would be more sensible and effective if efforts to decarbonise were focussed on other related sectors in energy and transportation where there might be a lower opportunity cost and higher return on effort, but a consensus has aligned around the message that shipping must play its part in a transition to a decarbonised world (26).

5. Propulsion in the Future

In order to meet significant reductions in GHG (CO_2, methane, nitrous oxide) it is the energy source and the energy conversion (and the interplay between them) that offer the greatest potential for impact. In the next sections we look at the main options that have emerged to help the shipping sector plot a course for decarbonisation.

6. The Energy Source

Figure 6 shows a number of energy source options available for shipping. This section will present the benefits and concerns for each.

6.1 Heavy Fuel Oil

Today, HFO and intermediate oils based on HFO (blended with distillate fuel) are the fuels of choice for international shipping. With well-developed supply chains and familiarity in operation, HFO has the benefit of incumbency and ready supply. It has advantages in cost as well as power density.

The fact that it is a carbon based fossil fuel will lead to a phase out of HFO in the longer term (50–70 years) (28, 29) but more immediate concerns over its detrimental impact on the local environment (SOx emissions) may effect more rapid change. Operators face a restricting uncertainty with respect to these sulfur containing fuels. As recently as January 2020 70% of fuels sold in Singapore, the world's largest bunkering hub, were

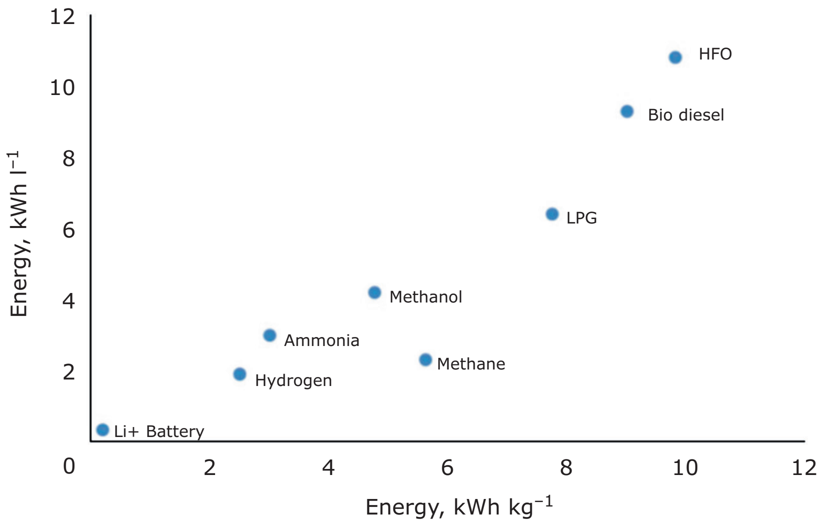

Fig. 6. Energy and energy density of alternative shipping fuels. Adapted from Royal Society policy briefing document on sustainable transport (27)

low sulfur (30). The IMO and US Environmental Protection Agency (EPA) rules allow for vessels to use HFO so long as the emissions are treated (with an on-board SOx scrubber) to meet compliance; however a growing number of regions, for example port authorities, have banned the use of the most popular 'open loop' scrubbers (31). This has raised a significant question over future demand of higher sulfur fuels and may accelerate adoptions of cleaner alternatives, i.e. cleaner, lower sulfur fuel such as marine gas oil (MGO).

- **Benefits of HFO**: incumbency, experience, economics and energy density
- **Concerns of HFO**: in the short term, local pollution (NOx, particulate matter, SOx/SO_3^{2-}). Over the longer term GHG from hydrocarbon combustion (CO_2 emissions), availability (if demand falls).

6.2 Marine Gas Oil

MGO is a distillate fuel with lower sulfur content (1000 ppm). MGO is similar to diesel fuel but has a higher density. It has found application in medium to high speed engines. Unlike HFO, MGO does not have to be heated during storage. MGO and diesel fuels are cleaner with lower (though still significant) emissions of local pollutants compared to HFO. They are more expensive than the HFO based fuels and do not allow significant steps toward decarbonisation. Carbon based fuels such as biodiesels offer potential towards decarbonisation.

- **Benefits of MGO:** experience and energy density (cleaner than HFO)
- **Concerns of MGO:** short term significant local pollution (NOx, particulate matter, SOx/SO_3^{2-}). Longer term, GHG from hydrocarbon combustion (CO_2 emissions).

6.3 Biofuel

Biofuels such as biodiesel, bio-methane, bio-methanol and hydrogenated vegetable oil are derived from biological waste in sectors such as agriculture, forestry and farming, or from dedicated biofuel crops. Depending on the type of biofuel used, they can achieve CO_2 reductions of up to 90% (32). However in 2018, less than 1% of the fuel supply in shipping made use of biofuel (33), with the few initiatives operational mostly involving inland or short-sea shipping. A recent report suggests around 11% of fuels sold at one large port are blended with at least some biofuel (34). A major problem with biofuels for shipping remains their cost but concerns over their sustainability have underlined the requirement that those used for shipping must be advanced generation biofuel (35). Even with advanced generation biofuels, demand from other applications will restrict an already limited availability for the shipping sector.

- **Benefits of biofuel**: potential for lower GHG emissions (well-to-wake)
- **Concerns of biofuel**: high cost, availability, local pollution (NOx, particulate matter). Hydrocarbon fuel producing point source GHG CO_2 emissions (tank-to-propeller).

6.4 Liquefied Natural Gas

Other carbon-based fuels that allow a step towards lower carbon propulsion include natural gas. Over the last 20 years there has been a significant strategic effort in developing LNG as a marine fuel. Today hundreds of LNG powered vessels are in operation, representing 2100 engines with about 30 million hours operational experience (36). Some LNG powered vessels are mono-fuelled, but most are dual fuelled. This fleet is supported by a fuelling infrastructure that is established and expanding. LNG is available (or planned) in virtually all the major ports. The commercial viability of LNG vessels is supported by a growing order book across most vessel types. Most if not all vessels that are LNG powered are fully compliant with existing legislation for SOx and NOx emissions (providing the engines operate in their preferred lean burn mode). LNG engines have very low emissions of particulate matter and in lean burn mode can also claim higher CO_2 efficiencies. Supporters of the technology report CO_2 emission reductions of 7–21% on a well-to-wake basis, and up to 28% on a tank-to-propeller analysis (25). The wide range belies one of the most critical factors to continued confidence in LNG as a ship fuel: its true GHG emissions. Under lean burn conditions significant fuel slip can occur, where uncombusted fuel enters the atmosphere. In the case of LNG this is methane slip and since methane has a GHG factor of ~28 any gain in CO_2 efficiency can quite rapidly be lost in real (GHG) terms.

- **Benefits of LNG**: availability, lower emissions including NOx, SOx and GHG (tank-to-propeller) if significant methane emissions are controlled. Established and growing infrastructure and experience
- **Concerns of LNG**: Energy density (requiring cooling or compression for storage), hydrocarbon fuel remains a point source of

Innovation Case Study: Addressing the Issue of Methane Slip

Uncombusted fuel from natural gas engines is largely the GHG methane. Compared to more functional hydrocarbons, methane is difficult to oxidise as illustrated in **Figure 7(a)**. This means conventional catalytic converters will not work. For methane oxidation catalyst systems higher temperatures are needed and for some engines this may require the system to be installed in a pre-turbo position. In addition to catalytic activity requiring higher temperatures, other performance related factors include resilience to hydrothermal ageing and susceptibility to sulfur poisoning. Improvements in the tolerance for hydrothermal ageing have been achieved *via* innovative catalyst development but the issue of sulfur is one that requires a more holistic system approach. Inhibition of catalyst activity occurs quite rapidly in the presence of sulfur species as indicated by the fall off in catalyst performance. Up to 50% of activity can be lost over a 24-hour period as indicated in **Figure 7(b)**. This decay in performance is reversible. By heating the catalyst, for example by inducing an exotherm through fuel injection, the catalyst performance can be regenerated, as illustrated in **Figure 7(c)**. Methane injection has little impact on regeneration but a pulse of a higher hydrocarbon such as propane proves very effective. The engine or oxidation catalyst system can be optimised to gain the lower carbon benefits of natural gas combustion with minimal methane slip.

There is a possibility to address the problem of methane slip, for example *via* deployment of catalytic aftertreatment to oxidise the methane (**Figure 8**). Another concern with natural gas is the fact that it has to be cooled and compressed or liquefied for storage. Converting natural gas or methane to methanol resolves this issue.

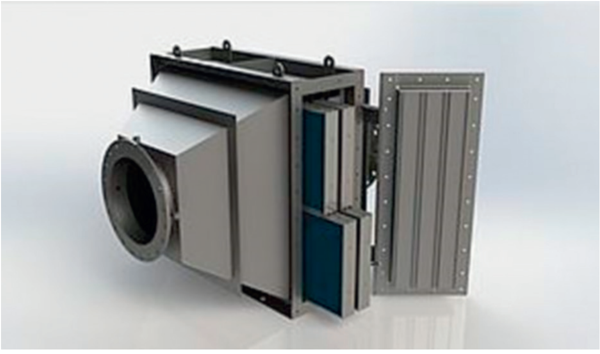

Fig. 8. A methane slip reactor. Courtesy of Johnson Matthey

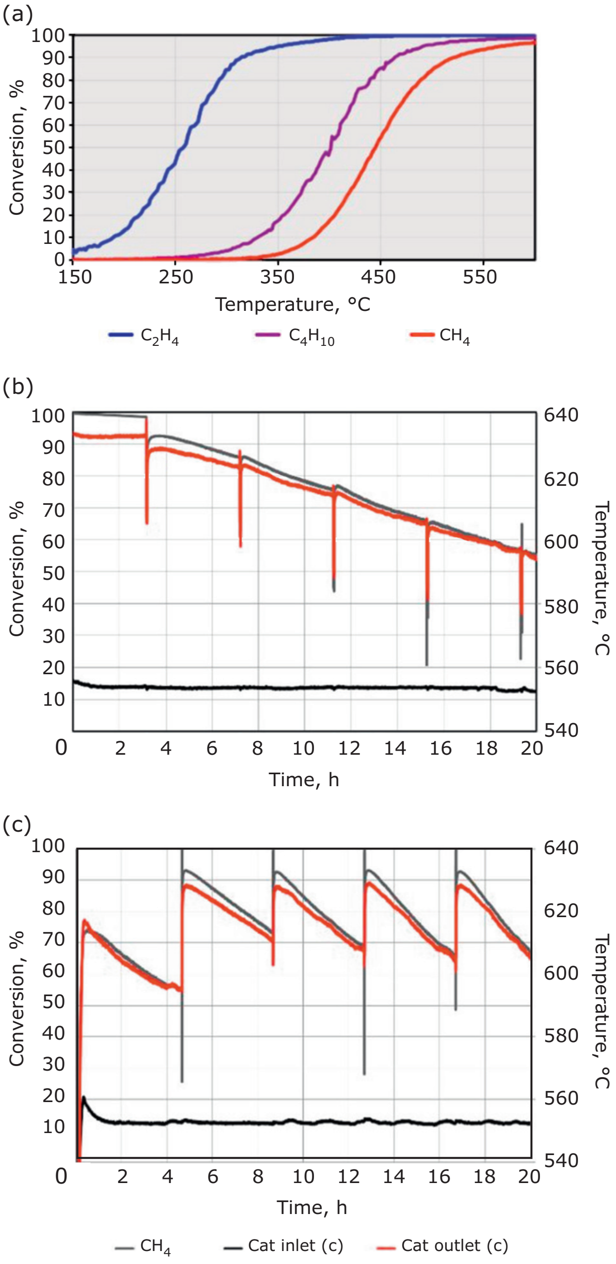

Fig. 7. (a) The light-off temperatures for some hydrocarbons over an oxidation catalyst; (b) decay in catalyst performance for CH_4 oxidation in presence of SO_2; (c) regenerating catalyst performance: C_3H_8 regeneration–30 s/60 s pulse–0.5 ppm SO_2

GHG CO_2 emissions (tank-to-propeller) and significant methane emission.

6.5 Methanol

Methanol (37, 38) is a safe, cost-effective alternative marine fuel. It is the simplest alcohol with a low carbon to hydrogen ratio and is a basic building block for hundreds of essential chemical commodities. With an annual production capability of the order of 100 million tonnes per annum (39) it is one of the top five chemical commodities. It has an existing global infrastructure and many close connections to major ports. It is produced from natural gas, but there is potential for methanol as an outlet for 'power-to-X' electric fuels (40) when it is produced from renewable sources such as biomass and recycled CO_2. Methanol is a liquid under ambient conditions which means that relatively minor modifications to the existing bunkering infrastructure are required to handle it. Naturally low in sulfur it has gained interest as a fuel for operation in Sulphur Emission Control Areas (SECAs) (41) and with clean combustion methanol has relatively low emissions of NOx and particulate matter. The well-to-wake emissions of methanol (produced from natural gas) is a little higher than that of oil fuels but this is reduced considerably if a power-to-X pathway to production is used.

- **Benefits of methanol**: availability, liquid, lower emissions including NOx, SOx and GHG (tank-to-propeller). Potential for low well-to-wake emissions (if renewable energy sources are used in production)
- **Concerns of methanol**: Energy density, hydrocarbon fuel remains a point source of GHG (CO_2 emissions) (tank-to-propeller).

6.6 Liquefied Petroleum Gas

Liquefied petroleum gas (LPG) is any mixture of propane and butane in a liquid state. It is a byproduct of oil and gas production and oil refining, but it is also possible to produce LPG from renewable origins, for example bio-LPG can be separated as a by-product of the production of renewable diesel by hydrogenation of the triglycerides of vegetable oil or animal fat. Propane is a gas under ambient conditions, but it has a boiling point of –42ºC and hence by applying a moderate pressure it can be handled as a liquid at room temperature. Butane's isomers have higher boiling points and liquefy at lower pressure. The use of LPG as a shipping fuel is at a much earlier stage in technology development with a number of projects in the approval stage (by classification societies) (42). Early interest in LPG was driven by the fuel's low sulfur content and thus applicability for operation in SECA regions. On a cost basis it is likely to be on a par with LNG (43). LPG also offers flexibility in terms of the combustion process used on board, capable of being applied to single fuel ICE, dual fuel engines, gas turbines and reformers linked to an ICE or fuel cell. LPG has fewer challenges related to temperature because in smaller tankers it is not kept at cryogenic temperatures, although larger tankers are cryogenic. However, it has challenges related to higher density as a gas and a lower ignition range. LPG combustion results in lower CO_2 emissions compared to oil-based fuels due to its lower carbon to hydrogen ratio. Considered in a lifecycle perspective, LPG production is associated with lower emissions than oil-based fuels or natural gas. The combination of low production and combustion emissions yields an overall greenhouse gas emissions reduction of 17% compared to HFO (44) on a well-to-wake basis. LPG combustion can also benefit from lower NOx emissions, but it does depend on the engine technology used. The development of bunkering infrastructure remains a barrier which is the case for the market adoption of any non-drop-in fuel, although such fuels could use LNG infrastructure.

- **Benefits of LPG**: liquid, lower emissions including NOx, SOx and GHG (tank-to-propeller). Potential for low well-to-wake emissions (if renewable energy sources used in production)
- **Concerns of LPG**: availability, ignition range, hydrocarbon fuel remains a point source of GHG (CO_2 emissions) (tank-to-propeller).

These fuels, including LNG, methanol, LPG and biodiesel, are still carbon based and though through use of renewable energy may have reduced GHG emissions on a well-to-wake analysis they will continue to make significant emissions at a tank-to-propeller basis. For low emissions on a tank-to-propeller basis, zero carbon fuels such as ammonia and hydrogen must be used.

6.7 Ammonia

As a fuel for shipping, ammonia (45) is at a very early stage of development, but as an energy carrier with no carbon it is very attractive on a tank-to-propeller basis and this can be extended to well-to-wake providing that a renewable energy source is used in a power-to-X channel of production. Ammonia is produced on an industrial scale by reacting hydrogen and nitrogen *via* the Haber-Bosch process. Hydrogen is supplied *via* steam reforming of natural gas, but this hydrogen could be produced *via* renewable energy, for example during times when there is surplus wind power. Though hydrogen is a fuel itself (see below) and can be compressed or liquefied, converting it to ammonia is attractive as it is then relatively easy to handle. Early stage adopters of ammonia as a fuel are still evaluating the options for on-board power generation. Ammonia can be used to fuel a conventional engine but the combustion system must be optimised to limit ammonia slip and emissions of N_2O (a GHG with an emission factor 298 times that of CO_2 (46)). In addition to the ICE, fuel cell technology is also attractive. Polymer electrolyte membrane (PEM) fuel cells require ammonia to be cracked to provide high-purity hydrogen whereas solid oxide fuel cells (SOFCs) can use ammonia fuel directly. The sector is particularly wary of this alternative fuel especially as it is caustic and hazardous and requires the development of new safety standards (47). It will require the development of infrastructure to support its bunkering. In the short term, it could be combined with LNG. What is very attractive however is its zero carbon emissions potential and it is for that reason that many see ammonia (and hydrogen) as being the long term winners in the race to fuel the global fleet (48).

- **Benefits of ammonia**: potential for low GHG emissions. Potential for use with different energy converters (engines), ICE and fuel cells
- **Concerns of ammonia**: availability and experience (safety). Risk of ammonia slip and N_2O emissions (significant GHG) during combustion.

6.8 Hydrogen

Hydrogen is expected to play an important role as an energy vector in a truly decarbonised economy. It has been described as the missing link in an integrated, sustainable and clean energy system (49). The product of its combustion in air is water which is also the starting material for its renewable production. Today hydrogen production *via* steam reforming is an industrial process that produces 70 million tonnes per annum (50), but it is as an outlet in a renewable power-to-hydrogen channel, for example *via* electrolysis of water, that excites most interest in terms of its future potential as a zero carbon energy vector.

Its major setback as a shipping fuel is linked to its relative energy density and storage (**Figure 6**). Hydrogen may be stored cryogenically in liquid form at –253ºC but this may incur a parasitic loss of up to 18% in energy of cooling. It can be compressed but such pressurisation requires triple-layer carbon fibre reinforced tanks that are bulky and expensive. Alternatively, storage as a metal hydride or other molecular solid structure is possible but real-world success has been limited and metal hydrides and other containment solids are often difficult and dangerous materials to work with. An option for larger vessels would be to de-risk technology deployment by using a combination of technologies such as a hydrogen powered ICE or combined cycle turbine for propulsion and a fuel cell for auxiliary power.

- **Benefits of hydrogen**: Low GHG emissions tank-to-propeller and potential for low well-to-wake emissions (if renewable energy sources used in production). Potential for mixing with other fuels (natural gas), use with different energy converters (engines) ICE and fuel cells
- **Concerns of hydrogen**: Storage, power density, experience (safety).

7. Energy Conversion

7.1 Combustion

The ICE has been the prime mover of international shipping for a century combusting hydrocarbon, mainly diesel fuels (HFO and ultra-low-sulfur diesel (ULSD)). Historically, improvements to engine design have focussed on maximising power and torque but more recently innovation has delivered more efficient, more environmentally friendly engines. Dual fuel engines that can switch between natural gas and diesel fuels smoothly during operation are now established (51). Their success underscores one of main strengths of the ICE: fuel flexibility. With an appreciation that a large range of fuels may be available in the future (as discussed above), with local variations in availability engine designers have targeted designs that need minor modifications to cope with different fuels.

7.2 Electric Drive: Fuel cells

A very different energy conversion process, from chemical to electrical energy is that used by fuel cells.

Fuel cells (52) offer potential for low pollution with high (theoretical) efficiency. Here the chemical energy of the fuel is directly converted to electricity, thus fuel cells are not restricted by the Carnot efficiency limit (53) like combustion and heat engines. This high efficiency is available over a large power and temperature range making them suitable for dynamic load cycles especially at very low loads. Compared with conventional combustion engines, fuel cells' application in shipping is at a much earlier stage of the development cycle. Significant progress has been made on making the technology more reliable and durable with considerable effort being devoted to achieving this at more acceptable cost (54–56). Over the last decade fuel cells have been the subject of early stage demonstration trials. Many types of fuel cell have been studied including molten carbonate, PEM and SOFCs. One of the problems holding back fuel cell applications in the shipping segment, as with many regulation driven markets, is the difficulty in displacing the entrenched incumbent technology (57). Few companies can continue to invest in product development for a period of many years in the hope that a market will eventually materialise.

There has been successful application of fuel cell technology in the shipping sector. PEM fuel cells using hydrogen are already established in the niche markets of submarines (58). Here the propulsion motor is electrical and the electric power to move the motor is produced by the diesel generator. When submerged, the energy to move the electric motor is obtained from an electrical source such as a battery or fuel cell. Capable of meeting high energy demand for short periods of time, hydrogen PEM fuel cells are particularly useful when the submarine needs maximum power.

7.3 Battery Technology

The use of large batteries in electric or hybrid ships is still at an early stage but already finding use in helping optimise power control and significantly reducing fuel costs, maintenance and emissions. Energy conversion and power generation units can be more compact compared to the current ICE systems and optimised for overall operation (average rather than peak load, and thereby reduce investment costs). Batteries can store energy harvested from several sources such as waste heat recovery and renewable energy. Additionally, they can improve propulsion systems based on LNG and other environmentally friendly fuels and improve the performance of emission abatement technologies. A study led by DNV GL (59) showed that the environmental impact of creating the battery system is small compared to the emissions savings and potential emission reductions can play an important role in reducing emissions from domestic and international shipping. Issues related to size, weight and range remain especially with application to long distance transportation.

The benefits of battery technology include zero emission at the point of use (tank-to-propeller). They can be complimentary to other energy converters (engines), ICE and fuel cells.

8. Discussion

The shipping sector is facing its greatest period of change since the transition of sail to steam. Today, the predominant market force effecting change is not economic but regulatory, driven by a societal demand for cleaner sustainable shipping and the growing interest in sustainable supply chains (60). Having defined its objectives, the sector will rely on market forces to determine the winning technologies and technology pathways to deliver zero emissions shipping by the end of this century. The 2050 target is a relative one, so could be impacted for example by a (COVID-19 caused) global recession and prolonged downturn in shipping (61, 62) (**Figure 9**). The exact nature of this and any future event that impacts the fleet will effectively make that goal a moving target. However, it is expected that post-recession there will be an economic recovery and that the shipping industry will return to growth (63).

8.1 Insight from the Transition to Steam Power

The transition from wind to onboard power generation in the 19th century and the eventual establishment of the diesel engine as prime mover in the 20th century was not a rapid one and faced many challenges (**Figure 10**). The first was the incumbent technology with all the associated benefits developed over many centuries, a firmly established practice with a well-trained workforce with specialised knowledge in navigation, an appreciation not only of the elements, but of

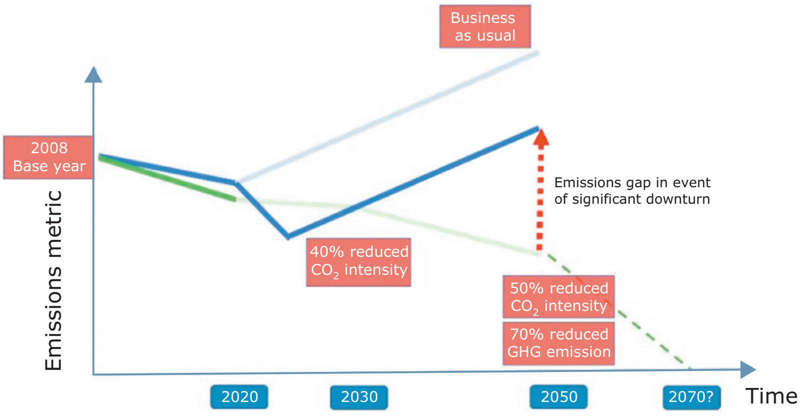

Fig. 9. A revised target for 2040 and 2050 assuming a sharp recession in 2020/21 followed by economic recovery. Schematic summarising the IMO CO_2 and GHG strategy. Source: DNV GL

Fig. 10. The evolution of the diesel powered engine

rigging and sailing in all its aspects, especially in how to sail close to the wind to achieve optimum performance at acceptable risk.

For significant technology transitions to be successful a skilled workforce is required. The supporting infrastructure must be developed, and the costs associated with the new technology must be acceptable (or offer promise of lower costs *via* a cost-down trajectory, engaging economies of scope, scale and the learning curve). The force of the transition is likely to be dominated by the superior characteristics or benefits (above the incumbent) brought by the new technology. In the case of the sail to steam transition it was driven by the overwhelming benefit of on-board power's capability to operate independently of the hitherto effective but unreliable energy source: the wind (**Figure 11**). It suffered major drawbacks, in particular the safety issues, related to coal and coal dust related fires and costs associated with both storage (parasitic space) and cost of the energy source (coal). During a successful transition these issues are resolved or managed giving time for infrastructure development (for example, water and coal supply).

Critical to success is the identification of a niche market where the benefits are particularly valuable and the where some of the issues are more easily managed. For steam shipping this niche was inland waterways where the ability to move unassisted by external forces (for example, horse power) was valued, the need for an expensive supporting infrastructure less of an issue and the space requirements less of a concern. Crucially it allowed some of the critical concerns and barriers to adopting to be resolved. Issues of coal dust related fires became better understood, and risks mitigated. Operational experience led to a workforce trained and skilled in the new technology and its on board operation. As the issues of concern were resolved or managed, so the barriers to adoption were removed and the key benefit of continuous operation independent of the elements pulled the technology into the mainstream.

This approach offers a first order analysis of why significant change occurs but more in-depth

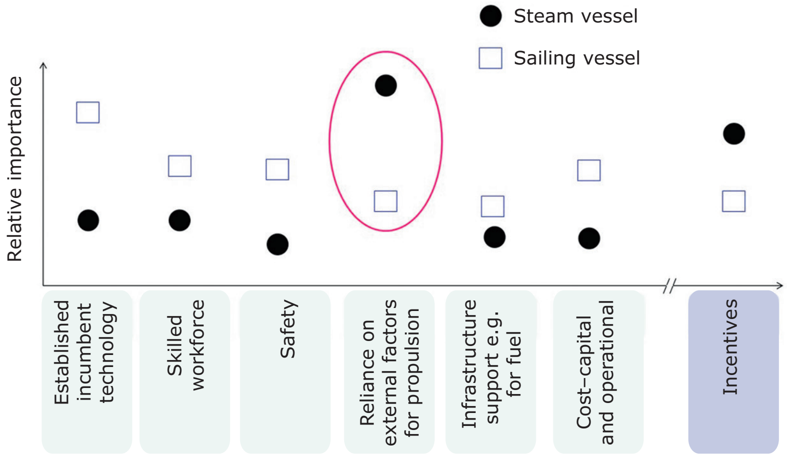

Fig. 11. Schematic showing the relative attractiveness of sailing vessel to steam vessels in 1820

analyses look into the mechanism of how by establishing what other factors supported the evolution. Geels' (64) approach is a more comprehensive study that uncovers the fine detail that facilitated and supported early steam powered vessels such as the deregulation of the British fleet and the impact of the Industrial Revolution and illustrates elegantly the importance of environmental or situational factors in how change evolves.

8.2 Towards Sustainable Shipping

In December 2019 at Marintec China, Martin Stopford of Clarkson Research (65) presented a model that would allow the shipping sector to meet its emission commitments. It is summarised in **Figure 12**.

The prime mover of a zero emission vessel is likely to have an electric drive based on a fuel cell using green hydrogen. Electric plants of this sort are not expected to be available for at least a decade so meeting the emission challenge will be a staged approach where each subsequent technology wave delivers decreased carbon intensity.

The first wave acknowledges two critical issues. That 2020 will see (the beginning of) a significant recession and recognises the current dominance of fossil fuels as an energy source and store (99% of cargo fleet) and the ICE as the energy conversion process (85% of cargo fleet) and that this will continue, due to the lack of any viable alternatives. Lower carbon and low polluting steps towards decarbonisation will focus on slow steaming and improved efficiency (66) through a more systems approach to vessel operation, using digital systems to communicate and optimise activity (67) and in so doing pave the way for a second wave. In this second wave or 'transition state', hybridisation of power technologies becomes the norm, placing greater emphasis on the role of the electric drive train and specifically on battery storage to reduce emissions on a tank-to-propeller basis. The third wave builds on this momentum to deliver designs for zero pollution, all-electric drive vessels and the emergence of new energy conversion mechanisms

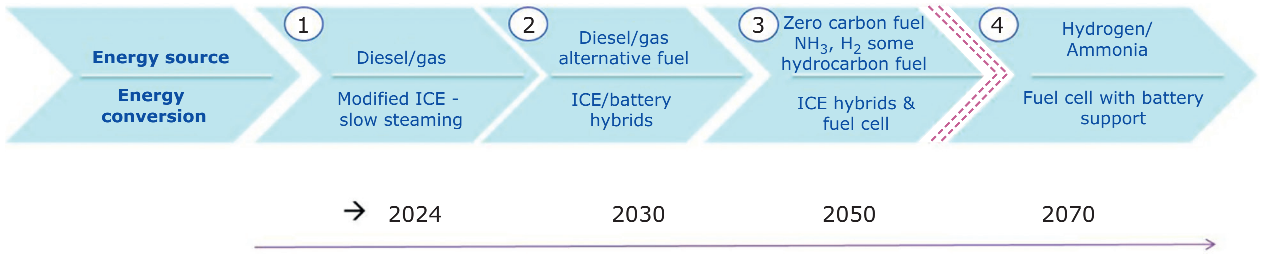

Fig. 12. Likely scenarios for meeting emissions based on the three wave concept developed by Stopford (12)

for propulsion such as the fuel cell. To be zero (or very low) emission on a well-to-wake basis the energy source or fuel must also be decarbonised. Synthetic fuel, electro-fuels or green ammonia and hydrogen fuels offer this possibility but require an economically available and renewable source of energy. Recent reports (68) are positive, noting that the costs of renewable energy can fall below that of new fossil fuel power plants at US\$0.05 kWh^{-1}–US\$0.15 kWh^{-1}. Hydroelectric power now has an average cost of US\$0.05 kWh^{-1} and off-shore wind generated power in places with good natural resources (with the right regulatory and institutional support) fall in the range US\$0.03 kWh^{-1}–US\$0.04 kWh^{-1}. Solar energy in South America and in the Middle East have seen a levelised cost of electricity at US\$0.03 kWh^{-1}.

8.3 Delivering This Objective

In December 2019 (69) the global maritime transport industry proposed the formation of the world's first collaborative shipping research and development (R&D) programme to help eliminate CO_2 emissions from international shipping. It recognises that addressing the challenges will require the deployment of new zero-carbon technologies and propulsion systems, such as green hydrogen and ammonia, fuel cells, batteries and synthetic fuels produced from renewable energy sources and acknowledge that these do not yet exist in a form or scale that can be applied to large commercial ships, especially those engaged in transoceanic voyages which are currently dependent on fossil fuels. They envision a new non-governmental R&D organisation to pave the way for decarbonisation of shipping by encouraging the development of commercially viable zero-carbon emission ships by the early 2030s. Part of the proposal is the establishment of an International Maritime Research and Development Board (IMRB), that would be overseen by IMO member states and financed by shipping companies worldwide *via* a mandatory R&D contribution of US\$2 per tonne of marine fuel purchased for consumption by shipping companies worldwide. This would generate about US\$5 billion in core funding over a 10-year period. The proposal sets an ambition for the IMRB to be operational by 2023 and expects it to run for 10–15 years. Though universally welcomed, there is concern in some quarters (70) that it falls short of a strategy to cut emissions.

Decarbonisation of shipping is a complex problem, integrated with the wider ambition to decarbonise the power and (land based) transport sectors. On the face of it, the overall aim, for shipping to decarbonise as soon as possible this century, is challenging, but there is concern over how aspirational and how demanding it really is. Some have questioned the use of 2008 as a base line, since the economic downturn led to a reduction in CO_2 emissions from shipping between 2008–2015 (71, 72), and how meaningful the interim challenges really are. A study by the International Council on Clean Transport (ICCT) (72) has shown that the IMO's 2030 goal was actually already three-quarters met when it was approved in 2018, which has prompted calls for a rethink of the target. Without a forceful impetus driving innovation there is fear that a lack of meaningful action will lead to delay (73) especially as there are suspicions that the IMO process will not address the issue.

The frustration with the IMO process goes beyond disgruntled environmental NGOs. In December 2019 the European Commission announced its new Green Deal (74) indicating that shipping would be included in the EU Emissions Trading System (EU ETS) by 2023. This possibility had already been signalled by the European Parliament's Environment Committee in 2016 warning (75) that (that to avoid inclusion in the EU ETS) the IMO needed to "deliver a further global measure to reduce GHG emissions for international shipping by 2021". The IMO has warned that this could seriously undermine the global effort. If this leads to a further and significant development of the patchwork nature of shipping regulations the IMO will be deemed to have failed. If the IMO does not facilitate the meaningful reduction of emissions in the short term it will be deemed to have failed. Could another policy approach be more successful?

In his study of technology transitions, Geels (76) recognises three kinds of paradigms of innovation policy: how it can be supported at a governmental level. One of the models is based on setting a regulation with top down governance. A second uses market based incentives where the governance focuses on establishing the framework and the conditions. A third model that facilitates radical innovation involves network governance to help establish a vision and bring teams to work collaboratively to achieve a goal. Geels also recognises the attraction of cutting loose from a bureaucratic approach based on the desire to reach consensus but is cautious as for these problems there is no easy solution. New entrants tend to suffer from a lack of adequate skills, finance and scale-up capability and fail to recognise the magnitude of the challenges they face. Incumbents may seem locked into the current regime with their 'sunk investments', their technical capabilities, operations, mindset, identity and practices but under certain circumstances incumbents can re-orient to radical innovation, collaborating with the disrupters, following a path outlined in **Figure 13**.

The first step is characterised by resistance and easy dismissal, for example on the grounds that it will not work or it is too expensive. In the second step the incumbent recognises some potential and invests in options and in the third targets early markets. In the fourth step the organisation has committed to scaling up. Regime transformation is not a deterministic process; though it may thrive given the right conditions, supportive policy, public attention and market demand, it may falter at any step if the impetus is not sustained.

The economic impact of COVID-19 is unprecedented but so too are governments' responses to it: establishing stimulus packages to help economies recover. European State Aid rules have been suspended allowing nation states to act; for example, Germany's Federal Government has committed €1.32 trillion (38% of its 2019 gross domestic product (GDP)) in liquidity and guarantee measures. The World Health Organization (WHO) suggests that "support to resuscitate the economy after the pandemic should promote health, equity and environmental protection" (77) i.e. these vast sums should support a green economy, furthering climate goals and preventing a return to business-as-usual which is not aligned with the goals of the Paris Agreement. The European Commission had indicated that recovery investments must be linked to green and digital transitions, and that "the Green Deal is not a luxury that we drop when we hit another crisis". How much of this will impact shipping is unclear but any significant investment in the decarbonisation on land to accelerate technology development for both energy conversion and green energy storage (fuels) should benefit the decarbonisation effort in shipping.

9. Conclusions

Evolution is a scientific theory developed for the biological sciences and seeks to explain how change occurs in living systems, over long periods of time, how environmental factors, for example, create conditions where inheritable physical or behavioural traits bring a distinct advantage and thus improve the chances of survival and of passing on those traits to subsequent generations. The term evolution has found meaning to explain change in other complex systems, though the concept of inheritable traits is less tangible. Notwithstanding, studies on how and why innovation is successful suggest that there are common themes or 'winner's traits': an innovative spirit, excellent network, access to high quality information or intelligence, an open attitude that embraces change, agility and timing of response.

Transitions in shipping take long periods, in part due the lifetime of the asset. Planning for 2040 and 2050 may seem like tomorrow's concern, but they require decisions today and the wrong decision risks creating stranded assets. Even the best-informed decision makers face what Donald Sull (78) referred to as the "Fog of Uncertainty". Those with resources can adopt a portfolio approach to distribute risk, others may be forced to take calculated risks. Some of the subtly important factors may only be comprehended in retrospect: seemingly trivial events that turn the tide. The decoupling of mail delivery from the rest of shipping in 1820 might not even be a footnote in history yet played a key role in the sail to steam transition. It isolated a growing need that was valued by the market so faster information transfer was incentivised and newer risky technologies, such as steam power, were developed, demonstrated and deployed.

So as the decision makers plot a course through the fog of uncertainty, they hope they have the most important of sea-faring traits. In some ways it is the sum of all the important traits outlined above. It is the trait that Napoleon (79, 80) reportedly demanded of his generals: "to be lucky".

Fig. 13. A simple schematic of Geels' theory of regime transformation (76)

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