Expert assessments of the cost and expected future performance of proton exchange membrane fuel cells for vehicles

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Despite decades of development, proton exchange membrane fuel cells (PEMFCs) still lack wide market acceptance in vehicles. To understand the expected trajectories of PEMFC attributes that influence adoption, we conducted an expert elicitation assessment of the current and expected future cost and performance of automotive PEMFCs. We elicited 39 experts’ assessments of PEMFC system cost, stack durability, and stack power density under a hypothetical, large-scale production scenario. Experts assessed the median 2017 automotive cost to be $75/kW, stack durability to be 4,000 hours, and stack power density to be 2.5 kW/L. However, experts ranged widely in their assessments. Experts’ 2017 best cost assessments ranged from $40 to $500/kW, durability assessments ranged from 1,200 to 12,000 hours, and power density assessments ranged from 0.5 to 4 kW/L. Most respondents expected the 2020 cost to fall short of the 2020 target of the US Department of Energy (DOE). However, most respondents anticipated that the DOE’s ultimate target of $30/kW would be met by 2050 and a power density of 3 kW/L would be achieved by 2035. Fifteen experts thought that the DOE’s ultimate durability target of 8,000 hours would be met by 2050. In general, experts identified high Pt group metal loading as the most significant barrier to reducing cost. Recommended research and development (R&D) funding was allocated to “catalysts and electrodes,” followed in decreasing amount by “fuel cell performance and durability,” “membranes and electrolytes,” and “testing and technical assessment.” Our results could be used to inform public and private R&D decisions and technology roadmaps.

Significance

We offer an assessment of the cost and performance of automotive proton exchange membrane fuel cells (PEMFCs). Informed by expert opinion, our study characterizes the uncertainty associated with PEMFCs’ future trajectory, identifies barriers to improving cost and performance, and prioritizes research and development (R&D) areas. Our results could be used to inform technology roadmaps and future R&D funding. Experts suggested that PEMFCs would meet the ultimate cost and performance targets of the US Department of Energy (DOE) but would fall short of the DOE’s 2020 cost target. Furthermore, our results could serve as inputs into cost models. Fuel cell electric vehicles’ capital and life cycle costs could be calculated and compared with those of other vehicles.


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we reviewed government reports and automakers’ specifications to determine which metrics to elicit. The DOE relies upon benchmarks and targets published in the Multi-Year Research, Development, and Demonstration (MYRD&D) Plan of the Fuel Cell Technologies Office (FCTO) to guide funding priorities. The MYRD&D Plan highlights cost and durability as the “primary challenges” to commercializing automotive PEMFCs (37). Automakers shy away from reporting cost and durability, but Toyota (39) and Honda (40) report stack power densities.

We intend for our study to contribute to a larger body of work on fuel cell and hydrogen technology development and decision making. The availability of refueling infrastructure is a key factor in FCEV market development (27). In separate literature, researchers have assessed refueling station costs (34) and hydrogen delivery pathways (35). Furthermore, battery electric vehicles could cost less than FCEVs on a per mile basis, depending on trends in capital and fuel costs (36). Our study identifies the greatest challenges to reducing PEMFC production costs.

Scope of Expert Elicitation

We reviewed government reports and automakers’ specifications to assess PEMFC cost and performance. We review previous expert elicitation in SI Appendix, section S2.

Expert elicitation is intended to complement, not replace, analytical methods (22). Learning curves (28) and scenario analyses (29) describe a technology’s potential trajectory at a high level of system detail. Other methods, such as process-based cost models (30), disaggregate system cost into component manufacturing costs. Expert elicitation, in contrast, enables component-by-component assessment of performance and uncertainty while identifying potential research and development (R&D) pathways. We recognize that cognitive heuristics (31), overconfidence (22), motivational bias (32), and peer pressure (33) influence an expert’s assessments. To the extent possible, we minimized anchoring and adjustment by asking experts to provide their lower and upper bounds before providing their best estimate (22). We briefed experts about the cognitive heuristic of availability (31) and the bias of overconfidence (22) before conducting interviews. To capture diverse viewpoints, we recruited experts from various backgrounds (23).

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Fig. 1. Experts’ assessments of PEMFC cost and performance in 2017, 2020, 2035, and 2050. Each square represents the median of experts’ best estimates, and the error bars represent the IQRs of experts’ best estimates. For each metric, we show the DOE’s 2015 estimate (plotted in 2017), the DOE’s 2020 target, and the DOE’s ultimate target (plotted in 2050). (A) Automotive PEMFC system cost (assessments in 2017 USD). (B) PEMFC stack durability. (C) PEMFC stack power density.

most respondents provided higher assessments than the DOE’s targets from 2017 to 2035. Experts’ median 2017 assessment of $75/kW exceeded the DOE’s 2015 estimate of $53/kW. Experts’ 2020 and 2035 median assessments, which were $62/kW and $46/kW, respectively, exceeded the DOE’s 2020 target of $40/kW. Experts ranged widely in their 2017 and 2020 assessments but narrowed in their 2035 and 2050 assessments. We sought to determine whether these trends applied after controlling for affiliation. SI Appendix, section S5 presents experts’ assessments separated into academic, government, and industry affiliations. As shown in SI Appendix, Fig. S3 and Table S1, several experts from each affiliation anticipated that the ultimate cost target would be met by 2050. Government experts provided narrower IQRs than academic and industry experts.

Fig. 1 B and C present experts’ stack durability and power density assessments, respectively. Fifteen experts expected the 2020 durability target of 5,000 h to be met by 2020, and 15 experts expected the ultimate durability target of 8,000 h to be met by 2050. As shown in SI Appendix, Fig. S4 and Table S2, academic experts provided median assessments less than the DOE’s targets in 2020 and 2050. Government experts provided narrower IQRs than academic and industry experts. As shown in Fig. 1C, experts provided a 2035 median power density assessment of 3 kW/L, but most respondents provided assessments less than 3 kW/L in earlier years. Experts’ median 2017 and 2020 assessments were 2.5 and 2.75 kW/L, respectively. In contrast, Toyota (39) and Honda (40) report a stack power density of 3.1 kW/L. Government experts provided median assessments of ~3 kW/L across all years (SI Appendix, Fig. S5 and Table S3).

Fig. 2 presents experts’ recommended funding levels. We also show the FCTO’s FY 2017 request (47) and appropriation (48). Experts recommended $54 million (median) in total funding, allocating the most funding to “catalysts and electrodes,” followed in decreasing amount by “fuel cell performance and durability,” “membranes and electrolytes,” and “testing and technical assessment.” The middle 50% of experts recommended two to three times more funding for “fuel cell performance and durability” than that appropriated in FY 2017, and two to five times more funding for “membranes and electrolytes” than that requested in FY 2017. For membranes and electrolytes, the middle 50% of industry experts recommended three to eight times more funding than the FY 2017 request. We conducted a simple test for conflict of interest influencing motivational bias. SI Appendix, section S6 describes our method and results. We did not detect motivational bias associated with experts’ funding sources.

Individual Assessments. To elucidate differences among assessments, we present experts’ individual assessments, organized by self-assessed expertise (0, not familiar; 7, very familiar). As shown in Fig. 3, experts’ 2017 best estimates ranged from $40 to $500/kW [confidence intervals (CIs): $20 to $1,100/kW]. Experts who provided high assessments commented on the challenge of reaching 500,000 units/year. Expert 2 remarked that current production volumes are not close to this assumption of 500,000 units/year, remarking, “When we talk about manufacturing in 2017, but then we talk about 500,000 units/year...that’s just completely out of bounds...we’re talking about a hypothetical cost.” Expert 33 instead assumed thousands of units/year in 2017, 50,000–200,000 units in 2035, and 500,000 units in 2050. [Because expert 33 assumed 2017, 2020, and 2035 production volumes that differed from that stated in the question (500,000 units/year), we excluded expert 33’s cost assessments from our calculations (range, median, etc.) for these years.]

Fig. 4 presents experts’ assessments of stack durability. Experts’ 2017 best estimates ranged from 1,200 to 12,000 h (CIs, 500–20,000 h). Experts 26 and 30 provided higher best estimates and upper bounds in 2017 and 2020 than other experts. When asked to justify their 2017 range, expert 26 explained that their lower bound of 2,000 h reflected manufacturing quality limitations. Expert 30 mentioned that they adjusted their durability assessments from a 30% power threshold to a 10% threshold, which could explain this expert’s wide range. Experts 4, 9, and 27 provided 2050 assessments equal to or greater than 15,000 h. Expert 4 mentioned that stacks could reach 40,000 h for general applications, including stationary applications. Expert 9 considered a durability target of 20,000 h. Expert 27 remarked that the durability of an automotive stack could approach that of a stationary stack due to advancements in system configuration or architecture, or improvements in the durability of electrodes and membranes. Experts 6, 7, 14, 15, 16, 20, 23, and 26 maintained the same best estimate and upper and lower bounds between 2035 and 2050. Most of these experts remarked that reducing costs would take precedence to improving durability in these years.
Experts could probably increase the power density above 3.1 kW/L if more Pt were used, but expert 14 thought that the power density did not need significant improvement beyond today’s performance. Expert 14 also remarked that not all car companies are necessarily manufacturing stacks at power densities as high as 3.1 kW/L. Experts 2, 3, 4, 12, 18, and 20 provided 2017 best estimates less than 1.5 kW/L. Expert 2 explained that FCEVs are probably not designed as fuel cell cars from scratch, and expert 2 shared an experience of trying to fit fuel cells into a limited space. Expert 3 said that documentation and their research informed their assessments. Expert 4 explained that the stack enclosure must be large enough to accommodate the gas flow channels. Expert 20 calculated the upper bound of power density by dividing 80 kW_{net} by an enclosure volume of 3 ft³ and the lower bound by dividing the same power by about 4.5 ft³.

**Barriers to Improving Cost and Performance.** In addition to quantitatively assessing metrics, experts were asked to rank barriers to improving cost and performance. Fig. 5 presents experts’ rankings of barriers to reducing system cost. Most experts identified high Pt group metal (PGM) loading as the most significant barrier. Gröger et al. (49) review Pt reduction strategies, including shape-controlled Pt alloys (50), dealloyed catalysts (51), core and core–shell substrates coated with Pt monolayers (52, 53), nanostructured thin films (54), and non-PGM catalysts (55). A scenario analysis (56) indicates that, at high FCEV production volumes, the scarcity and price volatility of Pt could necessitate the use of non-Pt catalysts. Several experts highlighted bipolar plate (BPP) cost as a significant barrier to reducing system cost. Hydroforming, which uses high-pressure liquid to form flow channels (57), could reduce the BPP press and tooling capital costs while increasing the number of plates produced per stamp (58). Anticorrosion coating also contributes significantly to the BPP cost (58). In the 2014 Mirai, Toyota replaced gold-coated stainless-steel separator plates with carbon-coated titanium plates (59). Fourteen experts identified the

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**Fig. 2.** Experts’ recommended government R&D funding levels in FY 2018. For each R&D area, we present the median of experts’ recommended funding levels, the FCTO’s FY 2017 request, and the FCTO’s FY 2017 appropriation. The error bars represent the IQRs of experts’ funding levels. "Catalysts and electrodes" addresses PGM loading, activity, durability, and impurity tolerance of electrodes and electrocatalysts, and electrode design and fabrication. "Fuel cell performance and durability" refers to the durability and stability of PEMFC components, and the performance, diagnostics, characterization, and modeling of PEMFCs. "Membranes and electrolytes" addresses the conductivity, stability, fabrication, testing, characterization, and cost of electrolytes. "Testing and technical assessment" includes economic and technical analyses, experimentation on long-term stack failure, property characterization of fuel cell components and stacks, and technology status updates (37).

**Fig. 3.** Experts’ assessments of PEMFC system cost (2017 USD). Each data point represents an expert’s best estimate, and the uncertainty ranges represent experts’ judgments of a 95% CI. Expert 36 provided only a lower bound across all years. The group interview is marked by an asterisk. (A) 2017 values. The horizontal line represents the DOE’s 2015 estimate of $53/kW. The vertical axis is broken between $500/kW and $1,000/kW. (B) 2020 values. The horizontal line represents the DOE’s 2020 target of $40/kW. (C) 2035 values. The horizontal line represents the DOE’s ultimate target of $30/kW. (D) 2050 values. The horizontal line represents the DOE’s ultimate target of $30/kW.
membrane cost as the second most significant barrier. 3M has developed a perfluorimide acid ionomer, which is a multifaceted acid polymer electrolyte that allows for lower equivalent weights (higher conductivity) without problematic increases in water solubility (60). *SI Appendix, section S7 and Figs. S15 and S16* present experts’ written-in barriers to reducing cost.

*SI Appendix, section S7 and Figs. S15 and S16* present experts’ rankings of barriers to improving stack durability and stack power density, respectively. Several experts identified the instability of alloyed catalysts, Pt sintering, Pt dissolution, and carbon support corrosion as the most significant barriers to improving durability. Preleaching, or dealloying, improves retention of the alloyed catalyst’s base metal (61). Experts identified the high cathode activation loss and the Pt–electrolyte O2 transport resistance (44) as the most significant barriers to improving power density. Pt3Ni nanoframe catalysts (50), among other options, have exhibited a significantly higher mass activity than that of Pt/C.

**Summary and Conclusions**

We elicited experts’ assessments of automotive PEMFC system cost, stack durability, and stack power density. We asked experts to quantitatively assess PEMFCs’ cost and performance, rank barriers to improving performance, and recommend government R&D funding levels necessary to achieve the DOE’s targets.

Most respondents anticipated that the DOE’s ultimate cost target of $30/kW would be met by 2050, but most respondents provided 2020 assessments higher than the DOE’s 2020 target of $40/kW. Reaching 500,000 units/y in the near term, given any performance level, is uncertain because of the learning required to produce at this scale. Experts identified Pt, membrane, and BPP costs as significant barriers to reducing system cost.

From 2020 to 2050, over 45% of respondents expected the DOE’s targets for stack durability to be met. Experts identified the instability of alloyed catalysts, Pt sintering, Pt dissolution, carbon support corrosion, and membrane degradation as the most significant barriers to improving durability.

Experts suggested that a median stack power density of 3 kW/L could be achieved by 2035 but specified lower median performance in 2017 and 2020. Improving stack power density would reduce the amount of materials and, therefore, stack cost.

R&D funding recommendations were allocated to “catalysts and electrodes,” followed in decreasing amount by “fuel cell performance and durability,” “membranes and electrolytes,” and “testing and technical assessment.”

Expert elicitation could be an ongoing method to reevaluate program goals in a rapidly evolving energy landscape. Our elicitation could inform the development of current benchmarks, characterize future uncertainty, and help prioritize science and engineering activities for PEMFCs.

**Fig. 4.** Experts’ assessments of PEMFC stack durability. (A) 2017 values. The solid horizontal line represents the DOE’s 2015 stack durability estimate of 3,900 h. The dashed horizontal line represents the DOE’s 2015 membrane electrode assembly durability estimate of 2,500 h. (B) 2020 values. The horizontal line represents the DOE’s 2020 stack durability target of 5,000 h. (C) 2035 values. The horizontal line represents the DOE’s ultimate stack durability target of 8,000 h. (D) 2050 values. The horizontal line represents the DOE’s ultimate stack durability target of 8,000 h.

**Fig. 5.** Experts’ rankings of barriers to reducing automotive PEMFC system cost. The number of experts who selected each barrier is indicated (darker cells indicate more experts). The barriers shown were selected from a list.

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