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 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). 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-H₂ year⁻¹ is used today in pure form, mostly for oil refining and ammonia manufacture for fertilisers. A further 45 million tonne-H₂ 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 by renewable energy sources such as wind, solar, biomass, geothermal and hydroelectric power (16–30).
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).
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).
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...
5.64 kg-H₂₂, 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-H₂ 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

![Image](https://example.com/image.png)
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
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

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

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

\(^a\)The driving range values on a single charge were obtained from the fuel economy tests in South Korea
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™, to offer commercial passenger service in Germany in September 2018 (44, 45). The Coradia iLint™
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](image-url)
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.

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.
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...
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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