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.

fuel cell electric vehicle | expert elicitation | cost | durability | power density

Since their invention in the 1950s, proton exchange membrane fuel cells (PEMFCs) have powered spacecraft (1), submarines (2), buses (3), material handling equipment (4), buildings (5), and automobiles (6). Over the past several decades, PEMFCs have evolved technically. In 1967, General Electric replaced PEMFCs' sulfonated polystyrene membrane with a more chemically stable membrane, Nafion (7–9). In the 1980s and 1990s, Los Alamos National Laboratory reduced PEMFCs' Pt loading over 20-fold (10–12). In 1996, Ballard reported a stack power density over three times greater than that of the company's previous generation (3). Between fiscal year (FY) 1990 and FY 2016, the US Department of Energy (DOE) invested $2.4 billion to advance fuel cell and hydrogen technologies (13). The United States has promoted the adoption of PEMFCs through such policies as the Fuel Cell Motor Vehicle tax credit (14), California's Zero Emission Vehicle Regulation (15), and state rebates (16). *SI Appendix*, section S1 reviews PEMFCs' history in more detail.

Despite decades of development, significant public and private support, and the inception of incentive-based policies, automotive PEMFCs lack wide market acceptance. In 2017, 12,000 fuel cell units were shipped worldwide for transportation applications (17). (The 2017 shipment data in ref. 17. includes projections for November and December.) However, these shipments constituted less than 0.1% of the 97 million vehicles produced globally in 2017 (18). Several countries have set targets to increase production, but these targets range widely. Japan aims to produce 200,000 automotive fuel cell electric vehicles (FCEVs) cumulative by 2025 (19), the United Kingdom aims to produce tens of thousands of FCEVs (cars, trucks, and buses) cumulative by 2025 (20), and China aims to produce 1 million FCEVs cumulative by 2030 (21). Uncertainty characterizes PEMFCs' path to widespread commercialization.

In this paper, we offer an expert elicitation assessment of the current and expected future cost and technical performance of automotive PEMFCs. We interviewed 39 experts, spread across academia, government, and industry, to assess system cost, stack durability, and stack power density. Expert elicitation, which is a formal, systematic procedure for gathering experts' assessments of a technology's cost and performance (22, 23), enables the identification of technical and economic barriers and characterizes the uncertainty associated with future technological developments. Prior expert elicitations have assessed the cost and performance of solar technologies (24), wind power (25), and nuclear reactors (26), as well as the market potential of FCEVs (27). We offer an expert

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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elicitation to assess PEMFC cost and performance. We review previous expert elicitations 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) can 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).

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 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. *SI Appendix*, section S3 describes our materials and methods, and *SI Appendix*, section S4 presents our interview protocol.

When preparing our interview protocol, we sought to minimize linguistic uncertainty, or uncertainty associated with a question's wording or presentation (41). When eliciting experts' assessments of automotive system cost, we provided experts with the layout of a 2015 system analyzed in a DOE-funded study (42). The system comprises the PEMFC stack, air precooling and stack cooling systems, cathode humidification system, air loop, and fuel loop. The system excludes hydrogen storage, power electronics, electric drive, and the battery. Consistent with one of the DOE-funded study's cost scenarios, we asked experts to (*i*) assume a total production volume of 500,000 units/y, although we recognize that today's production volumes are in the thousands of units/year (17); (*ii*) exclude any sales markup applied by the final system assembler for profit, overhead, and other business expenses; and (*iii*) assume a power system rated to generate 80 $\mathrm{kW_{net}}$.

Table 1. Summary of experts' background information

Description	No.
Experts interviewed	39
Institutions and organizations represented	30
Years spent working with fuel cells*	
Cumulative	>700
Average	18 (SD = 8)
Experts working in:	
Academia[†]	9
Government	13
Industry[‡]	17
Highest degree earned	
PhD	33
Master's	6
Average self-assessed expertise in:	
PEMFC light-duty vehicle systems	5.5 (SD = 1.7)
PEMFC components	6.0 (SD = 1.7)
PEMFC stationary power systems	4.5 (SD = 1.6)

*Two experts provided lower bounds for their years of experience (e.g., 25+ y). We included these experts' lower bounds in our calculations.

[†] Academia includes all educational institutions.

[‡] Industry includes public–private partnerships and government consultants.

When eliciting experts' assessments of stack durability and stack power density, we asked experts to assume definitions and protocols consistent with those published in the MYRD&D Plan (37). We defined durability as the time until the stack's rated power reduces to a value that is 10% less than its beginning-of-life rated power under the DOE's drive-cycle durability protocol. We defined the stack power density as the PEMFC system's rated net power, which equals the stack power minus balance-of-plant power, divided by the stack enclosure's volume. We specified that the stack operates on direct hydrogen and air up to 150 $\mathrm{kPa_{abs}}$ at its inlet.

For each of cost, durability, and power density, we gave experts a list of 7–10 barriers, and we asked experts to rank the 3 most significant barriers to improving PEMFC cost and performance. We formed these lists based on government reports (37, 42), peer-reviewed literature (43, 44), and feedback that we received during our testing sessions. We describe our testing sessions in *SI Appendix*, section S3. When eliciting experts' funding recommendations, we asked experts to specify the minimum funding that they thought would be necessary to meet the DOE's targets (37).

We interviewed 39 experts from academia, government, and industry who had worked extensively with PEMFCs, hydrogen storage, or both technologies. Table 1 summarizes experts' background. We identified experts based on their work experience, publications, patents, and academic training. Three of our experts participated in a group interview, resulting in 37 interviews total. All but one government expert worked in a DOE National Laboratory, and one government expert worked for a government agency. Industry experts comprised chief technology officers, chief executive officers, presidents, managers, specialists, scientists, and researchers. All but one academic expert worked as a university professor. In the figures that follow, we mark results from the group interview with an asterisk, as groups could be biased by groupthink (45) or group polarization (46). We conducted 8 interviews face-to-face and 29 interviews over the phone or Skype. All but one expert resided in the United States. [We interviewed only experts who were residing in or visiting the United States. Carnegie Mellon's Institutional Review Board (IRB) required that we obtain permission from an expert's home country or institution prior to interviewing experts residing and located outside the United States.] At the end of each interview, we asked the expert to self-assess their expertise in PEMFC light-duty vehicle systems, PEMFC (cell) components, and PEMFC stationary power systems on a scale from 0 (not familiar) to 7 (very familiar). For the group interview, we report the highest self-assessment of the individuals in the group. Carnegie Mellon University's IRB approved our study. Before conducting interviews, we informed experts about our study and obtained their consent to participate.

Results and Discussion

Combined Assessments. Fig. 1*A* presents experts' assessments of PEMFC system cost (2017 USD). The medians of experts' best estimates are banded by interquartile ranges (IQRs), which span the 25th and 75th percentiles of experts' best estimates. Unless otherwise noted, the DOE values referenced hereafter have been published in the 2016 MYRD&D Plan (37). The DOE most recently published their targets in 2016, and the target of \$30/kW has remained the same since 2002 (38). [The DOE does not specify whether their targets are in nominal or real dollars, but the targets have remained constant over time when compared to estimated current costs in nominal dollars (38).] Fifteen experts expected the DOE's ultimate target of \$30/kW to be met by 2050. However,

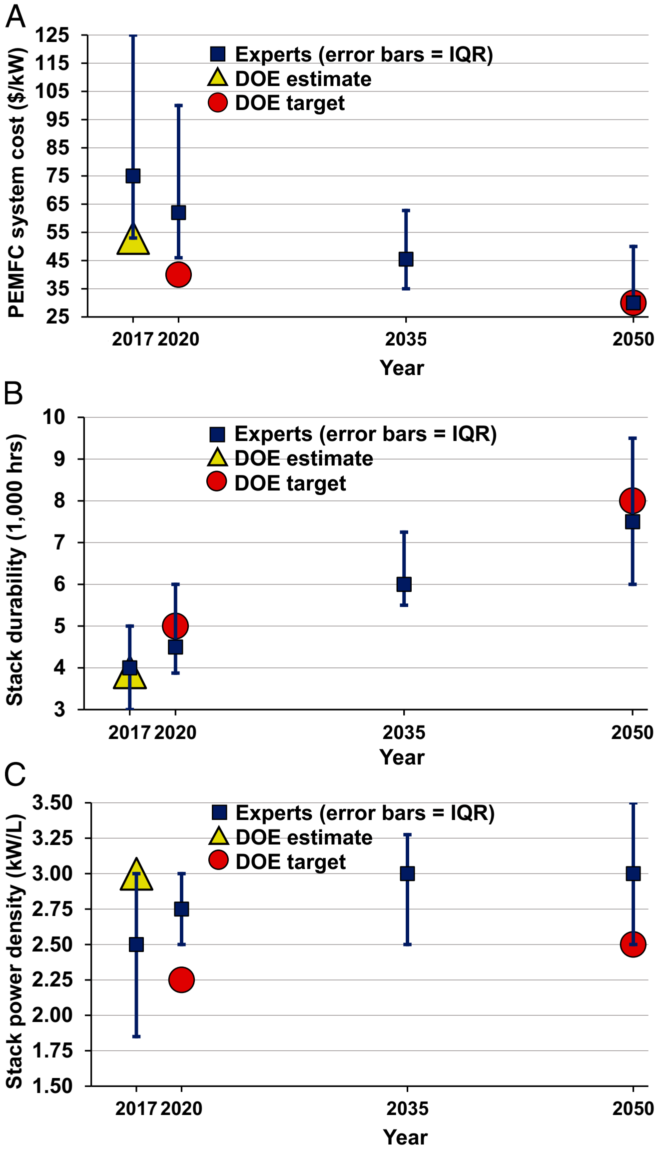


Fig. 1. Experts' assessments of PEMFC cost and performance in 2017, 2020, 2035, and 2050. Each square represents the median of experts' best estimates, and the error bars represent the IQRs of experts' best estimates. For each metric, we show the DOE's 2015 estimate (plotted in 2017), the DOE's 2020 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. 1*C*, 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. *SI Appendix*, section S5, Fig. S6, and Table S4 present experts' assessments organized by affiliation. For each R&D area, based on their median recommendations, academic experts recommended two to four times more funding than that appropriated 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/y. Expert 2 remarked that current production volumes are not close to this scale, and expert 8 commented that more learning needed to occur before manufacturing costs would decline. Expert 33 rejected our assumption of 500,000 units/y, 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, 50,000–100,000 units/y in 2020, 100,000–200,000 in 2035, and 500,000 in 2050. [Because expert 33 assumed 2017, 2020, and 2035 production volumes that differed from that stated in the question (500,000 units/y), 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.

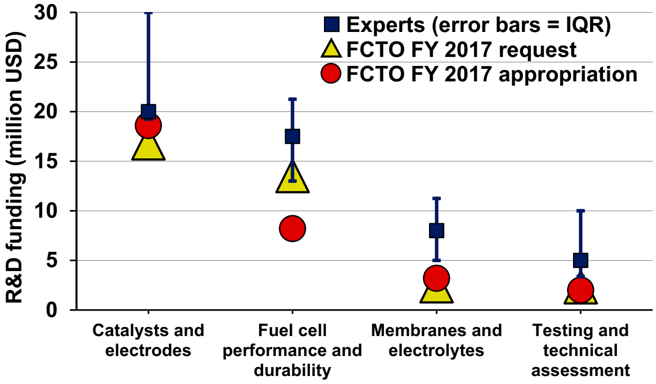


Fig. 2. Experts' recommended government R&D funding levels in FY 2018. For each R&D area, we present the median of experts' recommended funding levels, the FCTO's FY 2017 request, and the FCTO's FY 2017 appropriation. The error bars represent the IQRs of experts' funding levels. "Catalysts and electrodes" 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).

SI Appendix, section S5 and Fig. S7 present experts' assessments of stack power density. Experts' 2017 best estimates ranged from 0.5 to 4 kW/L (CIs, 0.3–5 kW/L). Expert 14 remarked that companies 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 ft^3 and the lower bound by dividing the same power by about 4.5 ft^3.

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

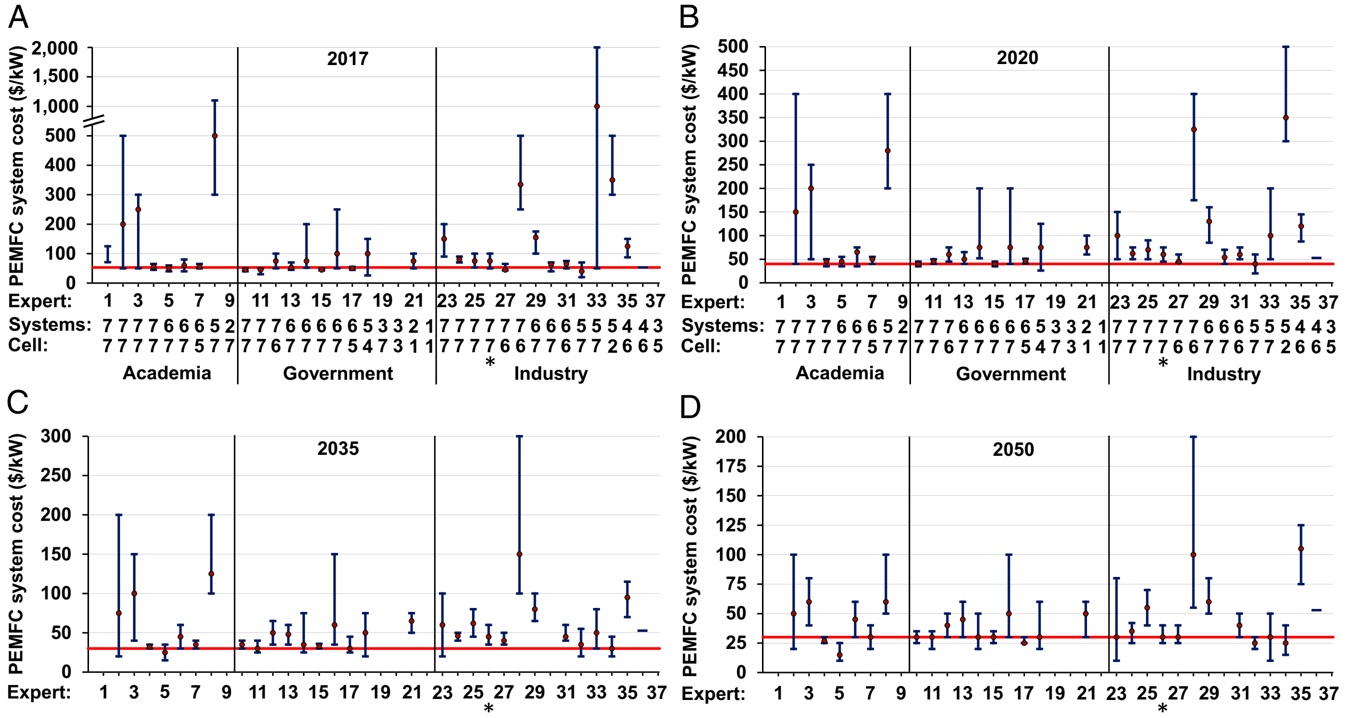


Fig. 3. Experts' assessments of PEMFC system cost (2017 USD). Each data point represents an expert's best estimate, and the uncertainty ranges represent experts' judgments of a 95% CI. Expert 36 provided only a lower bound across all years. The group interview is marked by an asterisk. (*A*) 2017 values. 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.

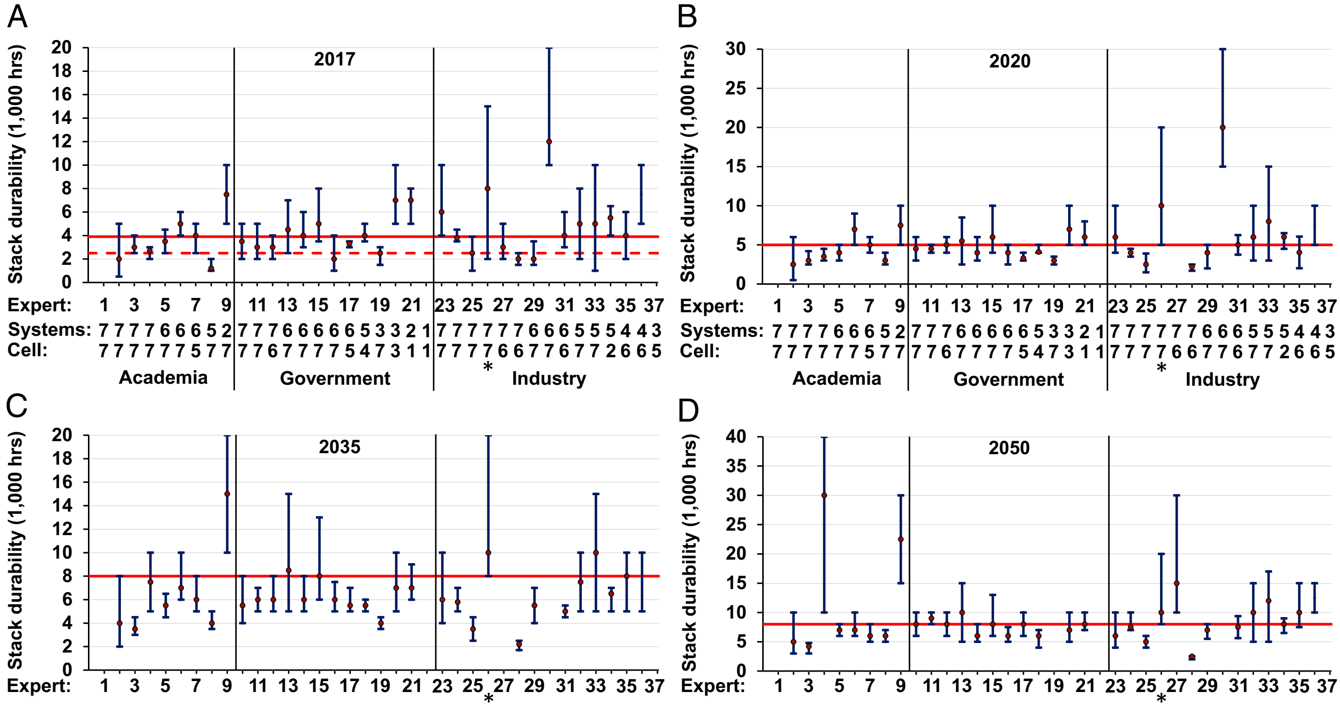


Fig. 4. Experts' assessments of PEMFC stack durability. (*A*) 2017 values. The solid horizontal line represents the DOE's 2015 stack durability estimate of 3,900 h. The dashed horizontal line represents the DOE's 2015 membrane electrode assembly durability estimate of 2,500 h. (*B*) 2020 values. The 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.

membrane cost as the second most significant barrier. 3M has developed a perfluorimide acid ionomer, which is a multiacid side chain polymer electrolyte that allows for lower equivalent weights (higher conductivity) without problematic increases in water solubility (60). *SI Appendix*, section S7 and Fig. S14 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 O_2 transport resistance (44) as the most significant barriers to improving power density. Pt_3Ni 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.

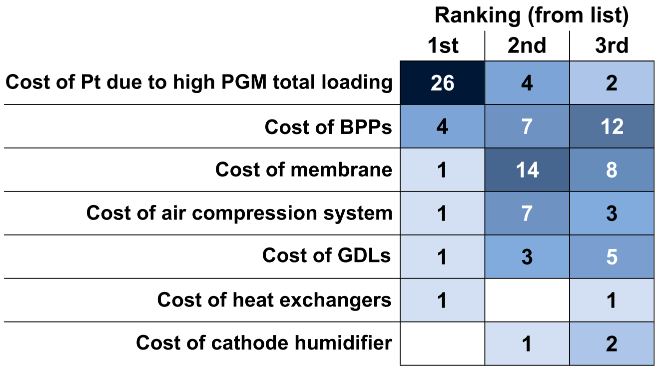
Most respondents anticipated that the DOE's ultimate cost target of \$30/kW would be met by 2050, but most respondents provided 2020 assessments higher than the DOE's 2020 target of \$40/kW. Reaching 500,000 units/y in the near term, given any performance level, is uncertain because of the learning required 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.



	Ranking (from list)		
	1st	2nd	3rd
Cost of Pt due to high PGM total loading	26	4	2
Cost of BPPs	4	7	12
Cost of membrane	1	14	8
Cost of air compression system	1	7	3
Cost of GDLs	1	3	5
Cost of heat exchangers	1		1
Cost of cathode humidifier		1	2

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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