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Current Opinion in Electrochemistry

Review Article

Current status of automotive fuel cells for sustainable transport

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Abstract

Automotive proton-exchange membrane fuel cells (PEMFCs) have finally reached a state of technological readiness where several major automotive companies are commercially leasing and selling fuel cell electric vehicles, including Toyota, Honda, and Hyundai. These now claim vehicle speed and acceleration, refueling time, driving range, and durability that rival conventional internal combustion engines and in most cases outperform battery electric vehicles. The residual challenges and areas of improvement which remain for PEMFCs are performance at high current density, durability, and cost. These are expected to be resolved over the coming decade while hydrogen infrastructure needs to become widely available. Here, we briefly discuss the status of automotive PEMFCs, misconceptions about the barriers that platinum usage creates, and the remaining hurdles for the technology to become broadly accepted and implemented.

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Current Opinion in Electrochemistry 2019, **16**:90–95

This review comes from a themed issue on **Electrochemical Materials and Engineering**

Edited by **Frank C. Walsh**

For a complete overview see the Issue and the Editorial

Available online 8 May 2019

https://doi.org/10.1016/j.coelec.2019.04.021

Keywords

Fuel cell vehicles, PEM fuel cells, Platinum, Non–precious metal catalysts, Hydrogen.

Introduction

Weaning the transport sector off hydrocarbons has been a major challenge for the automotive industry since the oil crash in the 1970s, and has intensified in the last decade with pressure to decarbonize [1,2]. Around one-fifth of global CO_2 emissions originate from internal combustion engines (ICEs) burning fossil fuels [3], and air pollution from particulates, NO_x, SO_2, and CO, causes 9 million premature deaths per year worldwide, more than those attributed to tobacco smoking [4]. These problems are only set to worsen as the global passenger vehicle fleet is expected to grow from 1 to 2.5 billion by 2050 [1,2] as the global population rises to 10 billion [5].

After two decades of intensive research costing billions of dollars, the commercialization of fuel cell electric vehicles (FCEVs) has commenced with several automakers launching models in the USA, Asia, and Europe (Table 1). Battery electric vehicle (BEV) sales exceed 1 million annually [6,7], whereas FCEVs are trickling, rather than flooding into the hands of consumers, in part because the hydrogen infrastructure is a decade behind BEV-recharging posts [8].

FCEVs offer many advantages over BEVs (Table 1): very fast refueling time (ca. 3–5 min), freedom from 'range anxiety' with up to 600 km between refueling, greater longevity (>200,000 km), better driver experience, and safety [9]. However, FCEVs still have higher capital and operating costs when compared with BEVs, with current models around twice as expensive [9]. The high FCEV cost is primarily due to the use of platinum (Pt) catalysts and current low production volumes. Although precious metal loadings have fallen dramatically in the last decade [10], it still remains a significant issue (Figure 1). For example, Daimler has cut Pt content in its FCEVs (Mercedes GLC F-Cell vs. B-Class F-Cell) by 90% since 2009, and Toyota is targeting a 50% reduction from current levels. However, it is anticipated that ultra-low loading Pt or non-precious metal catalysts, together with increased mass production of FCEVs, could achieve cost parity with BEVs by 2030 [9].

Misconceptions about platinum

The automotive industry is a major user of Pt, with catalytic converters requiring around 40% of annual global production. Since the 1990s, R&D has sought to replace Pt in FCEVs with cheaper, durable, highly performing, and easily accessible catalysts. The reasons are threefold: (i) high mining and refining costs mean Pt accounts for around one-third of the total cost of an automotive fuel cell stack, (ii) the mineral is 'scarce,'

Table 1

Specifications for the latest FCEV models currently in production.

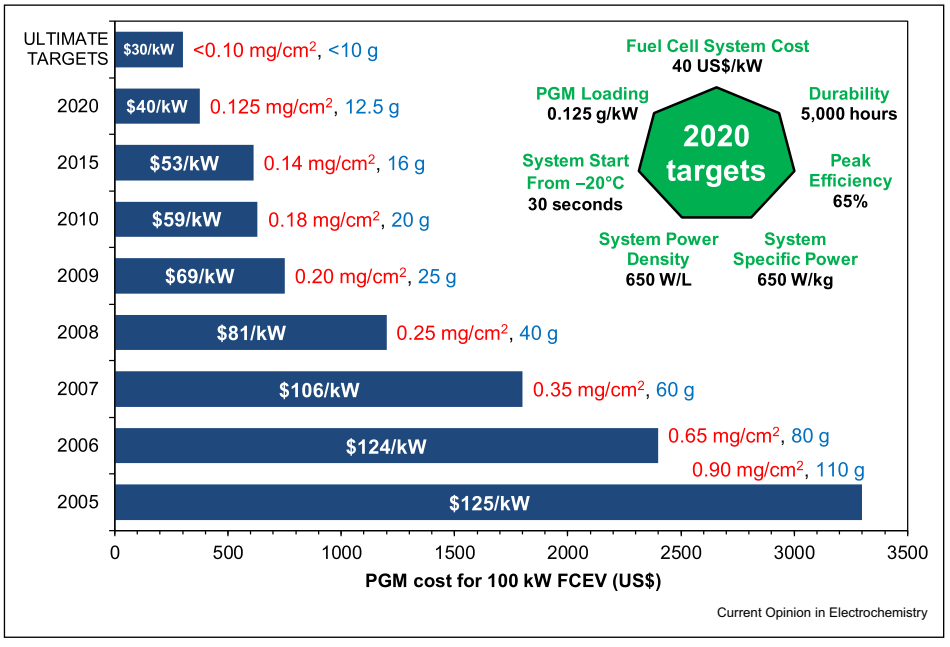
FCEV	Launch date	Mass (kg)	Fuel cell/ motor power (kW)	Power density (kW/L)	Acceleration time (s) 0–60 mph (100 km/h)	Fuel tank capacity (kg) (wt%)	Fuel pressure (MPa)	Estimated range (miles–km)	Fuel economy (kg hydrogen / 100 km)	Fuel consumption (mpg gasoline equivalent)[a]
Hyundai Nexo	2018	1873	95/120	3.10	9.5 (10)	6.33 (7.18 wt%)	70	370–595	0.84	57–61
Honda Clarity	2016	1875	103/130	3.12	9.2 (9.7)	5.46 (6.23 wt%)	70	366–589	0.97	67
Hyundai ix35 FCEV or Tucson FCEV	2014	1980	100/100	1.65	12.5 (13.2)	5.64 (6.43 wt%)	70	369–594	0.95–1.0	66
Toyota Mirai	2014	1850	90/114	3.10	9 (9.5)	5.0 (5.70 wt%)	70	312–502	0.76	67

FCEV, fuel cell electric vehicle.
For other FCEVs, see Pollet et al and Cano et al [1,2].
[a] Compared with sales-weighted average fuel economy in the USA of 25–43 mpg, depending on the vehicle class.

and (iii) Pt mining is concentrated in geopolitically and economically unstable regions [11]. At the time of writing, raw Pt trades at around US$30 per gram [12], which is around 50,000 times more expensive than stainless steel. Note that there are no economies of scale, so the cost of raw platinum group metal (PGM) stays constant independent of the quantity used.

Pt availability is thought of as a problem; however, global reserves are estimated at ~69,000 tonnes [13]. According to Cawthorn [14], the Bushveld Complex in South Africa alone could supply global Pt demand for up to a century, with a current annual production of 140 tonnes and the possibility of extracting Pt up to 10,000 tonnes (350 million oz) per km of vertical depth. A total of 2.5 billion FCEVs each containing 30 g of Pt (i.e. no technical progress from today) would require 75,000 tonnes of Pt. This excludes the potential of recycled Pt from spent automotive catalysts, with up to 95% recovery using present-day technologies [15]. It is therefore very unlikely that Pt availability will prove a major bottleneck for the automotive sector, especially given

Figure 1



Evolution of total platinum group metal (PGM) cost and loading for a 100-kW FCEV, showing historic development, current status, and targets. Bars show the total PGM cost based on current raw Pt prices (≈US$30/g). Values inside bars give the total fuel cell stack cost for a manufacturing volume of 500,000 per year. Values outside bars give the total PGM loading per unit cell area (mg/cm^2) and for a 100-kW FCEV (g). Inset figure shows a broader set of technical targets for FCEVs in 2020. FCEV, fuel cell electric vehicle.

the likelihood that the present target of $<0.1\ g_{Pt}\ kW^{-1}$ will be achieved by 2050. This would place FCEV stacks on par with current Pt loadings for catalytic converters (ca. 1 g for petrol and 8–10 g for diesel).

Status of FCEVs

Unlike the extensive global rollout of BEVs, FCEVs are leased and sold in small quantities and in limited areas. A decade since Honda publicly launched the FCX Clarity, the fuel cell variant is still only available in Japan and California. The Toyota Mirai and Hyundai ix35 are available more widely, although only 15 countries have public stations to refuel them at present [9]. A total of 5600 FCEVs now operate in the USA, with a comparable number in the rest of the world combined [16].

Worldwide, governments are preparing for a major push toward FCEVs. By 2030, the USA targets 1 million FCEVs in California alone [17], while China, Japan, and South Korea aim for 1, 0.8, and 0.6 million, respectively [9]. Japan aims to deploy 200,000 FCEVs by 2025, costing ~ US$6000 more than a standard hybrid, versus US$27,000 premium today, with a cost target for the fuel cell stack falling from U$200 to US$50 per kW [18].

Increasingly, it is argued that hydrogen's main role may lie beyond passenger vehicles, decarbonizing heavy transportation sectors that batteries cannot easily serve [1,2]. The suitability of the proton-exchange membrane fuel cell (PEMFC) for buses, trucks, trains [9], shipping [19], and even aviation [20] is of significant interest worldwide.

There is broad agreement that hydrogen-powered transport is an essential component of climate change mitigation, especially if global warming is to be limited to 1.5°C (Figure 2). Decarbonization scenarios see hydrogen supplying a tenth of global transportation energy demand as early as the mid-2040s [21]. This requires a sustained period of scale-up: the median pathway to achieving 1.5°C sees hydrogen usage growing by >20% year-on-year for the next three decades. Reduced ambition to mitigate climate change still presents a major role for hydrogen, albeit delayed by several decades [21].

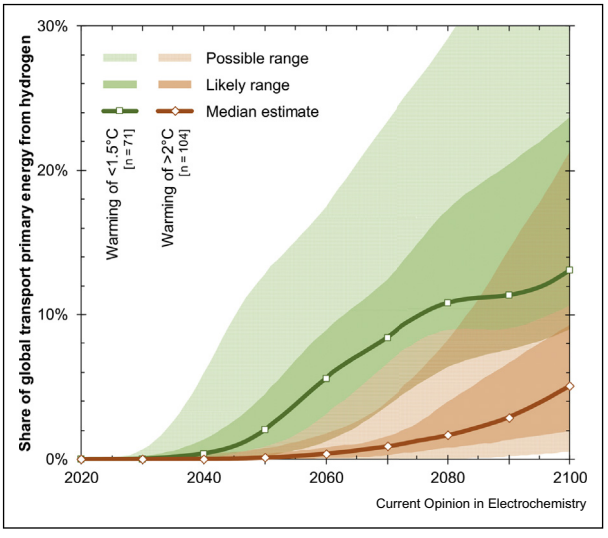
Status of fuel cell systems

At this time, durability and cost are the primary challenges still to be met. The 2020 US Department of Energy targets for fuel cell systems are a cost of US$40/kW with an efficiency of 65% at peak power and with 12.5 g of Pt, based on 500,000 automotive fuel cell systems produced per year (Figures 1 and 3). The PEMFC stack cost breakdown identifies that the catalyst contributes significantly to the total cost (41%) when compared with the bipolar plate, membrane, gas diffusion layer, electrodes and gaskets, and balance of plant costs [22] (Figure 3). This can be attributed to the material processing costs and manufacturer markup, which lead specialized Pt catalysts to be several times more expensive than untreated Pt metal. Manufacturing scale-up has reduced the costs of PEMFCs at a comparable pace with lithium-ion batteries [23]. According to Moreno et al. [24], reducing the membrane electrode assembly (MEA) cost up to 30% makes the US$40/kW cost target by 2020 reachable, corresponding to a reduction in catalyst cost to < US$4/kW and the membrane to < US$1/kW. However, the catalyst cost is predominantly a material cost and does not fall with the number of systems produced per year. Thus, lowering the amount of Pt-based catalyst used while maintaining the durability is essential. The catalyst loading can be lowered by finding an improved catalyst with a higher oxygen reduction reaction (ORR) activity, increasing the catalyst surface area and lowering the mass transport losses at high current densities.

Cathode ORR catalysts

Tremendous progress has been made over the last two decades in improving the anode and cathode catalyst layers that form the heart of the fuel cell, the two important layers that are sandwiched around the polymeric proton exchange membrane to form MEAs. However, continued research on alternative catalysts for the slow ORR on the cathode has been a prime focus, with the goal of lowering the total Pt content of the stack from 30 g to less than 10 g.

Figure 2



The share of global transportation provided by hydrogen during the 21st century, as modeled in scenarios for the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C [21]. The hydrogen share is measured in terms of primary energy input across all modes of transport. Lighter shaded areas show the central two-thirds of scenarios (17th to 83rd percentile); darker shaded areas show the central one-third (33rd to 67th percentile). Colors classify scenarios by their warming impact in 2100.

Current attention on the MEA is mainly focused on improving the cathode catalyst layer. The ORR reaction is sluggish, and Pt/C loadings of ~0.35 mg_{Pt}/cm^2 are typically needed. Improving ORR catalytic activity (e.g. alloy catalysts and novel structures) is being intensively studied as it would lower the total loading of Pt in the fuel cell stack and hence lower the cost of the stack [24]. Electrocatalyst activity may be enhanced through both improved surface area accessible to reactants (better mass activity mA/mg_{Pt}) and higher intrinsic activity (mA/cm^2_{Pt}). In addition, the cathode catalyst layer is subject to cyclic load cycling between 0.60 V and open circuit voltage (OCV), variable relative humidity, water generation as a function of current density, and start-up/shutdown losses. Each of these conditions degrades the performance of the catalyst layer over time.

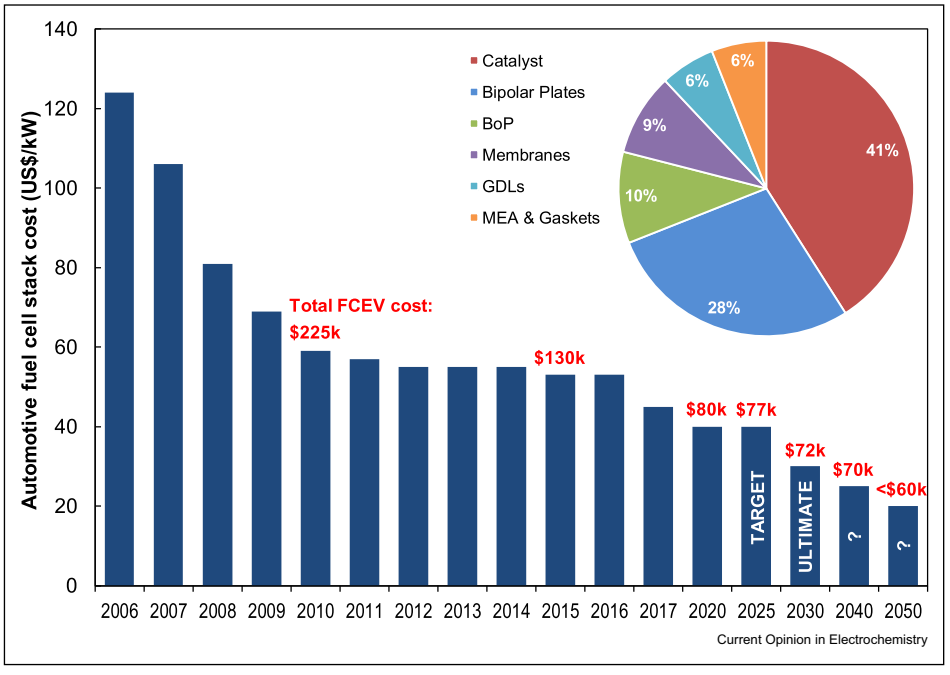
Numerous binary and ternary Pt-based electrocatalysts, such as Pt—Co, Pt—Ni, Pt—Cr and Pt—Co—Cr, Pt—Rh—Fe, were discovered while conducting research on phosphoric acid fuel cells in the late 20th century. These have shown durability of more than 40,000 h in commercial stationary fuel cells at 190°C [25], and this learning has been transferred to PEMFCs, with Pt—Co/C and Pt—Ni/C being the most commonly used binary alloys. Additional work had to be conducted to modify these catalysts for use in PEMFCs, in part because of the different electrode structure in PEMFCs compared with that of acid-filled gas diffusion electrodes of phosphoric acid fuel cells. Polytetrafluoroethylene (PTFE) has been eliminated, and the catalyst layer consists of solely catalyst/C and ionomer. Fundamentally, base metals tend to move to an alloy's surface and cannot be stopped because of surface segregation. The limited amount of ionomer (30%) in PEMFC cathodes means base metal leaching into the ionomer is a much more serious issue than in liquid acid-based fuel cells. For PEMFCs, Pt alloys are typically pre-leached to remove excess Co from the surface and minimize the increase in catalyst layer resistance (protonic resistance) over time. In addition, smaller Pt particles can be used in PEMFC cathodes because the operating temperature does not exceed 90°C.

MEAs have been widely reported with exotic catalyst structures that exhibit >10 times the activity of the nanoparticle Pt/C [26—28]. These novel classes of electrocatalysts tackle the problem that most atoms in a Pt nanoparticle remain unused because only the surface participates in reactions. Particles below ca. 2 nm are unstable and will double in size after 1,000 h of operation because of dissolution and redeposition.

Cathode electrode structure

As the automotive industry uses ever-higher activity Pt alloy catalysts, Pt loadings are reduced correspondingly, in turn yielding thinner and mechanically weak catalyst layers and MEAs. For example, Pt—Co/C with 4 times the activity of Pt/C requires a catalyst layer with one-fourth of the thickness, impacting on stability and

Figure 3



Automotive fuel cell cost evolution and projection. Bars show the PEMFC stack cost (US$), while the cost of the total FCEV is printed for selected years. Inset figure: automotive fuel cell component cost distribution based on 500,000 fuel cell systems produced per year. BOP, balance of plant; GDL, gas diffusion layer; FCEV, fuel cell electric vehicle; MEA, membrane electrode assembly; PEMFC, proton-exchange membrane fuel cell.

durability. This problem is partly mitigated by reducing the wt% of Pt. The H_2-air performance curves do not shift uniformly over the range of current densities, and at high current densities, the limiting current has an early onset. Numerous studies have been conducted to understand this so-called anomalous effect [27]. Looking at specific current density, catalyst sites may become more severely stressed when loadings are reduced. The losses from this phenomenon have been attributed to the ionomer–catalyst interface and poisoning of the catalyst by the sulfuric acid groups on the ionomer.

Research into PGM-free ORR catalysts

Since the 2000s, some 65,000 articles have been published in the area of non-precious metal catalysts [29]. It is questionable whether PGM-free catalysts have a role to play as catalyst loadings approach the target of 10 g Pt per 100 kW stack. However, there has been renewed interest in PGM-free cathode catalysts, and their activity has been improved significantly albeit only under oxygen [30]. Because the intrinsic activity of PGM-free catalysts for ORR is low, more catalyst has to be applied to provide similar performance, especially under air. Higher loadings of PGM-free catalysts result in a much thicker catalyst layer (up to 100 times more than those containing PGM) concomitant with higher catalyst layer resistance and mass transport losses. Finally, most PGM-free catalysts still suffer from poor durability [30].

Closing remarks

The overall goal for automotive PEMFCs is to match the performance, cost, and durability of conventional engines. The performance and durability of all major stack components including bipolar plates, membranes, catalysts, gas diffusion layers, and balance of stack have been significantly improved over the last decade. It is now very likely that cost and durability targets will be met in the next decade, providing a commercially viable alternative to the internal combustion engine which has dominated for the last century.

Conflict of interest statement

Nothing declared.

Acknowledgement

Iain Staffell was funded by the Engineering and Physical Sciences Research Council through the IDLES programme (EP/R045518/1).

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- •• of outstanding interest

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