Supporting Information

Section S1

History of Proton Exchange Membrane Fuel Cells

www.pnas.org/cgi/doi/10.1073/pnas.1804221116

History of Applications

Fig. S1 presents a timeline of proton exchange membrane fuel cell (PEMFC) applications. PEMFCs were first used in the U.S. Gemini space missions, beginning with Gemini-5 in 1965 (1). The Gemini spacecraft relied on two, 1 kW PEMFC systems, manufactured by General Electric (GE), to provide on-board power and drinking water (2, 3). Allis-Chalmers operated the first fuel cell electric vehicle (FCEV), a fuel cell tractor, in 1959, and General Motors (GM) demonstrated the first fuel cell-powered van, the Electrovan, in 1966. Both of these vehicles ran on alkaline fuel cells (AFCs) (4–7). GE began developing PEM electrolyzers in 1967 (8), and by 1991, the U.S. had operated electrolyzer systems for over 350,000 hrs cumulative across all systems to generate O_2 aboard nuclear submarines (9). In 1993, the California Institute of Technology's Jet Propulsion Laboratory and University of Southern California invented the direct methanol fuel cell (DMFC), which is a PEMFC fueled by methanol (10). In 2003, Toshiba announced the development of the first DMFC laptop (11).

PEMFC automobiles and buses began emerging in the 1990s. In 1994, DaimlerChrysler developed the first PEMFC-powered vehicle, the New Electric Car Number 1 (NECAR 1), which ran on a 50 kW PEMFC system and stored hydrogen gas at 300 bar. In 1996, DaimlerChrysler developed the NECAR 2. The NECAR 2's fuel cell system operated at a power density 10 times higher than that of the NECAR 1 (12). In 2002, Toyota leased the first commercial FCEV, the Fuel Cell Hybrid Vehicle (FCHV), and between 2002 and 2012, Daimler, Ford, GM, Nissan, Hyundai, Kia, and Honda demonstrated FCEV models (13). Toyota began selling their Mirai FCEV in 2014 (14). In 1993, Ballard announced the completion of the first demonstration PEMFC transit bus (15). In 1996, Ballard reported the completion of a

commercial PEMFC bus prototype. This prototype operated on a 200 kW PEMFC system and had a range of 250 miles (16).

More recently, PEMFCs have emerged in stationary power applications. The Japanese government deployed over 3,000 PEMFC residential CHP systems between 2005 and 2008 as part of its ENE-FARM demonstration project, leading to the commercialization of Japan's ENE-FARM system in 2009. Japan expanded their micro-CHP offerings to include solid oxide fuel cell systems in 2012 (17). As of October 2017, Japan had sold 223,000 ENE-FARM systems cumulative (18).

History of Technical Developments

Fig. S2 presents a timeline of PEMFC technical developments. The first PEMFC, invented by Willard T. Grubb at GE, incorporated a sulfonated polystyrene membrane (19–22). In 1967, aboard the Biosatellite spacecraft (3, 23), NASA began using Dupont's Nafion membrane, a perfluorosulfonic acid (PFSA) membrane that is more chemically stable than sulfonated polystyrene (24) and remains widely used today. In the 1980s and 1990s, Los Alamos National Laboratory (LANL) reduced PEMFCs' Pt loading from 4 mg/cm^2 to less than 0.2 mg/cm^2. These ultra-low Pt loadings emerged from a refinement of techniques at LANL, including the impregnation of Pt/C catalyst with Nafion ionomer (25), bonding thin film catalyst layers to the membrane and peeling away the Teflon decal substrates (26), and painting thin film catalyst layers onto the membrane (27). Texas A&M University investigated different techniques for depositing additional, thin Pt layers onto the electrodes, including painting, chemical deposition, and electrochemical deposition (28). In 1993, Texas A&M reported the performance of Pt alloy (Pt-Ni, Pt-Cr, Pt-Co) catalysts. The Pt alloys exhibited specific activities 2.4–3.6 times greater than that of Pt/C (29). Toyota used Pt-Co catalyst in their 2014 Mirai FCEV.

Ballard Power Systems, headquartered in Vancouver, Canada, has advanced PEMFC technology since the 1980s. In 1987, Ballard improved PEMFCs' power density by replacing Nafion with a membrane manufactured by The Dow Chemical Company (30, 31). Between 1984 and 1986, Ballard undertook a government-funded project to (i) develop a stack that could operate on both air and pure oxygen and (ii) demonstrate a selective oxidation process to mitigate CO poisoning in PEMFCs. Within the next several years, Ballard would report stack hardware that could operate on air and CO-containing reformate while achieving an operating voltage comparable to that of an H_2/O_2 or H_2/air stack (30). In 2017, Ballard and Nisshinbo Holdings announced the development of the world's first PEMFC product catalyzed by a non-precious metal. Ballard had planned to launch this product in late 2017 (32).

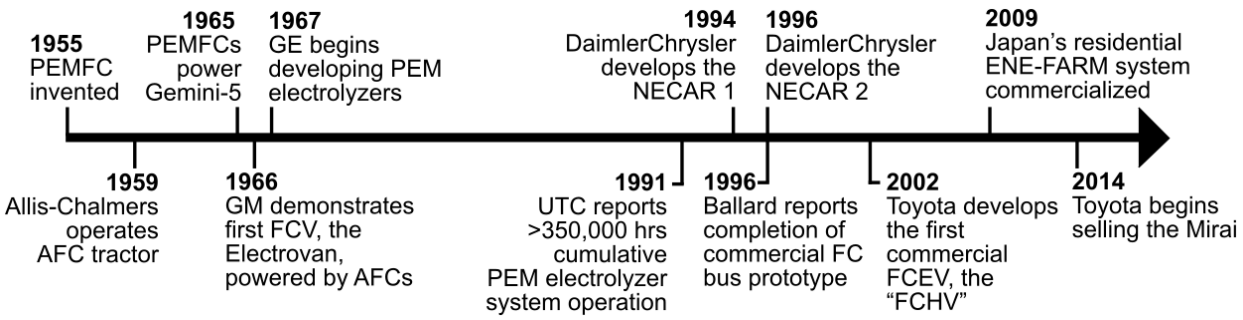


Fig. S1. History of PEMFC applications.

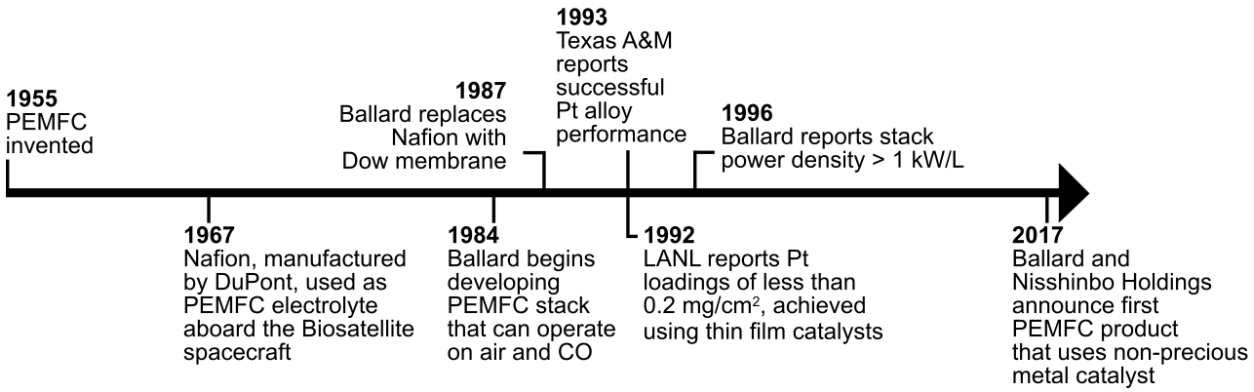


Fig. S2. History of PEMFC technical developments.

References

1. Maget HJR (1968) The ion exchange membrane fuel cell. *Fuel Cell Technology*, ed Berger C (Prentice-Hall, Englewood Cliffs), pp 423–493.

2. Chen E (2003) History. *Fuel Cell Technology Handbook*, ed Hoogers G (CRC Press, Boca Raton), pp 2-1–40.

3. Warshay M, Prokopius PR (1990) The fuel cell in space: Yesterday, today and tomorrow. *J Power Sources* 29(1–2):193–200.

4. Marks C, Rishavy EA, Wyczalek FA (1967) Electrovan—A fuel cell powered vehicle. *Automotive Engineering Congress and Exposition* (SAE International, Detroit, MI), pp 992–1002.

5. von Helmolt R, Eberle U (2007) Fuel cell vehicles: Status 2007. *J Power Sources* 165(2):833–843.

6. Garche J, Jürissen L (2015) Applications of fuel cell technology: Status and perspectives. *Electrochem Soc Interface* 24(2):39–43.

7. Ihrig HK (1960) The fuel cell powerplant for electrically propelled earthmoving machinary. *11th Annual Earthmoving Industry Conference* (SAE International), pp 1–4.

8. Russell JH, Nuttall LJ, Fickett AP (1973) Hydrogen generation by solid polymer electrolyte water electrolysis. *Division of Fuel Chemistry: Meeting 166* (American Chemical Society, Chicago, IL), pp 24–40.

9. McElroy JF, Molter TM, Roy RJ (1991) SPE Water Electrolyzers for Closed Environment Life Support. *21st International Conference on Envirornmental Systems* (SAE International, San Francisco, CA), pp 261–270.

10. Surampudi S, et al. (1997) Aqueous liquid feed organic fuel cell using solid polymer electrolyte membrane (U.S. Patent No. 5,599,638), U.S. Patent and Trademark Office.

11. Toshiba (2003) Toshiba announces world's first small form factor direct methanol fuel cell for portable PCs. Available at: https://www.toshiba.co.jp/about/press/2003_03/pr0501.htm [Accessed July 31, 2018].

12. Schmid H-P, Ebner J (2003) DaimlerChrysler fuel cell activities. *Handbook of Fuel Cells*, eds Vielstich W, Lamm A, Gasteiger HA (John Wiley and Sons, Chichester), pp 1167–1171.

13. Qin N, Raissi A, Brooker P (2014) *Analysis of fuel cell vehicle developments* Available at: http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1987-14.pdf.

14. Toyota's hydrogen-powered Mirai goes on sale in Japan (2014) *The Japan Times*. Available at: https://www.japantimes.co.jp/news/2014/12/15/business/toyotas-hydrogen-powered-mirai-goes-sale-japan/#.WjrTRt-nGM9 [Accessed July 31, 2018].

15. Prater KB (1994) Polymer electrolyte fuel cells: A review of recent developments. *J Power Sources* 51(1–2):129–144.

16. Prater KB (1996) Solid polymer fuel cells for transport and stationary applications. *J Power Sources* 61(1–2):105–109.

17. Ito H (2016) Economic and environmental assessment of residential micro combined heat and power system application in Japan. *Int J Hydrogen Energy* 41(34):15111–15123.

18. Yamakage M, Kawamura S (2017) *IPHE country update November 2017: Japan* Available at: https://docs.wixstatic.com/ugd/45185a_5f6d4c8dc906443cae4474c6b1d3002d.pdf.

19. Grubb WT (1959) Fuel cell (U.S. Patent No. 2,913,511), U.S. Patent and Trademark Office.

20. Grubb WT (1959) Batteries with solid ion exchange electrolytes: I. Secondary cells employing metal electrodes. *J Electrochem Soc* 106(4):275–278.

21. Grubb WT, Niedrach LW (1960) Batteries with solid ion-exchange membrane electrolytes: II. Low-temperature hydrogen-oxygen fuel cells. *J Electrochem Soc* 107(2):131–135.

22. Perry ML, Fuller TF (2002) A historical perspective of fuel cell technology in the 20th century. *J Electrochem Soc* 149(7):S59–S67.

23. General Electric (1980) *Solid polymer electrolyte fuel cell technology program* Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19800019300.pdf.

24. LaConti AB, Hamdan M, McDonald RC (2003) Mechanisms of membrane degradation. *Handbook of Fuel Cells*, eds Vielstich W, Lamm A, Gasteiger HA (John Wiley and Sons, Chichester), pp 647–662.

25. Srinivasan S, Ticianelli EA, Derouin CR, Redondo A (1988) Advances in solid polymer electrolyte fuel cell technology with low platinum loading electrodes. *J Power Sources* 22(3–4):359–375.

26. Wilson MS, Gottesfeld S (1992) Thin-film catalyst layers for polymer electrolyte fuel cell electrodes. *J Appl Electrochem* 22(1):1–7.

27. Wilson MS, Gottesfeld S (1992) High performance catalyzed membranes of ultra-low Pt loadings for polymer electrolyte fuel cells. *J Electrochem Soc* 139(2):L28–L30.

28. Srinivasan S, Manko DJ, Koch H, Enayetullah MA, Appleby AJ (1990) Recent advances in solid polymer electrolyte fuel cell technology with low platinum loading electrodes. *J Power Sources* 29(3–4):367–387.

29. Mukerjee S, Srinivasan S (1993) Enhanced electrocatalysts of oxygen reduction on platinum alloys in proton exchange membrane fuel cells. *J Electroanal Chem* 357(1–2):201–224.

30. Prater K (1990) The renaissance of the solid polymer fuel cell. *J Power Rouces* 29(1–2):239–250.

31. Ezzell BR, Carl WP (1995) Low equivalent weight sulfonic fluoropolymers (European Patent No. 0289869B1), European Patent Office.

32. Ballard Power Systems (2017) Ballard receives Nisshinbo P.O. for development program to advance use of non precious metal catalyst fuel cells in material handling. Available at: http://www.ballard.com/about-ballard/newsroom/news-releases/2017/09/18/ballard-receives-nisshinbo-p.o.-for-development-program-to-advance-use-of-non-precious-metal-catalyst-fuel-cells-in-material-handling [Accessed July 31, 2018].

Supporting Information

Section S2

Expert Elicitation Overview

Description of Expert Elicitation

Expert elicitation consists of several steps, beginning with preparation and testing. Researchers first determine which metrics to elicit (1). These metrics are often drawn from the scientific literature (2). For example, Sakti et al. (3) elicited experts' assessments of battery manufacturing costs, and Bistline (4) elicited experts' assessments of gas turbine efficiency. The metrics may also be specified by a client, who is the decision-maker for whom the expert elicitation is being conducted (5). After determining which metrics to elicit, the interview questions should be clearly and precisely written (6, 7). To ensure that the questions are clear and unambiguous, it is good practice to test the interview protocol prior to beginning the study (8, 9). Following testing, the experts are recruited based on their background (2) or peer nominations (10). Recruiting experts from diverse backgrounds helps ensure that the study captures diverse views (2, 9). While it has been recommended that expert elicitations involve between 6 and 12 experts to ensure the robustness of results and make the best use of resources (11), prior studies have ranged between 4 (e.g., Ref. (4)) and 163 (e.g., Ref. (12)) experts.

After the protocol has been written and tested, and experts have been recruited, the elicitation is carried out. During the elicitation interview, the expert's beliefs are "encoded," or recorded, according to a specified format, such as a probability distribution, ranking, or interval of values (2, 13). During the interview, the facilitator watches for signs of cognitive heuristics that could bias an expert's responses. Such heuristics include anchoring and adjustment, and availability (14). Conducting interviews face-to-face fosters interaction between the facilitator and expert. Conducting interviews by phone or survey may be more economical (15). After completing all interviews, researchers can combine experts' assessments or leave them separate. Clemen and Winkler (16) present methods for combing experts' assessments. Morgan (17)

mentions scenarios under which it would be best to leave the experts' assessments separate—namely, when experts differ significantly in their assumptions, or when the results are fed into a nonlinear model.

Previous Expert Elicitations

Previous expert elicitations have assessed the cost and performance of emerging technologies. Sakti et al. (3) elicited experts' manufacturing cost assessments of Li-ion batteries. Experts were asked to provide their best guesses, banded by 95% confidence intervals, for the costs of battery pack designs in 2013 and 2018. Experts generally agreed with values reported in the literature, but experts' system-level assessments disagreed with their component-level and the authors' process-based cost modeling assessments. Wiser et al. (12) elicited experts' assessments of the levelized costs of electricity of onshore and offshore wind energy, assuming a "typical" (median cost) project. Experts expected a 35–41% reduction in wind energy cost between 2014 and 2050. Previous studies have also elicited experts' assessments of nuclear reactor capital cost (8, 18, 19), coal-fired power plant efficiency and capital cost (20), biofuel capital and processing costs (21, 22), gas turbine efficiency (4), electrolyzer lifetime and capital cost (23), and technical challenges facing biofuels (22).

Several expert elicitations have assessed the cost and performance of solar technologies. Bosetti, Catenacci, Fiorese, and Verdolini (24) elicited experts' assessments of solar photovoltaic (PV) and concentrated solar power (CSP) costs of electricity. Experts estimated that PV would cost 11.7 ¢/kWh in 2030, which is consistent with the published values reviewed by the authors. Experts estimated that CSP, on the other hand, would cost 10.1 ¢/kWh in 2030, which is slightly lower than the published values reviewed by the authors. Curtright, Morgan, and Keith (25) elicited experts' assessments of PV prices. Experts were asked to specify the probabilities that

PV would achieve price thresholds by 2030 and 2050. Most experts assigned a probability of less than 0.5 that PV would achieve $0.30/W by 2030. On the other hand, most experts assigned a probability of greater than 0.5 that PV would achieve $0.30/W by 2050. Baker, Chon, and Keisler elicited experts' assessments of PV (26) and carbon capture and storage (27). The authors incorporated experts' assessments into an integrated assessment model to calculate the cost of CO_2 emissions abatement. Verdolini et al. (9) and Bistline (4) review additional energy-related expert elicitations.

In landscape ecology, Singh et al. (28) elicited experts' assessments of the severity of ecosystem stressors in New Zealand bays. Experts identified climate change, commercial fishing, sedimentation, and pollution as impactful stressors. In another study, Adams-Hosking et al. (29) elicited experts' estimates of the declining koala population in Australia. Experts indicated that the koala population is declining an average of 24% over a span of six generations. Teck et al. (30) asked experts to assess the vulnerability of California Current ecosystems to climate change, fishing, pollution, and other anthropogenic stressors. Experts indicated that coastal ecosystems are most threatened by invasive species and ocean acidification, and offshore ecosystems are most threatened by ocean acidification and demersal destructive fishing. Authors have also investigated changes in butterfly meadows over time (31), the effect of human activities on ecosystem health in the Great Lakes (32), and the extinction risk of Australian birds (33). McBride and Burgman (2) review landscape ecology studies.

In human health, authors have elicited experts' assessments of health effects and causes of illness. Hoek et al. (34) elicited experts' assessments of health effects due to ambient ultrafine particle (UFP) exposure. Experts estimated that reducing the UFP concentration by 1,000 particles/cm^3 would decrease all-cause mortality in the European Union by a median of 0.30%.

Knol et al. (10) investigated the likelihood of causal pathways between UFP exposure and cardiac events. Experts assigned the highest likelihood to the causal pathway involving respiratory inflammation, thrombosis, and plaque rupture. Hoffmann, Fischbeck, Krupnick, and McWilliams (35–37) elicited experts' estimates of the proportion of U.S. foodborne illnesses associated with various food pathogens. The authors surveyed 44 experts, whom the authors identified by peer nomination. Batz, Hoffman, and Morris (38) calculated the cost of illness and loss of quality-adjusted life years associated with pathogen-food pairs. Prior authors investigated the transmission routes of enteric illnesses (39) and the cost-effectiveness of cancer treatments (40).

References

1. Clemen RT, Reilly T (2014) *Making hard decisions* (South-Western, Cengage Learning, Mason). 3rd Ed.

2. McBride MF, Burgman MA (2012) What is expert knowledge, how is such knowledge gathered, and how do we use it to address questions in landscape ecology? *Expert Knowledge and Its Application in Landscape Ecology*, eds Perera AH, Drew CA, Johnson CJ (Springer Science+Business Media, New York), pp 11–38.

3. Sakti A, et al. (2017) Consistency and robustness of forecasting for emerging technologies: The case of Li-ion batteries for electric vehicles. *Energy Policy* 106:415–426.

4. Bistline JE (2014) Energy technology expert elicitations: An application to natural gas turbine efficiencies. *Technol Forecast Soc Change* 86:177–187.

5. O'Hagen A, et al. (2006) *Uncertain Judgements* (John Wiley & Sons, Chichester).

6. O'Hagen T (2005) Elicitation. *Significance* 2(2):84–86.

7. Sutherland WJ, Burgman MA (2015) Use experts wisely. *Nature* 526(7573):317–318.

8. Abdulla A, Azevedo IL, Morgan MG (2013) Expert assessments of the cost of light water small modular reactors. *Proc Natl Acad Sci U S A* 110(24):9686–9691.

9. Verdolini E, Anadón LD, Baker E, Bosetti V, Reis LA (2018) Future prospects for energy technologies: Insights from expert elicitations. *Rev Environ Econ Policy* 12(1):133–153.

10. Knol AB, et al. (2009) Expert elicitation on ultrafine particles: Likelihood of health effects and causal pathways. *Part Fibre Toxicol* 6:19.

11. Cooke RM, Probst KN (2006) *Highlights of the expert judgment policy symposium and technical workshop* Available at: http://www.rff.org/files/sharepoint/Documents/Conference-Summary.pdf.

12. Wiser R, et al. (2016) Expert elicitation survey on future wind energy costs. *Nat Energy* 1:1–8.

13. Spetzler CS, Staël von Holstein C-AS (1975) Probability encoding in decision analysis. *Manage Sci* 22(3):340–358.

14. Tversky A, Kahneman D (1974) Judgment under uncertainty: Heuristics and biases. *Science (80-)* 185(4157):1124–1131.

15. Knol AB, Slottje P, van der Sluijs JP, Lebret E (2010) The use of expert elicitation in environmental health impact assessment: A seven step procedure. *Environ Heal* 9:1–16.

16. Clemen RT, Winkler RL (1999) Combining probability distributions from experts in risk analysis. *Risk Anal* 19:187–203.

17. Morgan MG (2014) Use (and abuse) of expert elicitation in support of decision making for public policy. *Proc Natl Acad Sci U S A* 111(20):7176–7184.

18. Anadón LD, Nemet G, Verdolini E (2013) The future costs of nuclear power using multiple expert elicitations: Effects of RD&D and elicitation design. *Environ Res Lett* 8(3):1–10.

19. Anadón LD, Bosetti V, Bunn M, Catenacci M, Lee A (2012) Expert judgments about RD&D and the future of nuclear energy. *Environ Sci Technol* 46(21):11497–11504.

20. Chan G, Anadon LD, Chan M, Lee A (2011) Expert elicitation of cost, performance, and RD&D budgets for coal power with CCS. *Energy Procedia* 4:2685–2692.

21. Baker E, Keisler JM (2011) Cellulosic biofuels: Expert views on prospects for advancement. *Energy* 36(1):595–605.

22. Fiorese G, Catenacci M, Verdolini E, Bosetti V (2013) Advanced biofuels: Future perspectives from an expert elicitation survey. *Energy Policy* 56:293–311.

23. Schmidt O, et al. (2017) Future cost and performance of water electrolysis: An expert elicitation study. *Int J Hydrogen Energy* 42(52):30470–30492.

24. Bosetti V, Catenacci M, Fiorese G, Verdolini E (2012) The future prospect of PV and CSP solar technologies: An expert elicitation survey. *Energy Policy* 49:308–317.

25. Curtright AE, Morgan MG, Keith DW (2008) Expert assessments of future photovoltaic technologies. *Environ Sci Technol* 42(24):9031–9038.

26. Baker E, Chon H, Keisler J (2009) Advanced solar R&D: Combining economic analysis with expert elicitations to inform climate policy. *Energy Econ* 31:S37–S49.

27. Baker E, Chon H, Keisler J (2009) Carbon capture and storage: Combining economic analysis with expert elicitations to inform climate policy. *Clim Change* 96(3):379–408.

28. Singh GG, et al. (2017) Mechanisms and risk of cumulative impacts to coastal ecosytem services: An expert elicitation approach. *J Environ Manage* 199:229–241.

29. Adams-Hosking C, et al. (2016) Use of expert knowledge to elicit population trends for the koala (Phascolarctos cinereus). *Divers Distrib* 22(3):249–262.

30. Teck SJ, et al. (2010) Using expert judgment to estimate marine ecosystem vulnerability in the California Current. *Ecol Appl* 20(5):1402–1416.

31. Fabritius H, McBride M (2017) Modelling habitat persistence and impacts of management on the habitats of an endangered buttefly. *Insect Conserv Divers* 10(3):200–210.

32. Smith SDP, et al. (2015) Rating impacts in a multi-stressor world: A quantitative assessment of 50 stressors affecting the Great Lakes. *Ecol Appl* 25(3):717–728.

33. McBride MF, et al. (2012) Structured elicitation of expert judgments for threatened species assessment: A case study on a continental scale using email. *Methods Ecol Evol* 3(5):906–920.

34. Hoek G, et al. (2010) Concentration response functions for ultrafine particles and all-cause mortality and hospital admissions: Results of a European expert panel elicitation. *Environ Sci Technol* 44(1):476–482.

35. Hoffmann S, Fischbeck P, Krupnick A, McWilliams M (2007) Using expert elicitation to link foodborne illnesses in the United States to foods. *J Food Prot* 70(5):1220–1229.

36. Hoffmann S, Fischbeck P, Krupnick A, McWilliams M (2007) Elicitation from large, heterogeneous expert panels: Using multiple uncertainty measures to characterize information quality for decision analysis. *Decis Anal* 4(2):91–109.

37. Hoffmann S, Fischbeck P, Krupnick A, McWilliams M (2008) Informing risk-mitigation priorities using uncertainty measures derived from heterogeneous expert panels: A demonstration using foodborne pathogens. *Reliab Eng Syst Saf* 93(5):687–698.

38. Batz MB, Hoffman S, Morris, Jr. JG (2012) Ranking the disease burden of 14 pathogens in food sources in the United States using attribution data from outbreak investigations and expert elicitation. *J Food Prot* 75(7):1278–1291.

39. Butler AJ, Thomas MK, Pintar KDM (2015) Expert elicitation as a means to attribute 28 enteric pathogens to foodborne, waterborne, animal contact, and person-to-person transmission routes in Canada. *Foodborne Pathog Dis* 12(4):335–344.

40. Grigore B, Peters J, Hyde C, Stein K (2016) A comparison of two methods for expert elicitation in health technology technology assessments. *BMC Med Res Methdology* 16:1–11.

Supporting Information

Section S3

Materials and Methods

Preparation and Testing

We elicited experts' assessments of proton exchange membrane fuel cell (PEMFC) system cost, stack durability, and stack power density. The U.S. Department of Energy's (DOE's) Multi-Year Research, Development, and Demonstration (MYRD&D Plan), which is an extensive and regularly-updated roadmap for advancing PEMFCs, reports benchmarks and targets for system cost, stack durability, and stack power density (1). We anticipated that most experts would have opinions about, or at least be familiar with, the metrics reported therein. Similar to Abdulla, Azevedo, and Morgan (2) and Sakti et al. (3), we elicited experts' assessments as best guesses banded by 95% confidence intervals. We also asked experts to rank a list of barriers to reducing system cost and improving stack durability and stack power density. To mitigate the difficulty of ranking a long list, we asked experts to rank only the top three barriers in each list.

We worded our questions about funding to minimize motivational bias (4). We asked experts to recommend the *minimum* amount of government R&D funding in FY 2018 that they thought would be necessary to meet the technical and economic targets stated in the MYRD&D Plan (1). We asked experts to assume that funding levels after FY 2018 would remain similar to those in FY 2018. To keep our interview to a reasonable length, we removed questions about published estimates (i.e., is your estimate greater than, less than, or equal to published value X?). Throughout our interview protocol, we asked experts to express all monetary values in 2017 USD.

Prior to beginning our study, we conducted several test interviews to assess our interview protocol's clarity and organization. We interviewed three Ph.D. students, two experts from academia, and one expert from industry. One of our academic testers was co-author S. Litster.

All testers were familiar with PEMFCs from their research and work experience. None of our testers participated in the actual interviews. Based on testers' feedback, we made several changes to our protocol. One tester asked for clarification on the definition of stack power density. Did the enclosure contain only the stack, or the stack and additional system components? We added text explaining that the enclosure contained only the stack and no other components. The same tester asked for clarification on the term "production cost." At what stage of development was the markup applied? We added text explaining that no sales markup was applied by the final system assembler, but we allowed experts to consider markups applied by lower-tier suppliers. Testers specified several technical and economic barriers that we hadn't included in our original lists of barriers. Based on testers' feedback, we added the cost of gas diffusion layers to the list of cost barriers, instability of alloyed catalysts to the list of durability barriers, and large volume bipolar plates and high local Pt-electrolyte O_2 transport resistance to the list of power density barriers. Finally, we noticed that one tester looked at the MYRD&D Plan for some time during the interview. We added text at the beginning of the protocol stating that experts could use any resources before, during, or after the interview, but we asked experts to refrain from restating values from the literature if they didn't feel comfortable answering a question (5).

While not discussed in this paper, the second half of our protocol asked experts for their assessments of hydrogen storage cost and capacity. We intend to publish our hydrogen storage results in future work.

Expert Recruitment

We invited 88 experts to participate in our expert elicitation, 42 of whom accepted our invitation. Thus, our response rate was 48%. We recruited experts who had worked extensively with PEMFCs, hydrogen storage, or both technologies, as demonstrated by their education, work

experience, publications, and patents. Three of our experts chose to only answer questions related to hydrogen storage; these experts' assessments are not reported in this paper. Consequently, 39 experts' assessments are included in this paper. Experts from academia, government, and industry participated in our study. To capture a range of perspectives, we recruited experts from various backgrounds (5–9). Experts differed in their familiarity with light-duty vehicle systems and PEMFC components. We report experts' self-assessed expertise in Table 1 of the paper's main text. We completed all interviews between May 11, 2017 and August 2, 2017.

We received approval from Carnegie Mellon University's Institutional Review Board prior to conducting our study. We protected experts' identities by assigning each participant a number. We used this number on the recording, interview protocol, reports, and publications. Before conducting an interview at an expert's workplace, we obtained permission from the expert's supervisor, manager, or department head. If the expert had the authority to authorize the interview at their workplace, then the expert could self-authorize the interview.

Interviews

Before an experts' interview, we emailed the interview protocol and supplementary material to the expert. The supplementary material comprised the MYRD&D Plan's Fuel Cell and Hydrogen Storage chapters (10), a summary of the DOE's funding history, and an information sheet describing the study's purpose, procedures, compensation, and measures our research team took to protect experts' identities. The funding summary comprised breakdowns of the Fuel Cell Technologies Office's (FCTO's) budgets, between FY 2007–2017, into R&D categories. We obtained the FCTO's budgets from the DOE's Annual Merit Review proceedings (11) and annual Progress Reports (12).

After sitting down with the expert, we briefed the expert about our study.[*] We reminded the expert that the interview would be recorded but that we would protect the expert's identity by assigning them a number. We shared with the expert that we would only ask questions about publicly available system designs. The expert was encouraged to think out loud, ask questions, and make comments during the interview. We also briefed the expert about cognitive heuristics. We explained the bias of overconfidence, which describes an uncertainty range that fails to capture a metric's true value (13, 14). To illustrate overconfidence, we described Henrion and Fischhoff's (15) study of the historical estimates of the speed of light. The uncertainty ranges failed to capture the physical constant's true value. We also highlighted the heuristic of availability, which describes a respondent's tendency to assess an event's probability based on how readily they recall instances of that event (16, 17). To illustrate availability, we described Lichtenstein, Slovic, Fischhoff, Layman, and Combs's (18) experiment on individuals' judgments of the frequency of death due to various causes. People tended to overestimate the number of deaths due to relatively rare causes, whereas they underestimated the number of deaths due to relatively common causes. Lastly, we discussed the heuristic of anchoring and adjustment, which is the selection of an initial value that serves as the starting point for subsequent estimation and prediction. The resulting uncertainty range is often too narrow (13, 14, 17).

At the beginning of each interview, the facilitator presented the expert with a practice question. The practice question illustrated the order in which the expert's responses would be recorded during the interview. To minimize anchoring and adjustment, the expert was asked to provide their lower bound estimate first, followed by their upper bound estimate, and finally,

[*] Throughout this section, "we" refers to the expert elicitation facilitator, co-author M. M. Whiston.

their "best guess," or most likely value (14, 19). During face-to-face interviews, the expert was asked to write their responses on their copy of the interview protocol. During phone or Skype interviews, the expert was asked to dictate their responses to the facilitator. On average, interviews lasted 1 hr, 13 mins. Interviews ranged in duration between 25 mins and 2 hrs, 32 mins.[†]

During each interview, we watched for signs that an expert misunderstood a question, made assumptions different from those specified in the question, or expressed values in units different than those requested in the question. If any of these issues were detected, we brought them to the expert's attention and gave them the opportunity to revise their responses.

At the end of the interview, we collected the expert's background information. We asked the expert to provide the title of their current position, fuel cell types with which they have worked, number of years they have spent working with fuel cells, the highest level of education (degree) they have attained, and their age. We also asked the expert to indicate, on a scale from 0 (not familiar) to 7 (very familiar), their level of expertise in the following areas: PEMFC stationary power systems, PEMFC light-duty vehicle systems, PEMFC components (anode, electrolyte, etc.), physical hydrogen storage, and materials-based hydrogen storage. Prior to collecting background information, we shared with the expert that their background information would minimally impact our results but that we collected this information to emphasize the areas of expertise captured in our study.

[†] Experts who participated in the group interview skipped to the first question after reviewing the study's objective and practice question. The group shared with the facilitator that they had read the introductory material prior to the interview, composed responses beforehand, and were prepared to proceed efficiently.

Follow-Up with Experts

After completing all interviews, our research team compiled experts' de-identified assessments into a summary report. Co-author M. M. Whiston emailed this summary report to all experts. We reminded each expert of their responses without revealing any other expert's identity. We asked each expert to confirm that their responses had been correctly captured. We allowed experts to revise their assessments for reasons other than correctness, but to minimize the effects of peer pressure (6), we stipulated that an expert's original and revised assessments would be reported if an expert chose to revise their responses for reasons other than correctness. Three experts chose to revise their responses. One expert asked to adjust their stack power density assessments after realizing that they confused stack power density with system power density. A second expert answered questions about stack power density that they had previously left blank. A third expert revised a funding amount that had been incorrectly captured. No other changes were requested.

References

1. U.S. Department of Energy (2017) *Multi-year research, development, and demonstration plan: Fuel cells* Available at: https://energy.gov/sites/prod/files/2016/10/f33/fcto_myrdd_fuel_cells.pdf.

2. Abdulla A, Azevedo IL, Morgan MG (2013) Expert assessments of the cost of light water small modular reactors. *Proc Natl Acad Sci U S A* 110(24):9686–9691.

3. Sakti A, et al. (2017) Consistency and robustness of forecasting for emerging technologies: The case of Li-ion batteries for electric vehicles. *Energy Policy* 106:415–426.

4. Spetzler CS, Staël von Holstein C-AS (1975) Probability encoding in decision analysis. *Manage Sci* 22(3):340–358.

5. Meyer MA, Booker JM (2001) Selecting and motivating the experts. *Eliciting and Analyzing Expert Judgment: A Practical Guide* (American Statistical Association and Society for Industrial and Applied Mathematics, Alexandria), pp 85–98.

6. Knol AB, Slottje P, van der Sluijs JP, Lebret E (2010) The use of expert elicitation in environmental health impact assessment: A seven step procedure. *Environ Heal* 9:1–16.

7. Verdolini E, Anadón LD, Baker E, Bosetti V, Reis LA (2018) Future prospects for energy technologies: Insights from expert elicitations. *Rev Environ Econ Policy* 12(1):133–153.

8. McBride MF, Burgman MA (2012) What is expert knowledge, how is such knowledge gathered, and how do we use it to address questions in landscape ecology? *Expert Knowledge and Its Application in Landscape Ecology*, eds Perera AH, Drew CA, Johnson CJ (Springer Science+Business Media, New York), pp 11–38.

9. Keeney RL, von Winterfeldt D (1991) Eliciting probabilities from experts in complex technical problems. *IEEE Trans Eng Manag* 38(3):191–201.

10. U.S. Department of Energy (2018) Fuel cell technologies office multi-year research, development, and demonstration plan. Available at: https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22 [Accessed October 22, 2018].

11. U.S. Department of Energy (2018) Annual Merit Review and Peer Evaluation. Available at: https://www.hydrogen.energy.gov/annual_review.html [Accessed August 1, 2018].

12. U.S. Department of Energy (2018) Annual Progress Reports. Available at: https://www.hydrogen.energy.gov/annual_progress.html [Accessed August 1, 2018].

13. Morgan MG, Henrion M (1990) *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis* (Cambridge University Press, Cambridge).

14. Morgan MG (2014) Use (and abuse) of expert elicitation in support of decision making for public policy. *Proc Natl Acad Sci U S A* 111(20):7176–7184.

15. Henrion M, Fischhoff B (1986) Assessing uncertainty in physical constants. *Am J Phys* 54(9):791–798.

16. Kahneman D, Slovic P, Tversky A eds. (1982) *Judgment under uncertainty: Heuristics and biases* (Cambridge University Press, New York).

17. Tversky A, Kahneman D (1974) Judgment under uncertainty: Heuristics and biases. *Science (80-)* 185(4157):1124–1131.

18. Lichtenstein S, Slovic P, Fischhoff B, Layman M, Combs B (1978) Judged frequency of lethal events. *J Exp Psyhchology Learn Mem Cogn* 4(6):551–578.

19. O'Hagen T (2005) Elicitation. *Significance* 2(2):84–86.

Supporting Information

Section S4

Expert Elicitation Interview Protocol

Elicitation of Expert Assessments of Proton Exchange Membrane Fuel Cell and Hydrogen Storage Performance

Interview Protocol

Expert number: [Expert number]

Date: [Date of interview]

Michael M. Whiston
Postdoctoral Research Associate
Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, PA 15213

Contact information removed

Inês Azevedo
Associate Professor
Engineering and Public Policy
Co-Director, Climate and Energy Decision Making Center
Carnegie Mellon University
Pittsburgh, PA 15213

Shawn Litster
Associate Professor
Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213

Kate S. Whitefoot
Assistant Professor
Mechanical Engineering
Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, PA 15213

Constantine Samaras
Assistant Professor
Civil and Environmental Engineering
Carnegie Mellon University
Pittsburgh, PA 15213

Nathan Cheng
Master's student
Energy Science, Technology and Policy
Carnegie Mellon University
Pittsburgh, PA 15213

Jay Whitacre
Professor
Materials Science and Engineering
Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, PA 15213

Outline of the Interview Protocol

Part 1. Introduction
Follow-up with experts

Part 2. How will this elicitation work?
Answering questions
Possible issues with expert elicitation
Supplementary material
Use of outside resources

Part 3. Demonstration for eliciting a range of values

Part 4. PEMFC automotive system cost

Part 5. PEMFC stack durability

Part 6. PEMFC stack power density

Part 7. Hydrogen storage gravimetric capacity

Part 8. Hydrogen storage volumetric capacity

Part 9. Hydrogen storage cost

Part 10. Government PEMFC R&D funding

Part 11. Government hydrogen storage R&D funding

Part 12. Demographic information

Part 13. Acknowledgements

Part 14. References

Part 1. Introduction

The objective of this expert elicitation is to assess the economic and technical performance of proton exchange membrane fuel cells (PEMFCs) and hydrogen storage in light-duty vehicles.[1] This elicitation asks questions about current and future system costs, current and future technical performance of system components, and barriers to improving PEMFCs' economic and technical performance.

Thank you for participating.

Will reference be made to proprietary system designs?
We will not ask for proprietary system designs. We will only ask questions about publicly available system designs.

What will you receive upon completion of the elicitation?
We plan to summarize the de-identified results from this study and send this summary to all participants. We will summarize the results in a way that ensures that the identity of participants cannot be determined or inferred.

How will participants' identity be protected?
We will assign each participant a number. We will use this number on the interview protocol, audio recording, and transcript. No names will be recorded on the interview protocol, audio recording, transcript, report(s), or journal article(s). Recordings will be destroyed after transcription.

[1]Part 1 of this protocol has been adapted from "Expert assessments of the cost of light water small modular reactors (Appendix S2)" [Supplemental material], by A. Abdulla, I. L. Azevedo, and M. G. Morgan, 2013, *Proceedings of the National Academy of Sciences of the United States of America*, *110*, p. 2. Copyright 2013 by the authors. Adapted with permission.

Follow-up with experts

We plan to follow up with you after this elicitation. We plan to summarize the de-identified results from the individual expert elicitations and email these results to all experts who participated. Within this summary, we will remind you of your individual assessments without revealing the identity of any other experts. **We will ask each expert to read the summarized results and determine whether he or she would like to revise his or her assessments.** We will collect the revised assessments via email and create a new summary of the de-identified results, which we will then email to all experts.

Part 2. How will this elicitation work?

In this elicitation, you will be asked questions about PEMFCs' economic and technical performance.[2] You will be asked to provide your **best current** and **future estimates** for the following metrics:

- PEMFC light-duty vehicle system cost ($\$/kW_{net}$)
- PEMFC stack durability (hours)
- PEMFC stack power density ($kW_{net}/L_{enclosure}$)
- Hydrogen storage gravimetric capacity (kg H_2/kg_{system})
- Hydrogen storage volumetric capacity (kg H_2/L_{system})
- Hydrogen storage cost ($\$/kWh_{H_2}$)

You will also be asked about what you perceive to be the most significant **barriers** to improving PEMFCs' **economic and technical performance**. Lastly, you will be asked about **government funding** for fuel cells and hydrogen storage. You will be asked to recommend funding levels for several fuel cell and hydrogen storage R&D areas, and you will be asked to rank fuel cell and hydrogen storage R&D areas according to how you think they should be prioritized.

[2]Part 2 of this protocol has been adapted from "Expert assessments of the cost of light water small modular reactors (Appendix S2)" [Supplemental material], by A. Abdulla, I. L. Azevedo, and M. G. Morgan, 2013, *Proceedings of the National Academy of Sciences of the United States of America*, *110*, p. 3. Copyright 2013 by the authors. Adapted with permission.

Answering questions

When asking for your best current and future estimates, we will first ask you for a **lower bound**. We will then ask you for an **upper bound**. Lastly, we will ask you for the **most likely** value. We ask questions in this way to avoid some of the pitfalls of expert elicitation, which are discussed in the right column of this page.

When providing your lower and upper bounds, please consider a range that corresponds to a **95% confidence interval**. The lower bound is the value below which you believe the true values resides 2.5% of the time. The upper bound is the value above which you believe the true value resides 2.5% of the time. The most likely value is your "best guess."

In each section, we hope to engage in substantive discussion. If you are uncomfortable with a question or feel that a question is outside your area of expertise, please do not hesitate to outline your grievances. **If you wish to interject with a note you believe to be of particular importance, please do not hesitate to do so.** This elicitation will be audio recorded only for the purpose of transcribing your responses. Audio recordings will be destroyed after transcription.

At the end of the elicitation, we will collect demographic information about you – the expert – in a form that does not directly identify you.

Possible issues with expert elicitation

We would like to make you aware of the **subjective nature of expert elicitation**. Research shows that respondents – both experts and laypeople – tend to be **overconfident** when answering questions. There remains no clear-cut formula for how to robustly assess and adjust for this subjectivity. For example, Figure 1 on the next page illustrates experts' overconfidence in recommending values for the speed of light. Figure 1's caption explains this particular case of overconfidence in more detail.

We would like to highlight the cognitive heuristics of availability, and anchoring and adjustment. The **availability heuristic** means that a respondent's answer depends on how easy it is to recall answers to previously-asked, similar questions. Figure 2 on the next page illustrates an example of the availability heuristic. Figure 2's caption explains this particular case of the availability heuristic in more detail. **Anchoring and adjustment** means that a respondent chooses an answer that then becomes an anchor. All discussion revolves around this natural starting point. This anchor, insufficiently adjusted, biases the result (Tversky & Kahneman, 1974).

For additional information on these heuristics and dealing with uncertainty in quantitative risk and policy analysis, please consult Morgan and Henrion (1990).

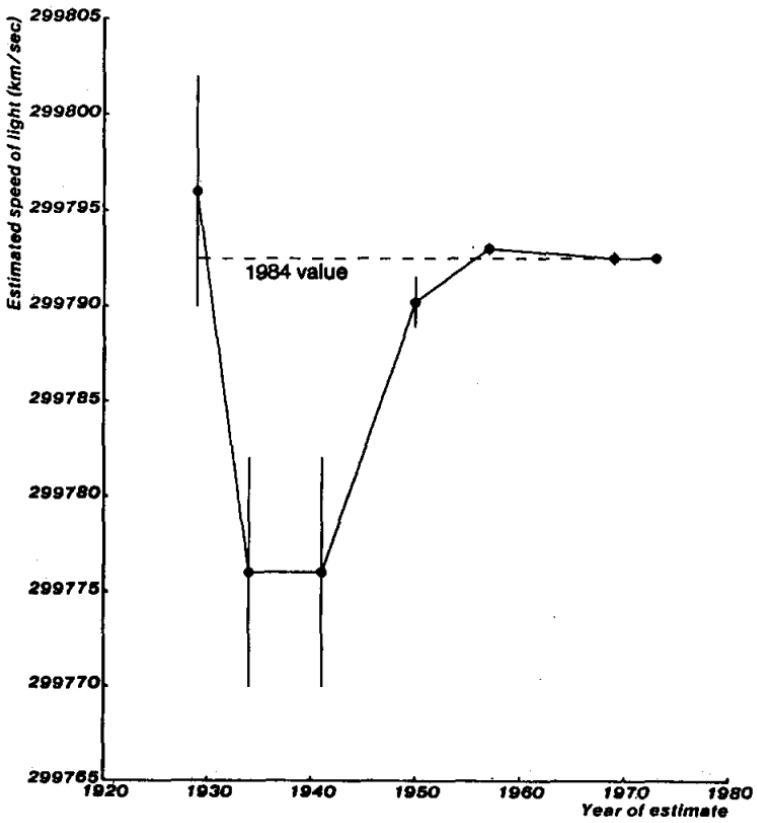


Figure 1. Speed of light, as recommended by various authors. The reported uncertainties are shown. Notice that the uncertainty intervals fail to capture the 1984 value, which is the true speed of light. From "Assessing uncertainty in physical constants," by M. Henrion and B. Fischhoff, 1986, *American Journal of Physics*, *54*, p. 793. Copyright 1986 by the American Association of Physics Teachers. Reprinted with permission.

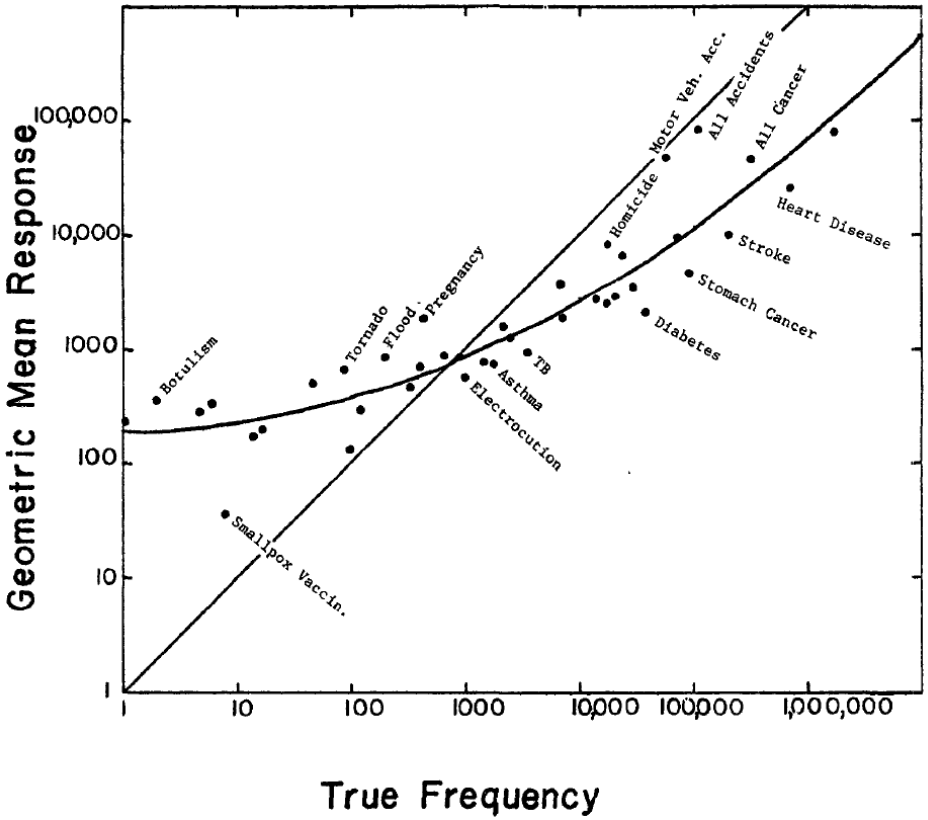


Figure 2. Respondents' estimates of number of deaths per year due to the causes shown. Notice that respondents overestimated the number of deaths due to botulism, which is shown toward the left of the figure, whereas they underestimated the number of deaths due to cancer, which is shown toward the right of the figure. It is likely easier to recall instances of botulism due to its higher press exposure than it is to recall instances of cancer. From "Judged frequency of lethal events," by S. Lichtenstein, P. Slovic, B. Fischhoff, M. Layman, and B. Combs, 1978, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *4*, p. 565. Copyright 1978 by the American Psychological Association. Reprinted with permission.

Supplementary material

Supplementary material accompanies this interview protocol. Please find Sections 3.3 and 3.4 of the U.S. Department of Energy's **Multi-Year Research, Development, and Demonstration (MYRD&D) Plan** included with this protocol. Section 3.3 (2015) is titled "Hydrogen Storage," and Section 3.4 (2016) is titled "Fuel Cells." We will refer to these documents in Parts 5, 10, and 11 of this interview.

Please also find the U.S. DOE's **PEMFC R&D Funding in Previous Years** and the U.S. DOE's **Hydrogen Storage Funding in Previous Years** included with this protocol. We will refer to these documents in Parts 10 and 11 of this interview.

Use of outside resources

Please answer all questions based on your expertise. You may use outside resources to support your answers, if you feel the need to do so. You may use any resources you like before, during, or after this interview. Resources include, but are not limited to, journal articles, reports, the supplementary material included with this protocol, textbooks, websites, your own research, and a calculator.

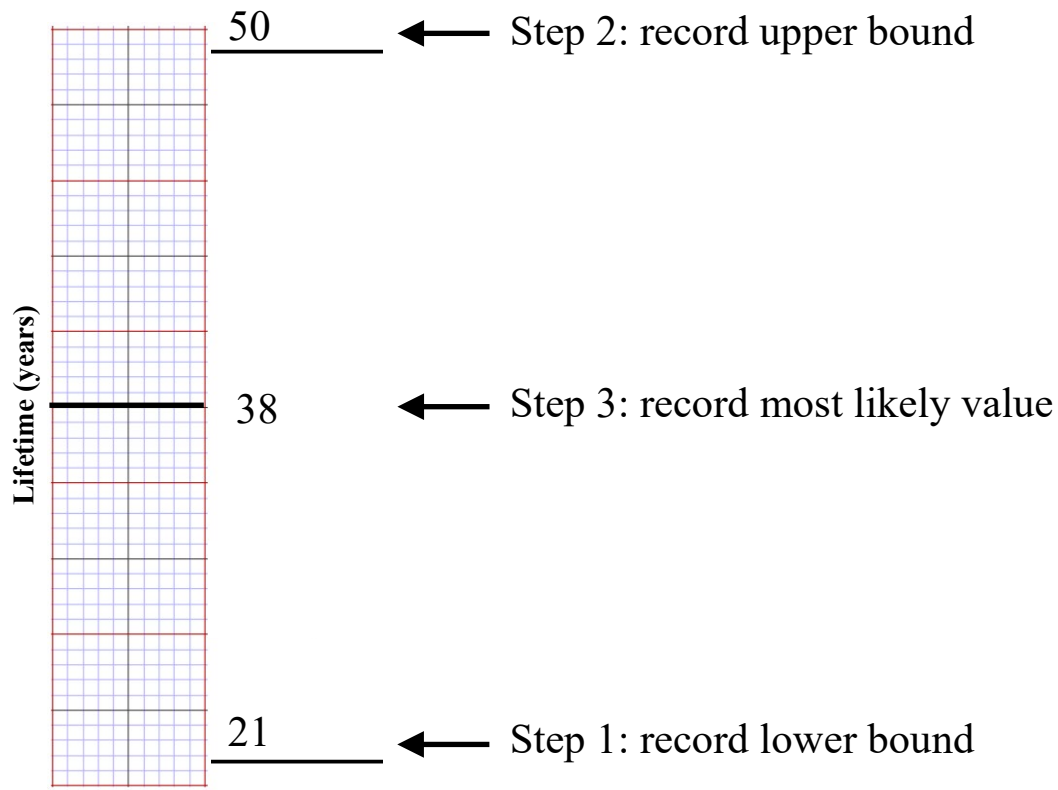
If you do not feel qualified to answer a question, you may skip the question. Please do not restate values from the literature if you do not feel qualified to answer a question. You may use outside resources to support your answers, but please do not rely on outside resources without also applying your own expert judgment.

Part 3. Demonstration for eliciting a range of values

[EXAMPLE] Given your expertise, what is the **lifetime** – in **years** – of a **coal-fired power plant**?

First, record your **lower bound estimate**. Second, record your **upper bound estimate.** Lastly, record your **most likely value**. Please provide lower and upper bounds that correspond to a **95% confidence interval**.

Lifetime of coal-fired power plant (years)



Note. The above graphic, which appears on subsequent pages, is adapted from "Expert assessments of the cost of light water small modular reactors" [Supplemental material], by A. Abdulla, I. L. Azevedo, and M. G. Morgan, 2013, *Proceedings of the National Academy of Sciences of the United States of America*, *110*. Copyright 2013 by the authors. Adapted with permission.

Part 4. Automotive PEMFC system cost

Part 4a. Automotive PEMFC system cost – system schematic

On the following pages, you will be asked questions about the production cost of an integrated light-duty vehicle PEMFC power system. Figure 3 below shows the **PEMFC power system's main components**.

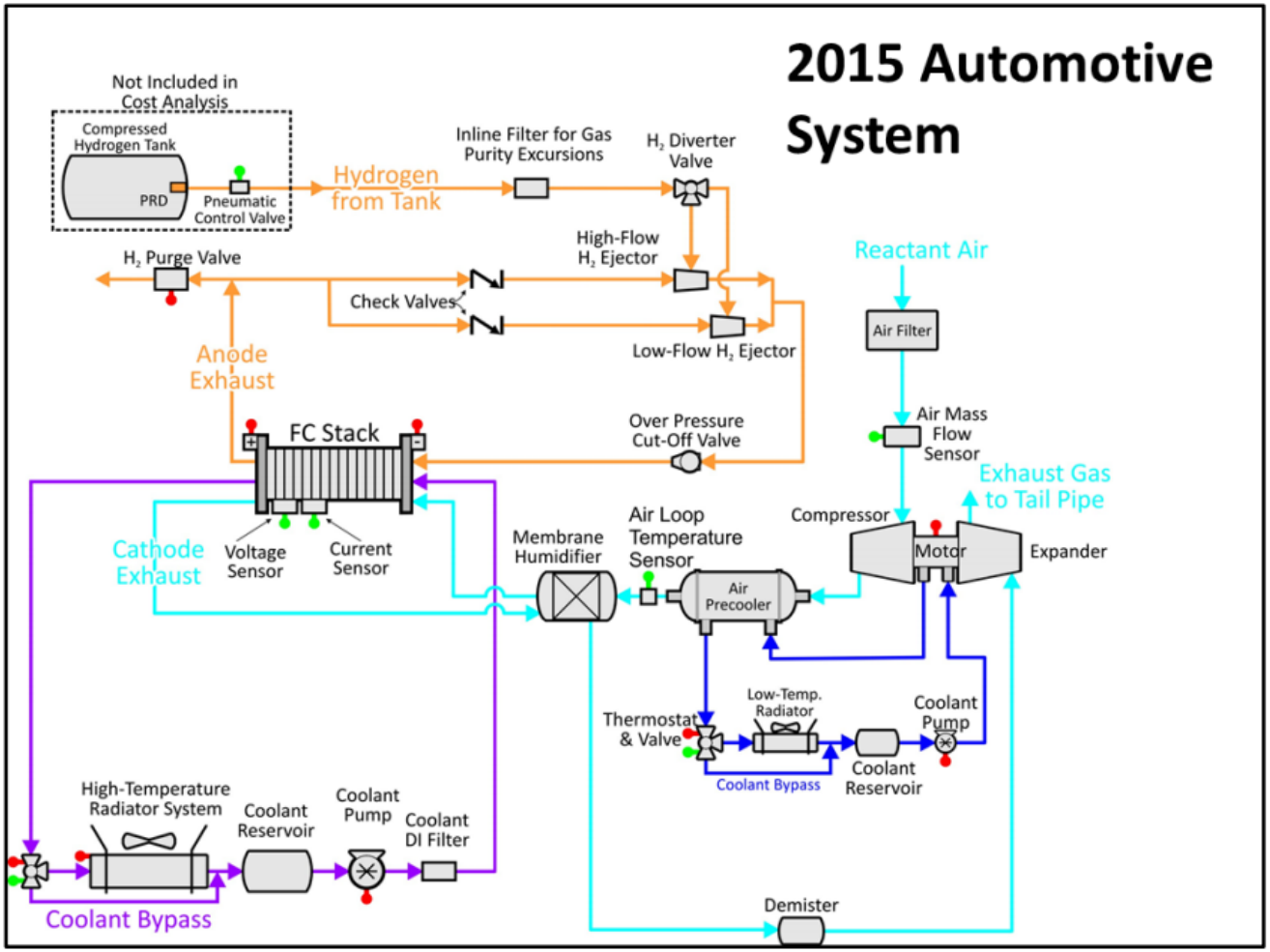


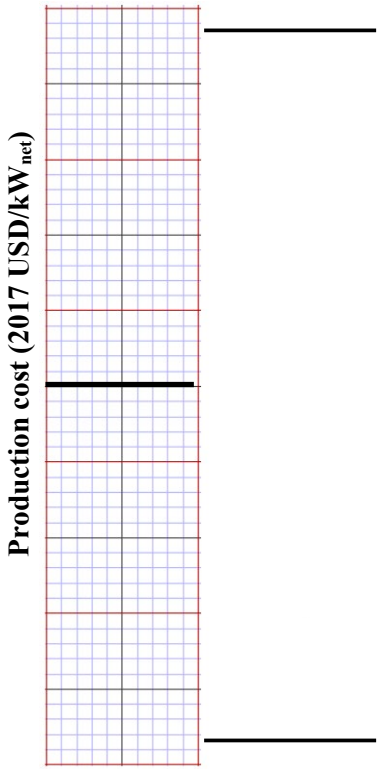
Figure 3. The PEMFC power system's main components. The PEMFC power system **also includes** the system controller, sensors, and miscellaneous balance-of-plant components (belly pan, mounting frames, wiring, and wiring and piping fasteners). The PEMFC power system **excludes** hydrogen storage, power electronics, electric drive, and the battery. From *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2015 Update* (p. 27), by B. D. James, J. M. Huya-Kouadio, and C. Houchins, 2015, retrieved from U.S. DOE website: https://energy.gov/sites/prod/files/2016/11/f34/fcto_sa_2015_pemfc_transportation_cost_analysis.pdf. Copyright 2015 by Strategic Analysis Inc. Reprinted with permission.

Part 4b. Automotive PEMFC system cost – expert's current estimate

In your view, what is the range of **production costs** – in **$/kW$_{net}$** – for an **integrated light-duty vehicle PEMFC power system** manufactured in **2017**? Please express all monetary values in 2017 United States dollars (USD) and assume the following (James, Huya-Kouadio, & Houchins, 2015):

(1) There is no sales markup applied by the final system assembler for profit, overhead, and other business expenses. You may consider markup(s) applied by lower-tier supplier(s), as you deem appropriate.
(2) The PEMFC power system's main components are shown in Figure 3 on p. 10. Figure 3's caption lists additional components.
(3) The PEMFC power system is rated to generate 80 kW$_{net}$.
(4) The total production volume is 500,000 units/year.

Production cost of integrated light-duty vehicle PEMFC power system in 2017 (2017 USD/kW$_{net}$)

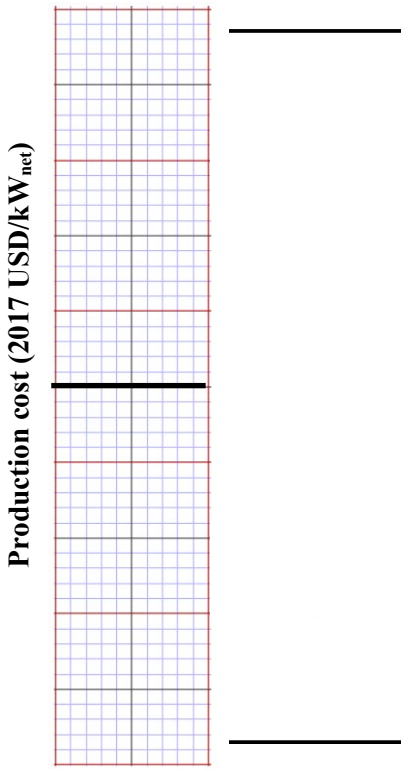


Part 4c. Automotive PEMFC system cost – expert's 2020, 2035, and 2050 estimates

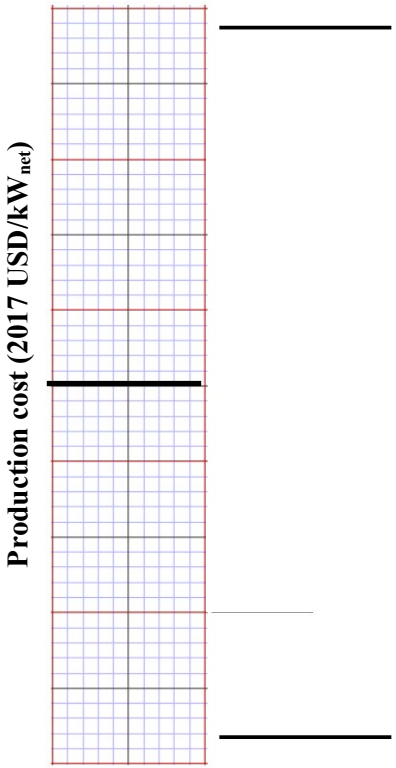
In your view, what is the range of **production costs** – in **$/kW$_{net}$** – for an **integrated light-duty vehicle PEMFC power system** manufactured in **2020**, **2035**, and **2050**? Please express all monetary values in 2017 USD and assume the following (James et al., 2015):

(1) There is no sales markup applied by the final system assembler for profit, overhead, and other business expenses. You may consider markup(s) applied by lower-tier supplier(s), as you deem appropriate.
(2) The PEMFC power system may differ from that shown in Figure 3 on p. 10, but you may use Figure 3 as a reference.
(3) The PEMFC power system is rated to generate 80 kW$_{net}$.
(4) The total production volume is 500,000 units/year.

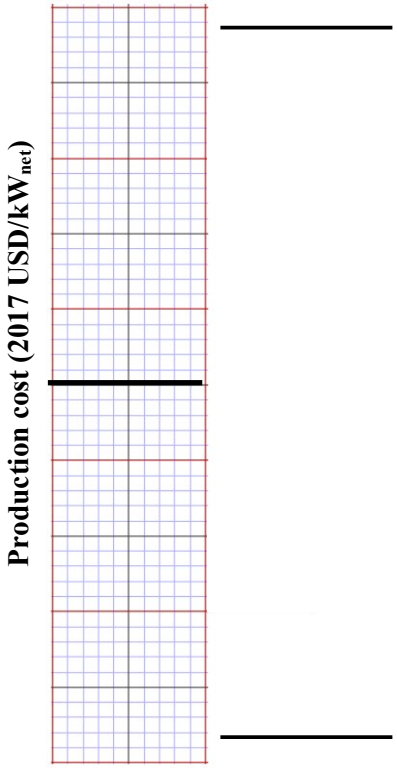
Production cost of integrated light-duty vehicle PEMFC power system in 2020 (2017 USD/kW$_{net}$)



Production cost of integrated light-duty vehicle PEMFC power system in 2035 (2017 USD/kW$_{net}$)



Production cost of integrated light-duty vehicle PEMFC power system in 2050 (2017 USD/kW$_{net}$)



Part 4d. Automotive PEMFC system cost – barriers to reducing cost

In your view, what are the **three most significant barriers** to reducing the **production cost** of an **integrated light-duty vehicle PEMFC power system**?

Please indicate the **most** (write "1"), **second most** (write "2"), and **third most** (write "3") **significant barriers** to reducing the **production cost** of an **integrated light-duty vehicle PEMFC power system**. The barriers below are based on information from James et al. (2015) and the U.S. DOE (2016). If you wish, you may write your own barrier(s) at the bottom of the page.

___Cost of platinum due to high platinum group metal (PGM) total loading on both electrodes

___Cost of cathode humidifier

___Cost of heat exchangers for thermal management

___Cost of bipolar plates

___Cost of air compression system (air compressor, expander, and motor controller)

___Cost of membrane

___Cost of gas diffusion layers

Other (please write your own barrier(s) and provide a ranking beside each barrier):

Part 5. PEMFC stack durability

Part 5a. PEMFC stack durability – measurement and testing protocols

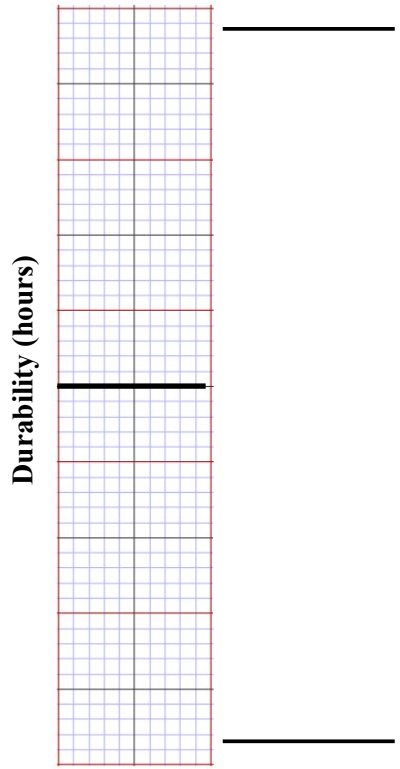
On the following pages, you will be asked questions about the durability of a PEMFC stack for a light-duty vehicle. For your reference, we have provided you with Section 3.4, titled "Fuel Cells," of the MYRD&D Plan (U.S. DOE, 2016) as a separate document. The MYRD&D Plan presents the **durability measurement and testing protocols** on the following pages:

- **Polarization protocol:** Table P.6 on pp. 51–52
- **Drive-cycle durability testing protocol:** Table P.7 on pp. 53–54
- **PEMFC membrane electrode assembly recovery protocol:** Table P.9 on p. 56

Part 5b. PEMFC stack durability – expert's current estimate

In your view, what is the range of **durability** – in **hours** – for a **light-duty vehicle PEMFC stack** manufactured in **2017**? Durability is defined as the time until the PEMFC stack's rated power reduces to a value that is 10% less than its beginning-of-life rated power (U.S. DOE, 2016).[3]

Durability of light-duty vehicle PEMFC stack in 2017 (hours)

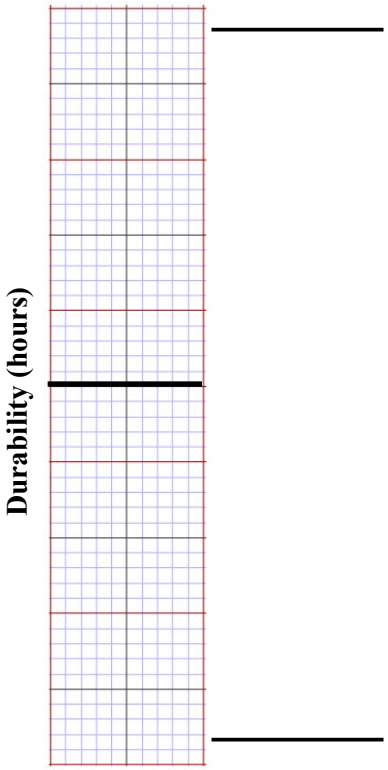


[3]The rated power is defined as the power at which the PEMFC voltage V = 77.6 / (22.1 + T[°C]), where T[°C] is the PEMFC's temperature. This equation comes from the requirement that $Q/\Delta T_i = 1.45$, where Q is the PEMFC's heat generation, ΔT_i is the difference between the stack coolant outlet temperature and the ambient temperature, and the stack coolant outlet temperature is approximated by the PEMFC's temperature. For further details about this equation, please consult Table 3.4.5 in the U.S. DOE (2016).

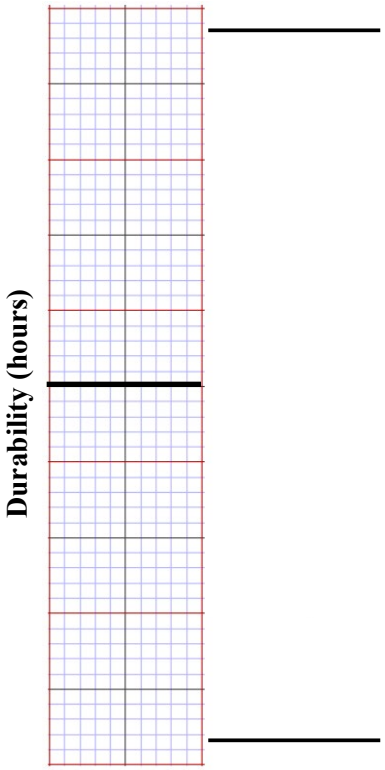
Part 5c. PEMFC stack durability – expert's 2020, 2035, and 2050 estimates

In your view, what is the range of **durability** – in **hours** – for a **light-duty vehicle PEMFC stack** in **2020**, **2035**, and **2050**? Durability is defined as the time until the PEMFC stack's rated power reduces to a value that is 10% less than its beginning-of-life rated power (U.S. DOE, 2016).[4]

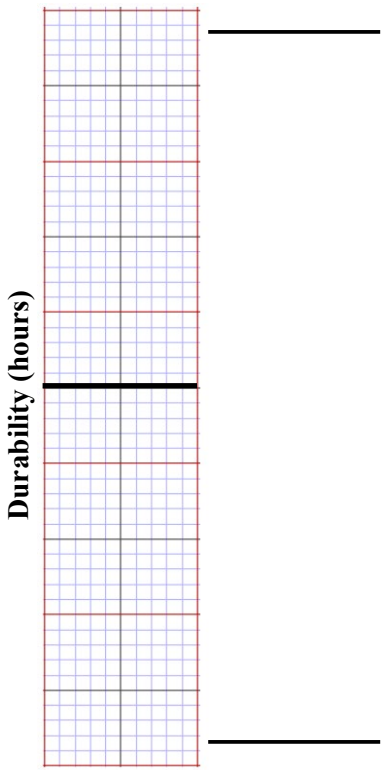
Durability of light-duty vehicle PEMFC stack in 2020 (hours)



Durability of light-duty vehicle PEMFC stack in 2035 (hours)



Durability of light-duty vehicle PEMFC stack in 2050 (hours)



[4]The rated power is defined in Footnote 3 on p. 16.

Part 5d. PEMFC stack durability – barriers to improving durability

In your view, what are the **three most significant barriers** to improving the **durability** of a **light-duty vehicle PEMFC stack**?

Please indicate the **most** (write "1"), **second most** (write "2"), and **third most** (write "3") **significant barriers** to improving the **durability** of a **light-duty vehicle PEMFC stack**. The barriers below are from de Bruijn, Dam, and Janssen (2008), Kongkanand (2017), O'Hayre, Cha, Colella, and Prinz (2016, pp. 337–338), and the (U.S. DOE, 2016). If you wish, you may write your own barrier(s) at the bottom of the page.

___Carbon support corrosion

___Catalyst poisoning due to fuel and air impurities

___Membrane mechanical failure due to humidity and temperature variation

___Membrane mechanical failure due to pinholes or foreign matter from manufacturing

___Membrane chemical degradation due to reaction with free radicals

___Membrane chemical degradation due to ionic contamination

___Bipolar plate corrosion

___Platinum sintering

___Platinum dissolution

___Instability of alloyed catalysts

Other (please write your own barrier(s) and provide a ranking beside each barrier):

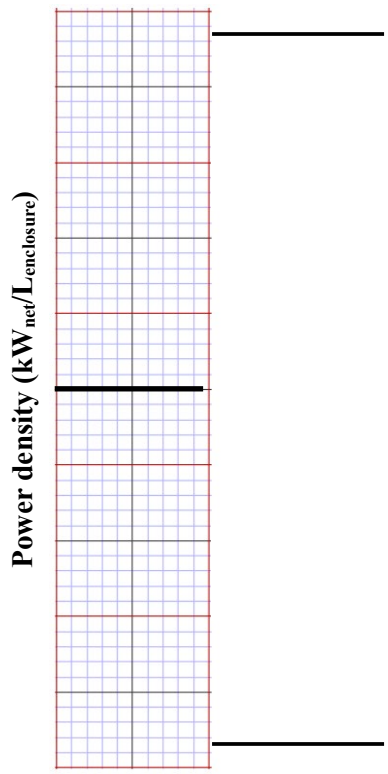
Part 6. PEMFC stack power density

Part 6a. PEMFC stack power density – expert's current estimate

In your view, what is the range of **power densities** – in **$kW_{net}/L_{enclosure}$** – for a **light-duty vehicle PEMFC stack** manufactured in **2017** (recall 1 L = 0.001 m^3)? Please assume the following (James et al., 2015; U.S. DOE, 2016):

(1) The PEMFC stack power density is defined 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, including dead space.
(2) The enclosure contains the PEMFC stack and no other components.
(3) The PEMFC stack operates on direct hydrogen and air.
(4) The PEMFC stack operates at up to 150 kPa_{abs} at its inlet.

Power density of light-duty vehicle PEMFC stack in 2017 ($kW_{net}/L_{enclosure}$)

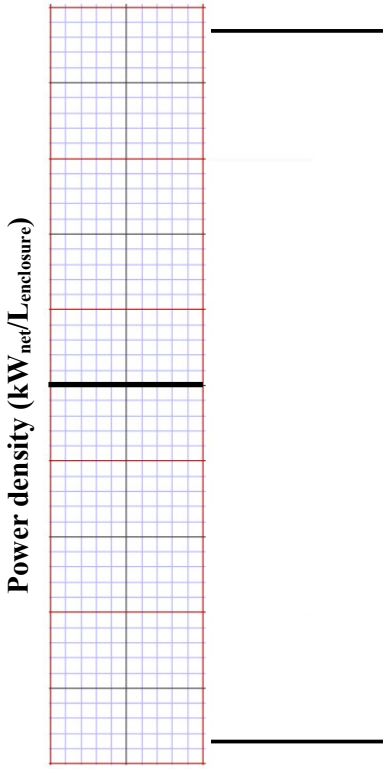


Part 6b. PEMFC stack power density – expert's 2020, 2035, and 2050 estimates

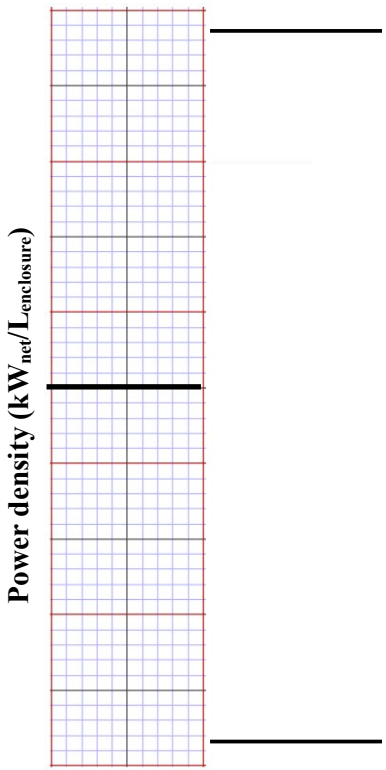
In your view, what is the range of **power densities** – in **$kW_{net}/L_{enclosure}$** – for a **light-duty vehicle fuel cell stack** manufactured in **2020**, **2035**, and **2050** (recall 1 L = 0.001 m^3)? Please assume the following (James et al., 2015; U.S. DOE, 2016):

(1) The PEMFC stack power density is defined 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, including dead space.
(2) The enclosure contains the PEMFC stack and no other components.
(3) The PEMFC stack operates on direct hydrogen and air.
(4) The PEMFC stack operates at up to 150 kPa_{abs} at its inlet.

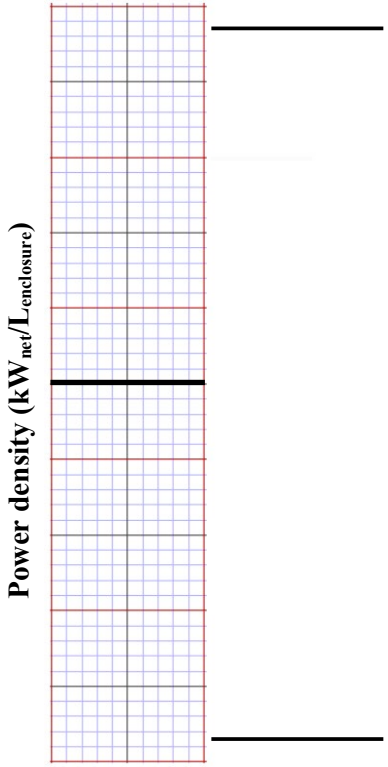
Power density of light-duty vehicle PEMFC stack in 2020 ($kW_{net}/L_{enclosure}$)



Power density of light-duty vehicle PEMFC stack in 2035 ($kW_{net}/L_{enclosure}$)



Power density of light-duty vehicle PEMFC stack in 2050 ($kW_{net}/L_{enclosure}$)



Part 6c. PEMFC stack power density – barriers to increasing power density

In your view, what are the **three most significant barriers** to increasing the **power density** of a **light-duty vehicle PEMFC stack**?

Please indicate the **most** (write "1"), **second most** (write "2"), and **third most** (write "3") **significant barriers** to increasing the **power density** of a **light-duty vehicle PEMFC stack**. The barriers below are based on information from Kongkanand and Mathias (2016) and the U.S. DOE (2016). If you wish, you may write your own barrier(s) at the bottom of the page.

___Low electrolyte ionic conductivity

___High cathode activation loss

___High electrical contact resistance between the electrodes and electrolyte

___High oxygen crossover through the electrolyte

___High hydrogen crossover through the electrolyte

___Low bipolar plate electrical conductivity

___High local platinum-electrolyte O_2 transport resistance

___Large bipolar plates

Other (please write your own barriers and provide a ranking beside each barrier):

Part 7. Hydrogen storage system gravimetric capacity

Part 7a. Hydrogen storage system gravimetric capacity – current status

On the following pages, you will be asked questions about the **gravimetric capacity** of **hydrogen storage systems** for light-duty vehicles. We summarize the **current status** of hydrogen storage systems for your reference in Table 1 below. If you wish to work in units of kWh H_2/kg_{system}, please convert your units using the lower heating value of H_2, which is 33.3 kWh H_2/kg H_2 (U.S. DOE, 2015).

Table 1

Gravimetric Capacities of Hydrogen Storage Systems

Hydrogen storage system	Gravimetric capacity (kg H_2/kg_{system})	Publication year
700 bar compressed gas (single tank, Type IV)[a,b]	0.0420[c]	2015
350 bar compressed gas (single tank, Type IV)[d]	0.054	2013
Metal hydride system ($NaAlH_4$/Ti)[e]	0.012	2016
Adsorbent system (HexCell/MOF-5 at 80 K and 100 bar)[e]	0.032	2016
Chemical system regenerable off-board (NH_3BH_3, or AB)[e]	0.046	2016

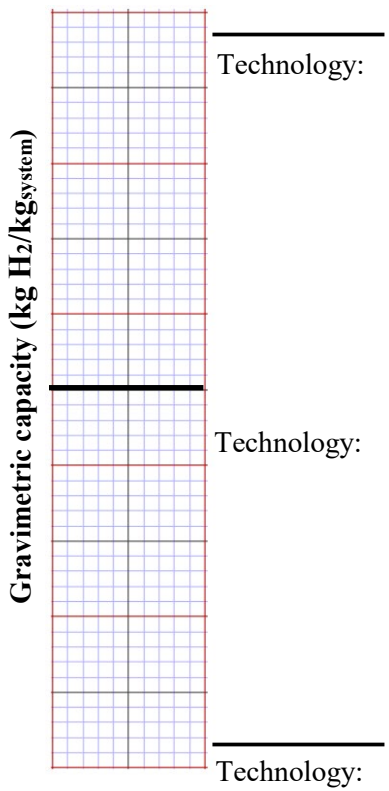
Note. The gravimetric capacity is defined as the mass of usable H_2 divided by the storage system's mass. Each system is assumed to store 5.6 kg of usable H_2.
[a]The following vehicles use 700 bar compressed gas: the Mirai (Toyota, 2015), the Tucson Fuel Cell (Hyundai, 2017), and the Clarity Fuel Cell (Honda, 2017).
[b]Source: Ordaz, Houchins, & Hua (2015, Table 1).
[c]Units converted using the lower heating value of hydrogen, 33.3 kWh H_2/kg H_2.
[d]Source: McWhorter and Ordaz (2013, Table 3).
[e]Source: Anton & Motyka (2016, p. 25).

Part 7b. Hydrogen storage system gravimetric capacity – expert's 2020, 2035, and 2050 estimates

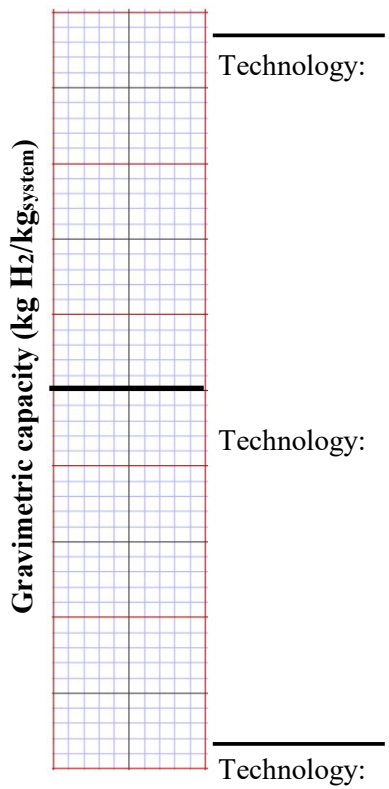
In your view, what is the range of **gravimetric capacities** – in **kg H_2/kg$_{system}$** – for a **hydrogen storage system on board a light-duty vehicle** manufactured in **2020**, **2035**, and **2050**? Please consider the hydrogen storage technology (or technologies) that you believe will be the most technically and economically viable in the given year, and indicate your technology selection(s) in the spaces provided. Please assume the following (U.S. DOE, 2015):

(1) The gravimetric capacity is defined as the mass of usable H_2 divided by the storage system's mass.
(2) The storage system stores 5.6 kg of usable H_2.
(3) The gravimetric capacity must be attainable at the end of service life (approximately 1,500 cycles, 5,000 hours of operation, or 150,000 miles).

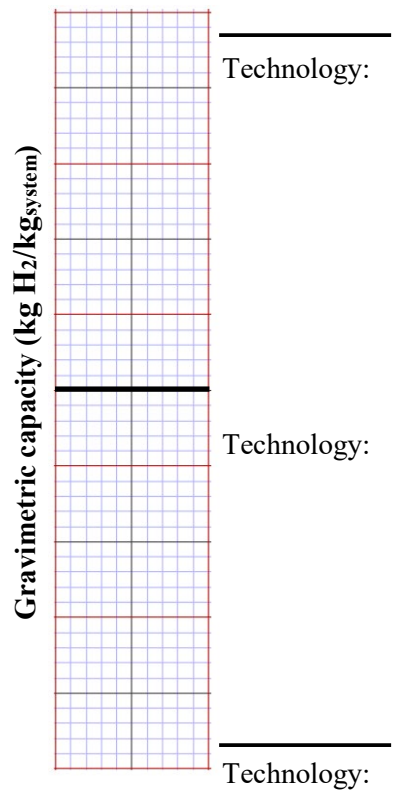
Gravimetric capacity of hydrogen storage in 2020 (kg H_2/kg$_{system}$)



Gravimetric capacity of hydrogen storage in 2035 (kg H_2/kg$_{system}$)



Gravimetric capacity of hydrogen storage in 2050 (kg H_2/kg$_{system}$)



Part 8. Hydrogen storage system volumetric capacity

Part 8a. Hydrogen storage system volumetric capacity – current status

On the following pages, you will be asked questions about the **volumetric capacity** of **hydrogen storage systems** for light-duty vehicles. We summarize the **current status** of hydrogen storage systems for your reference in Table 2 below. If you wish to work in units of kWh H_2/L_{system}, please convert your units using the lower heating value of H_2, which is 33.3 kWh H_2/kg H_2 (U.S. DOE, 2015).

Table 2

Volumetric Capacities of Hydrogen Storage Systems

Hydrogen storage system	Volumetric capacity (kg H_2/L_{system})	Publication Year
700 bar compressed gas (single tank, Type IV)[a,b]	0.024[c]	2015
350 bar compressed gas (single tank, Type IV)[d]	0.0177	2013
Metal hydride system ($NaAlH_4$/Ti)[e]	0.0115	2016
Adsorbent system (HexCell/MOF-5 at 80 K and 100 bar)[e]	0.0189	2016
Chemical system regenerable off-board (NH_3BH_3, or AB)[e]	0.0410	2016

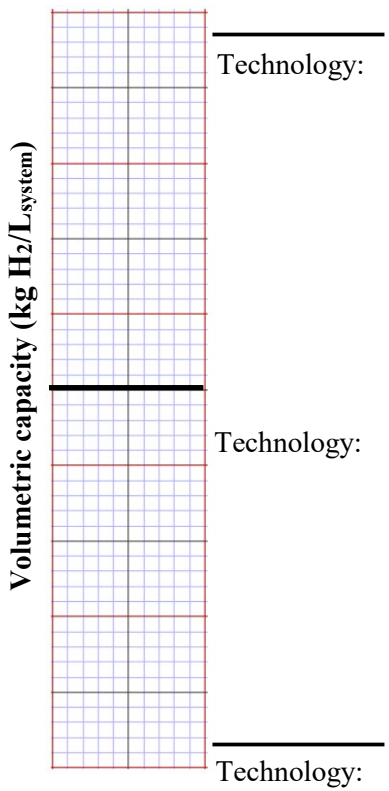
Note. The volumetric capacity is defined as the mass of usable H_2 divided by the storage system's volume. Each system is assumed to store 5.6 kg of usable H_2.
[a]The following vehicles use 700 bar compressed gas: the Mirai (Toyota, 2015), the Tucson Fuel Cell (Hyundai, 2017), and the Clarity Fuel Cell (Honda, 2017).
[b]Source: Ordaz, Houchins, & Hua (2015, Table 1).
[c]Units converted using the lower heating value of hydrogen, 33.3 kWh H_2/kg H_2.
[d]Source: McWhorter and Ordaz (2013, Table 3). [e]Source: Anton & Motyka (2016, p. 25).

Part 8b. Hydrogen storage system volumetric capacity – expert's 2020, 2035, and 2050 estimates

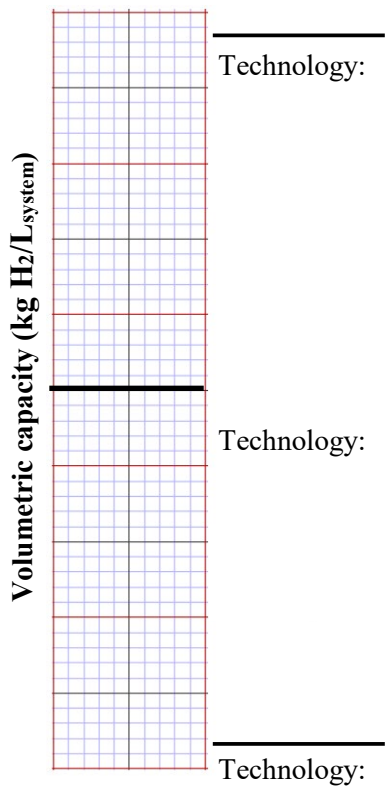
In your view, what is the range of **volumetric capacities** – in **kg H_2/L_{system}** – for a **hydrogen storage system on board a light-duty vehicle** manufactured in **2020**, **2035**, and **2050**? Please consider the hydrogen storage technology (or technologies) that you believe will be the most technically and economically viable in the given year, and indicate your technology selection(s) in the spaces provided. Please assume the following (U.S. DOE, 2015):

(1) The volumetric capacity is defined as the mass of usable H_2 divided by the storage system's volume.
(2) The storage system stores 5.6 kg of usable H_2.
(3) The volumetric capacity must be attainable at the end of service life (approximately 1,500 cycles, 5,000 hours of operation, or 150,000 miles).

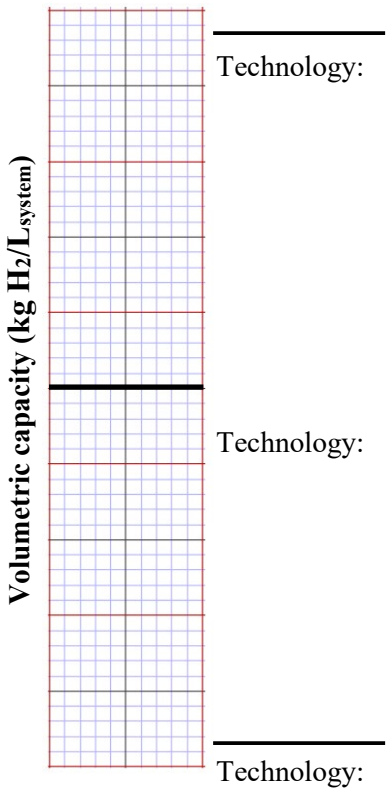
Volumetric capacity of hydrogen storage in 2020 (kg H_2/L_{system})



Volumetric capacity of hydrogen storage in 2035 (kg H_2/L_{system})



Volumetric capacity of hydrogen storage in 2050 (kg H_2/L_{system})



Part 9. Hydrogen storage system cost

Part 9a. Hydrogen storage system cost – current status

On the following pages, you will be asked questions about the **production cost** of **hydrogen storage systems** for light-duty vehicles. We summarize the **current status** of hydrogen storage systems for your reference in Table 3 below. If you wish to work in units of $\$/kg_{H_2}$, please convert your units using the lower heating value of H_2, which is 33.3 kWh H_2/kg H_2 (U.S. DOE, 2015).

Table 3

Production Costs of Hydrogen Storage Systems

Hydrogen storage system	Production cost[a] (2017 USD/kWh_{H_2})	Publication Year
700 bar compressed gas (single tank, Type IV)[b,c]	17	2015
350 bar compressed gas (single tank, Type IV)[d]	15	2013
Metal hydride system ($NaAlH_4$/Ti)[e]	49	2016
Adsorbent system (HexCell/MOF-5 at 80 K and 100 bar)[e]	17	2016
Chemical system regenerable off-board (NH_3BH_3, or AB)[e]	19	2016

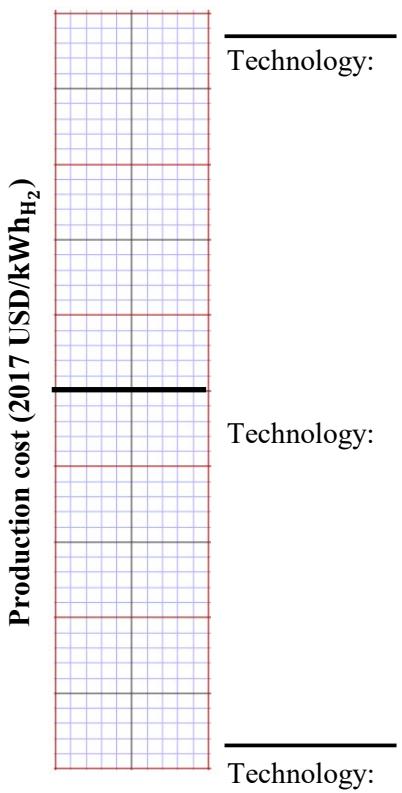
Note. The production cost is defined as the storage system's total production cost divided by the lower heating value of useable H_2. There is no sales markup applied by the final system assembler. The total production volume is 500,000 units/year, and each system is assumed to store 5.6 kg of usable H_2.
[a]Monetary values were converted from 2007 USD to 2017 USD using the producer price index (U.S. Department of Labor, 2017).
[b]The following vehicles use 700 bar compressed gas: the Mirai (Toyota, 2015), the Tucson Fuel Cell (Hyundai, 2017), and the Clarity Fuel Cell (Honda, 2017).
[c]Source: Ordaz, Houchins, & Hua (2015, Table 1).
[d]Source: McWhorter and Ordaz (2013, Table 7).
[e]Source: Anton & Motyka (2016, p. 25).

Part 9b. Hydrogen storage system cost – expert's 2020, 2035, and 2050 estimates

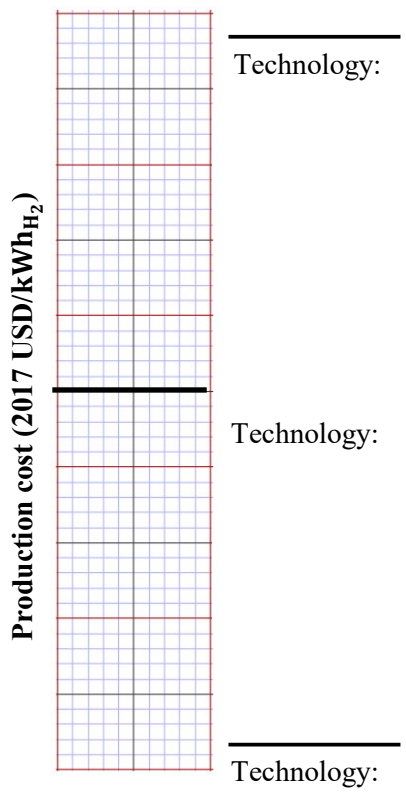
In your view, what is the range of **production costs** – in **$/kWh$_{H_2}$** – for a **hydrogen storage system on board a light-duty vehicle** manufactured in **2020**, **2035**, and **2050**? Please consider the hydrogen storage technology (or technologies) that you believe will be the most technically and economically viable in the given year, and indicate your technology selection(s) in the spaces provided. Please express all monetary values in 2017 USD and assume the following (Ordaz et al., 2015; U.S. DOE 2015):

(1) The production cost is defined as the system's total production cost divided by the lower heating value of usable H_2.
(2) There is no sales markup applied by the final system assembler for profit, overhead, and other business expenses. You may consider markup(s) applied by lower-tier supplier(s), as you deem appropriate.
(3) The total production volume is 500,000 units/year.
(4) The storage system stores 5.6 kg of usable H_2.

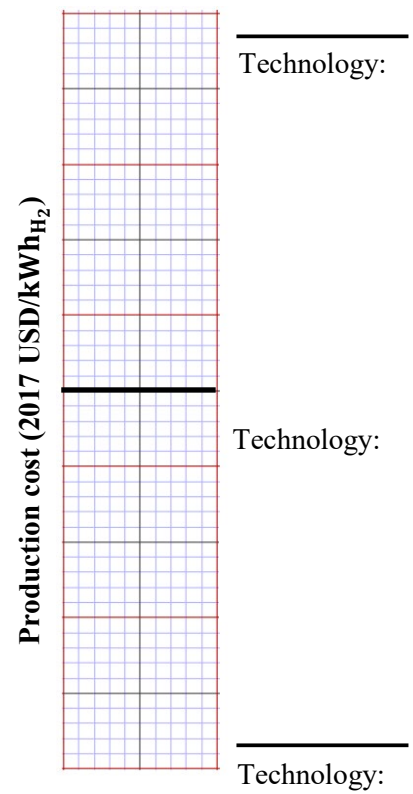
Production cost of hydrogen storage in 2020 (2017 USD/kWh$_{H_2}$)



Production cost of hydrogen storage in 2035 (2017 USD/kWh$_{H_2}$)



Production cost of hydrogen storage in 2050 (2017 USD/kWh$_{H_2}$)



Part 10. Government PEMFC R&D funding

Part 10a. Government PEMFC R&D funding – R&D areas and targets

On the following pages, you will be asked to recommend government funding levels for several PEMFC R&D areas (Papageorgopoulos, 2017). For your reference, we have provided you with Section 3.4, titled "Fuel Cells," of the MYRD&D Plan (U.S. DOE, 2016) as a separate document. The MYRD&D Plan describes the **PEMFC R&D areas** and **PEMFC technical and economic targets** on the following pages:

- **PEMFC R&D areas:** Table 3.4.2 on pp. 7–9
- **PEMFC technical and economic targets:** Table 3.4.3 on p. 17 through Table 3.4.16 on p 30

In addition, we have provided you with the **U.S. DOE's PEMFC R&D Funding in Previous Years** as a separate document.

Part 10b. Government PEMFC R&D funding – expert's recommended funding levels

In your view, what is the **minimum amount** of **government R&D funding** that should be allocated in **FY 2018** to each of the four **PEMFC R&D areas** below to achieve the technical and economic targets stated in Section 3.4 of the MYRD&D Plan (U.S. DOE, 2016)? Please express all monetary values in 2017 USD and assume that funding levels after FY 2018 will be similar to the funding levels in FY 2018.

Recommended minimum government R&D funding

Testing and technical assessment	_____	2017 USD
Catalysts and electrodes	_____	2017 USD
Fuel cell performance and durability	_____	2017 USD
Membranes/electrolytes	_____	2017 USD

Did you consider funding in previous year(s) when answering this question? If so, what information did you consider?

Part 10c. Government PEMFC R&D funding – expert's ranking of R&D areas

In your view, how should the four **PEMFC R&D areas** below be **ranked** in terms of **government funding priority** in **FY 2018** to achieve the technical and economic targets in Section 3.4 of the MYRD&D Plan (U.S. DOE, 2016)?

Please **rank** the following **R&D areas** according to how you think they should be prioritized in **FY 2018**, where "1" indicates the highest priority. Please provide justification for your rankings at the bottom of the page.

	Rank
Testing and technical assessment	____
Catalysts and electrodes	____
Fuel cell performance and durability	____
Membranes/electrolytes	____

Please provide justification for your rankings in the space below:

Part 11. Government hydrogen storage R&D funding

Part 11a. Government hydrogen storage R&D funding – R&D areas and targets

On the following pages, you will be asked to recommend government funding levels for several hydrogen storage R&D areas. The **hydrogen storage R&D areas** are summarized below (N. Stetson, 2017; N. T. Stetson, 2016; U.S. DOE, 2015):

- **Advanced tanks:** Advanced physical hydrogen storage
- **Materials development:** Materials-based hydrogen storage
- **Engineering:** Systems-level engineering
- **Testing and analysis:** Cost modeling and technical analysis

For your reference, we have provided you with Section 3.3, titled "Hydrogen Storage," of the MYRD&D Plan (U.S. DOE, 2015) as a separate document. The MYRD&D Plan describes the **hydrogen storage technical and economic targets** on the following pages:

- **Hydrogen storage technical and economic targets:** Tables 3.3.3 on p. 11 through Table 3.3.7 on pp. 15–16

In addition, we have also provided you with the **U.S. DOE's Hydrogen Storage Funding in Previous Years** as a separate document.

Part 11b. Government hydrogen storage R&D funding – expert's recommended funding levels

In your view, what is the **minimum amount** of **government R&D funding** that should be allocated in **FY 2018** to each of the four **hydrogen storage R&D areas** below to achieve the technical and economic targets stated in Section 3.3 of the MYRD&D Plan (U.S. DOE, 2015)? Please express all monetary values in 2017 USD and assume that funding levels after FY 2018 will be similar to the funding levels in FY 2018.

	Recommended minimum government R&D funding
Advanced tanks	_____ 2017 USD
Materials development	_____ 2017 USD
Engineering	_____ 2017 USD
Testing and analysis	_____ 2017 USD

Did you consider funding in previous year(s) when answering this question? If so, what information did you consider?

Part 11c. Government hydrogen storage R&D funding – expert's ranking of R&D areas

In your view, how should the four **hydrogen storage R&D areas** below be **ranked** in terms of **government funding priority** in **FY 2018** to achieve the technical and economic targets stated in Section 3.3 of the MYRD&D Plan (U.S.DOE, 2015)?

Please **rank** the following **R&D areas** according to how you think they should be prioritized in **FY 2018**, where "1" indicates the highest priority. Please provide justification for your rankings at the bottom of the page.

	Rank
Advanced tanks	____
Materials development	____
Engineering	____
Testing and analysis	____

Please provide justification for your rankings in the space below:

Part 12. Demographic information

We will now collect basic demographic information.[5] This information will have little bearing on our final results. We collect this information to more accurately highlight the sum of skills and experience that we have managed to incorporate into our study.

Title of your current position: _____

Fuel cell types with which you have worked: _____

Number of years spent working with fuel cells: _____

Highest level of education (degree earned): _____

Age: _____

Please indicate your level of expertise in each of the following areas by circling a number on the scale below:

	Not familiar	Slightly familiar						Very familiar
1. PEMFC stationary power systems	0	1	2	3	4	5	6	7
2. PEMFC light-duty vehicle systems	0	1	2	3	4	5	6	7
3. PEMFC components (anode, electrolyte, etc.)	0	1	2	3	4	5	6	7
4. Physical hydrogen storage	0	1	2	3	4	5	6	7
5. Materials-based hydrogen storage	0	1	2	3	4	5	6	7
6. Other fuel cell-related area(s) (please specify):	0	1	2	3	4	5	6	7

[5]Part 12 of this protocol has been adapted from "Expert assessments of the cost of light water small modular reactors (Appendix S2)" [Supplemental material], by A. Abdulla, I. L. Azevedo, and M. G. Morgan, 2013, *Proceedings of the National Academy of Sciences of the United States of America*, *110*, p. 4. Copyright 2013 by the authors. Adapted with permission.

Part 13. Acknowledgements

This interview protocol is similar in format to the following:

Abdulla, A., Azevedo, I. L., & Morgan, M. G. (2013). Expert assessments of the cost of light water small modular reactors (Appendix S2) [Supplemental material]. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, 9686–9691. doi: 10.1073/pnas.1300195110

Sakti, A., Azevedo, I. M. L., Fuchs, E. R. H., Michalek, J. J., Gallagher, K. G., & Whitacre, J. F. (2017). Consistency and robustness of forecasting for emerging technologies: The case of Li-ion batteries for electric vehicles (Supplemental Information 1) [Supplemental material]. *Energy Policy*, 106, 415–426. doi: 10.1016/j.enpol.2017.03.063

Part 14. References

Anton, D. L., & Motyka, T. (2016). Hydrogen storage engineering center of excellence. In *Annual Merit Review Proceedings*. Washington, D.C. Retrieved from https://www.hydrogen.energy.gov/pdfs/review16/st004_anton_2016_o.pdf

de Bruijn, F. A., Dam, V. A. T., & Janssen, G. J. M. (2008). Review: Durability and degradation issues of PEM fuel cell components. *Fuel Cells*, *8*(1), 3–22. https://doi.org/10.1002/fuce.200700053

Honda. (2017). Clarity Fuel Cell. Retrieved August 28, 2017, from http://world.honda.com/CLARITY/technology/index.html

Hyundai. (2017). Drive the world's first mass-produced fuel cell compact SUV. Retrieved April 26, 2017, from https://www.hyundaiusa.com/tucsonfuelcell/index.aspx

James, B. D., Huya-Kouadio, J. M., & Houchins, C. (2015). *Mass production cost estimation of direct H_2 PEM fuel cell systems for transportation applications: 2015 update*. Retrieved from https://energy.gov/sites/prod/files/2016/11/f34/fcto_sa_2015_pemfc_transportation_cost_analysis.pdf

Kongkanand, A. (2017). Highly-accessible catalysts for durable high-power performance. In *Annual Merit Review Proceedings*. Washington, D.C. Retrieved from https://www.hydrogen.energy.gov/pdfs/review17/fc144_kongkanand_2017_o.pdf

Kongkanand, A., & Mathias, M. F. (2016). The priority and challenge of high-power performance of low-platinum proton-exchange membrane fuel cells. *The Journal of Physical Chemistry Letters*, *7*(7), 1127–1137. https://doi.org/10.1021/acs.jpclett.6b00216

McWhorter, S., & Ordaz, G. (2013). *DOE Fuel Cell Technologies Office record (Record # 13010)*. Retrieved from https://www.hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf

Morgan, M. G., & Henrion, M. (1990). *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis*. Cambridge: Cambridge University Press.

O'Hayre, R. P., Cha, S.-W., Colella, W. G., & Prinz, F. B. (2016). *Fuel cell fundamentals* (3rd ed.). Hoboken, NJ: John Wiley & Sons.

Ordaz, G., Houchins, C., & Hua, T. (2015). *Onboard Type IV Compressed Hydrogen Storage System - Cost and Performance Status 2015 (Record # 15013)*. Retrieved from https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

Papageorgopoulos, D. (2017). *FY 2016 progress report for the DOE Hydrogen and Fuel Cells Program (Report No. DOE/GO-102017-4891): Fuel cells program overview*. Retrieved from https://www.hydrogen.energy.gov/pdfs/progress16/v_0_papageorgopoulos_2016.pdf

Stetson, N. (2017). *FY 2016 progress report for the DOE Hydrogen and Fuel Cells Program (Report No. DOE/GO-102017-4891): Hydrogen Storage Program Overview*. Retrieved from https://www.hydrogen.energy.gov/pdfs/progress16/iv_0_stetson_2016.pdf

Stetson, N. T. (2016). Hydrogen Storage Program Area - Plenary Presentation. In *Annual Merit Review Proceedings*. Washington, D.C. Retrieved from https://www.hydrogen.energy.gov/pdfs/review16/st000_stetson_2016_o.pdf

Toyota. (2015). *2016 Mirai product information*. Retrieved from http://pressroom.toyota.com/releases/2016+toyota+mirai+fuel+cell+product.htm

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science*, *185*(4157), 1124–1131.

U.S. Department of Energy. (2015). *Multi-year research, development, and demonstration plan: Hydrogen storage*. Retrieved from https://energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf

U.S. Department of Energy. (2016). *Multi-year research, development, and demonstration plan: Fuel cells*. Retrieved from https://energy.gov/sites/prod/files/2016/10/f33/fcto_myrdd_fuel_cells.pdf

U.S. Department of Labor. (2017). Producer Price Indexes [Data file]. Retrieved from https://www.bls.gov/ppi/

Supporting Information

Section S5

Assessments Separated by Affiliation and Expert Number

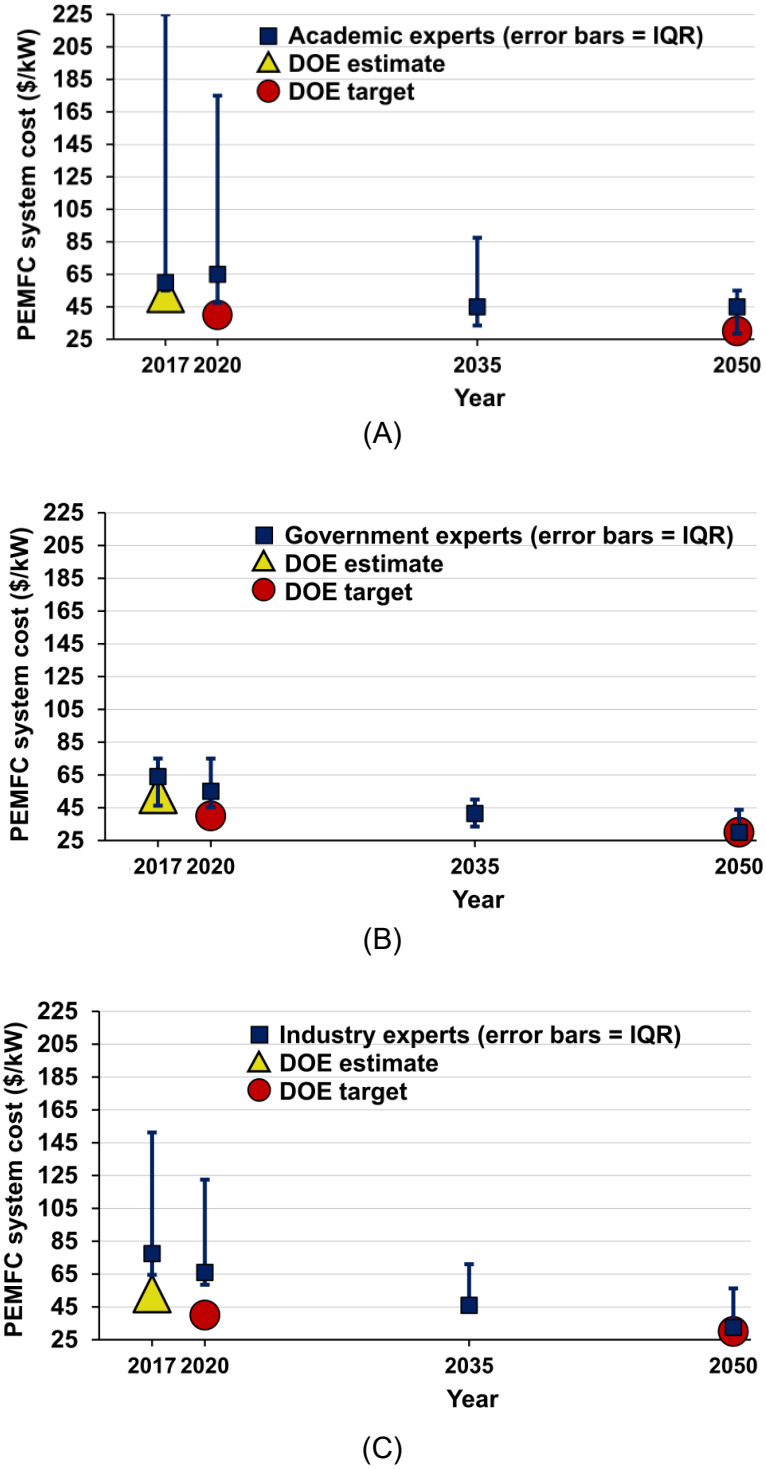


Fig. S3. Experts' assessments of PEMFC automotive system cost in 2017, 2020, 2035, and 2050. Each square represents the median of experts' best estimates, and the error bars represent the IQRs of experts' best estimates. In each subfigure, we show the DOE's 2015 estimate (plotted in 2017), the DOE's 2020 target, and the DOE's ultimate target (plotted in 2050). (*A*) Academic experts. (*B*) Government experts. (*C*) Industry experts.

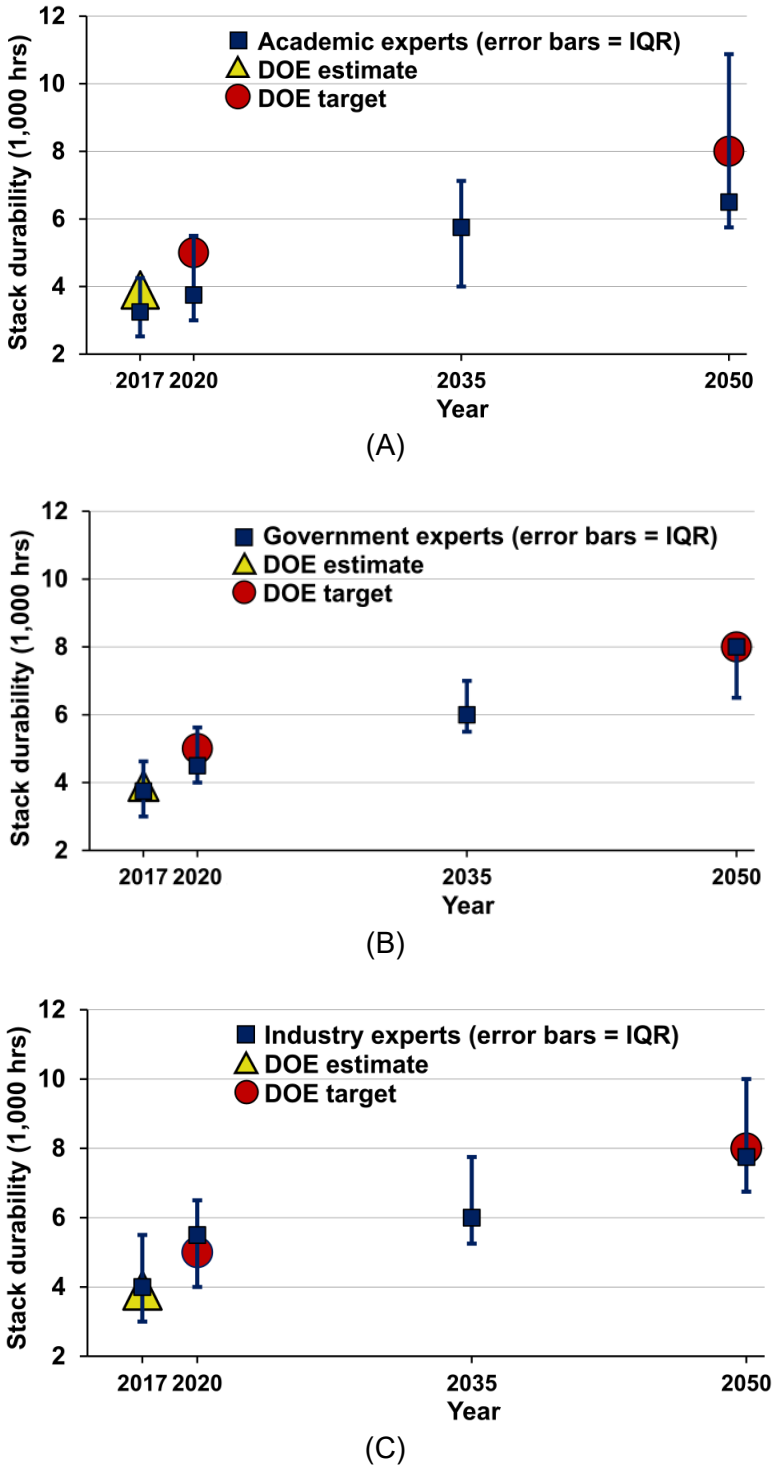
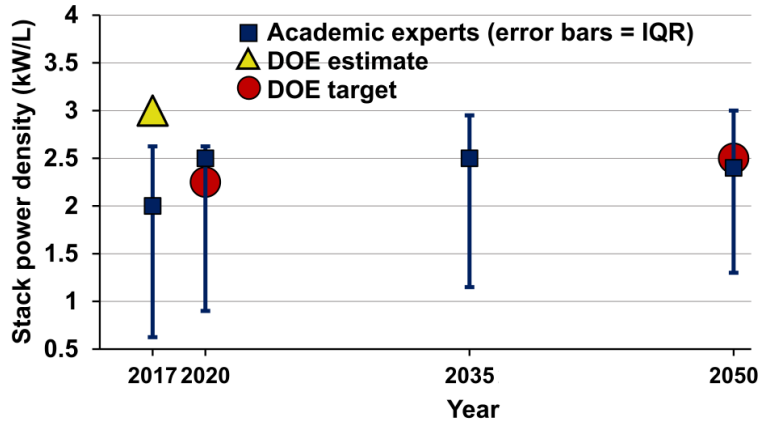
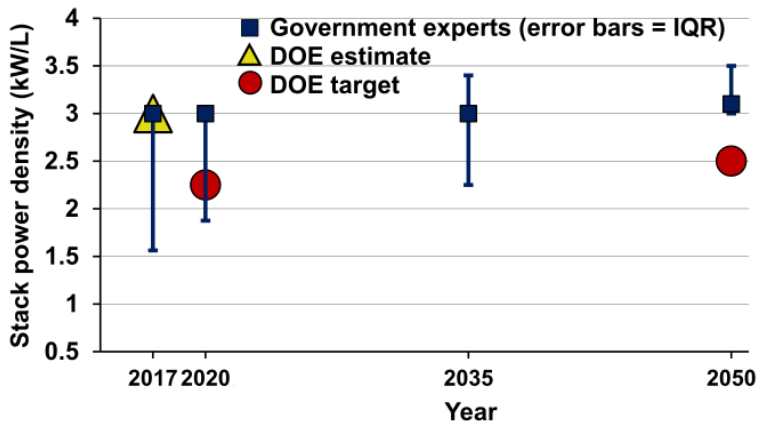


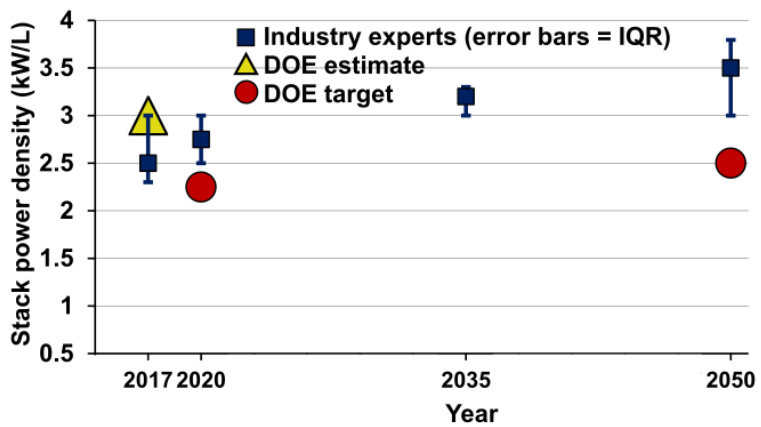
Fig. S4. Experts' assessments of PEMFC stack durability in 2017, 2020, 2035, and 2050. Each square represents the median of experts' best estimates, and the error bars represent the IQRs of experts' best estimates. In each subfigure, we show the DOE's 2015 estimate (plotted in 2017), the DOE's 2020 target, and the DOE's ultimate target (plotted in 2050). (*A*) Academic experts. (*B*) Government experts. (*C*) Industry experts. Because (industry) expert 33 assumed production volumes different than 500,000 units/year in 2017, 2020, and 2035, we excluded this expert's cost assessments from our calculations (range, median, etc.) for these years.



(A)

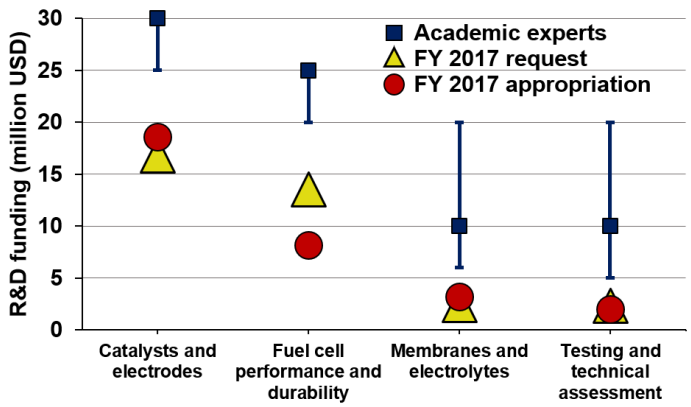


(B)

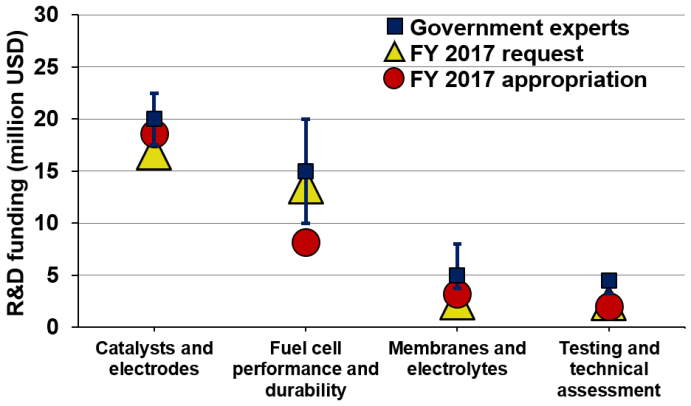


(C)

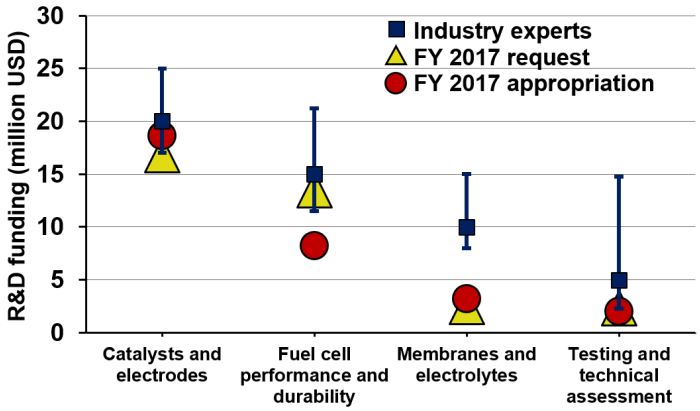
Fig. S5. Experts' assessments of PEMFC stack power density in 2017, 2020, 2035, and 2050. Each square represents the median of experts' best estimates, and the error bars represent the IQRs of experts' best estimates. In each subfigure, we show the DOE's 2015 estimate (plotted in 2017), the DOE's 2020 target, and the DOE's ultimate target (plotted in 2050). (*A*) Academic experts. (*B*) Government experts. (*C*) Industry experts.



(A)



(B)



(C)

Fig. S6. Experts' recommended government R&D funding levels, separated by affiliation, in FY 2018. For each R&D area, we present the median of experts' recommendations, the FCTO's FY 2017 request, and the FCTO's FY 2017 appropriation. The error bars represent the IQRs of experts' funding levels. (*A*) Academic experts. (*B*) Government experts. (*C*) Industry experts.

Table S1. Summary statistics of experts' assessments of PEMFC automotive system cost.

	Best estimate ($/kW)					95% confidence interval ($/kW)	
	Minimum	25th percentile	Median	75th percentile	Maximum	Minimum lower bound	Maximum upper bound
All							
2017	40	53	75	125	500	20	1,100
2020	40	46	62	100	350	20	500
2035	25	35	45.5	62.75	150	15	300
2050	15	30	30	50	105	10	200
Academia							
2017	50	55	60	225	500	40	1,100
2020	45	47.5	65	175	280	35	400
2035	25	33.5	45	87.5	125	15	200
2050	15	28.5	45	55	60	10	100
Government							
2017	45	46.25	64	75	100	26	250
2020	40	45.25	55	75	75	26	200
2035	30	33.5	41.5	50	65	20	150
2050	25	30	30	43.75	50	20	100
Industry *							
2017	40	64.5	77.5	151.25	350	20	500
2020	40	58.5	66	122.5	350	20	500
2035	30	42.5	46	71	150	20	300
2050	25	30	32.5	56.25	105	10	200

* Because expert 33 assumed 2017, 2020, and 2035 production volumes that differed from that stated in the question (500,000 units/year), we excluded this expert's cost assessments from our calculations (range, median, etc.) for these years.

Table S2. Summary statistics of experts' assessments of PEMFC stack durability.

	Best estimate (hrs)					95% confidence interval (hrs)	
	Minimum	25th percentile	Median	75th percentile	Maximum	Minimum lower bound	Maximum upper bound
All							
2017	1,200	3,000	4,000	5,000	12,000	500	20,000
2020	2,200	3,875	4,500	6,000	20,000	500	30,000
2035	2,200	5,500	6,000	7,250	15,000	1,700	20,000
2050	2,500	6,000	7,500	9,500	30,000	2,000	40,000
Academia							
2017	1,200	2,525	3,250	4,250	7,500	500	10,000
2020	2,500	3,000	3,750	5,500	7,500	500	10,000
2035	3,500	4,000	5,750	7,125	15,000	2,000	20,000
2050	4,200	5,750	6,500	10,875	30,000	3,000	40,000
Government							
2017	2,000	3,000	3,750	4,625	7,000	1,000	10,000
2020	3,000	4,000	4,500	5,625	7,000	2,500	10,000
2035	4,000	5,500	6,000	7,000	8,500	3,500	15,000
2050	6,000	6,500	8,000	8,000	10,000	4,000	15,000
Industry							
2017	2,000	3,000	4,000	5,500	12,000	1,000	20,000
2020	2,200	4,000	5,500	6,500	20,000	1,500	30,000
2035	2,200	5,250	6,000	7,750	10,000	1,700	20,000
2050	2,500	6,750	7,750	10,000	15,000	2,000	30,000

Table S3. Summary statistics of experts' assessments of PEMFC stack power density.

	Best estimate (kW/L)					95% confidence interval (kW/L)	
	Minimum	25th percentile	Median	75th percentile	Maximum	Minimum lower bound	Maximum upper bound
All							
2017	0.5	1.85	2.5	3	4	0.3	5
2020	0.5	2.5	2.75	3	4	0.4	5
2035	0.6	2.5	3	3.275	5	0.6	6
2050	0.7	2.5	3	3.5	6	0.65	7
Academia							
2017	0.5	0.625	2	2.625	3	0.3	3.5
2020	0.5	0.9	2.5	2.625	3	0.4	3.5
2035	0.6	1.15	2.5	2.95	3.5	0.6	4
2050	0.7	1.3	2.4	3	3.5	0.65	5
Government							
2017	0.7	1.5625	3	3	3.1	0.5	5
2020	0.7	1.875	3	3	3.8	0.5	5
2035	0.7	2.25	3	3.4	4	0.6	5
2050	0.8	3	3.1	3.5	5.2	0.7	5.6
Industry							
2017	1.8	2.3	2.5	3	4	1	5
2020	2.5	2.5	2.75	3	4	2	5
2035	2.5	3	3.2	3.3	5	2	6
2050	2.5	3	3.5	3.795	6	2	7

Table S4. Summary statistics of experts' R&D funding recommendations, separated by affiliation.

	R&D Funding (million 2017 USD)				
	Minimum	25th percentile	Median	75th percentile	Maximum
All					
Catalysts and electrodes	12	19.25	20	30	200
Fuel cell performance and durability	5	13	17.5	21.25	150
Membranes and electrolytes	2	5	8	11.25	50
Testing and technical assessment	0	3.375	5	10	50
Academia					
Catalysts and electrodes	20	25	30	30	200
Fuel cell performance and durability	15	20	25	25	150
Membranes and electrolytes	5	6	10	20	30
Testing and technical assessment	5	5	10	20	30
Government					
Catalysts and electrodes	15	17.5	20	22.5	35
Fuel cell performance and durability	5	10	15	20	27
Membranes and electrolytes	2.5	3.75	5	8	10
Testing and technical assessment	1.5	3.25	4.5	5	5
Industry					
Catalysts and electrodes	12	16.5	20	26.25	50
Fuel cell performance and durability	10	13	15	20	50
Membranes and electrolytes	2	7.25	10	19.75	50
Testing and technical assessment	0	2	5	10	50

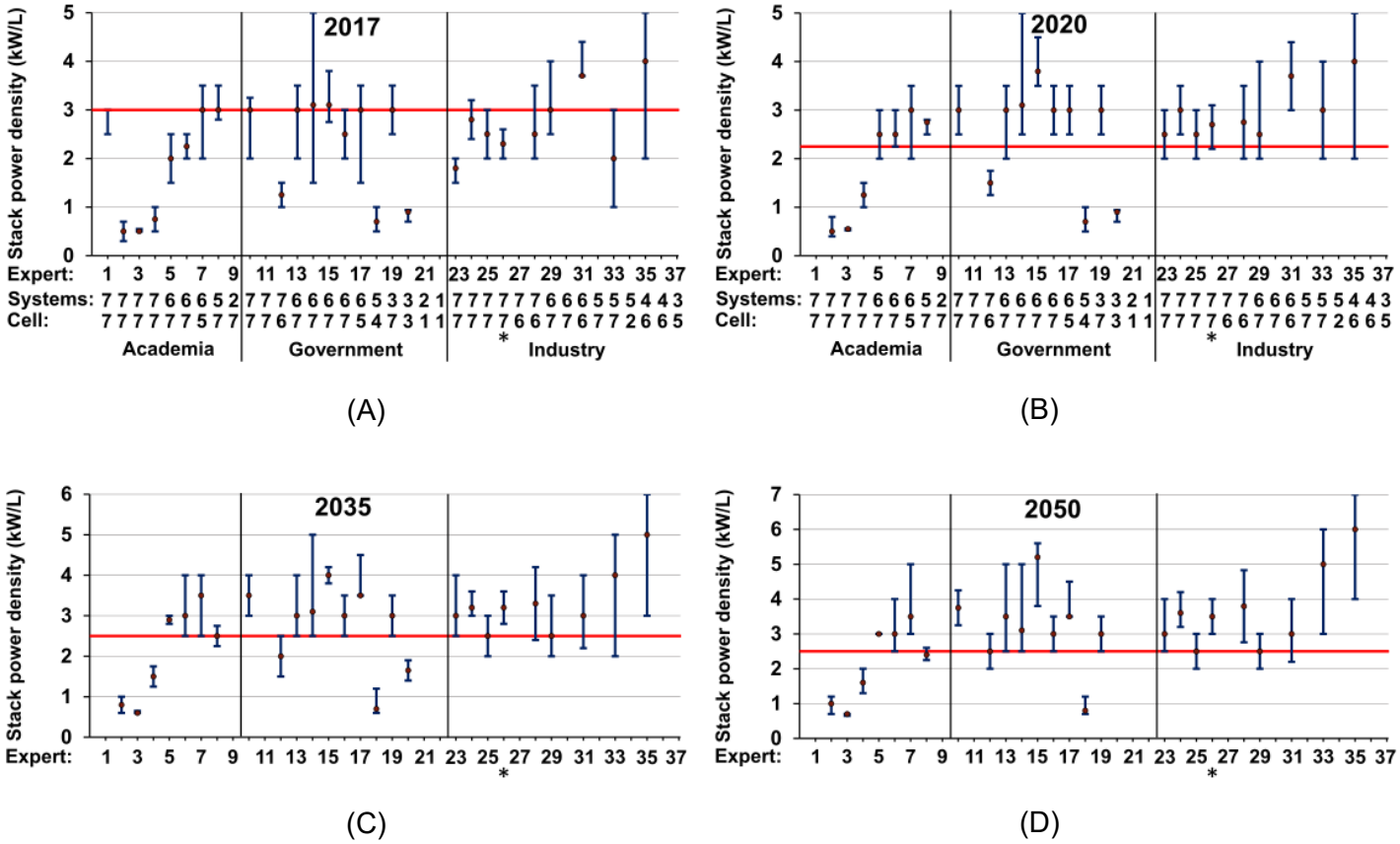


Fig. S7. Experts' assessments of PEMFC stack power density. Each data point represents an expert's best estimate, and the uncertainty ranges represent experts' judgments of a 95% confidence interval. Experts 10 and 26 assumed that the PEMFC stack operated at "up to 250 kPa_{abs}" at its inlet, which differs from the assumption of "up to 150 kPa_{abs}" stated in the question. The group interview is marked by an asterisk. (*A)* 2017 estimates. The horizontal line represents the DOE's 2015 estimate of 3 kW/L. (*B*) 2020 values. The horizontal line represents the DOE's 2020 target of 2.25 kW/L. (*C*) 2035 values. The horizontal line represents the DOE's ultimate target of 2.5 kW/L. (*D*) 2050 values. The horizontal line represents the DOE's ultimate target of 2.5 kW/L.

Expert

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
A	1	2	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1		3	1	1	1	1	2		2			
B																	3								2					3							
C				3																															1		
D	2	1			2	2	3	1		2	3	2		3	3	3		3	2					3	3	3	1		3		3	1			3		2
E						3						3	2		2					3				2	2	2									2	2	1
F	3	3	2	2	3		2		3	3	2		3	2		2	2	2	3	1		2	2					2	2	2*	2			3			
G			3					2	2					4									3				2	3				3		1			3

* Expert 30 emphasized the cost of the ionomer in barrier F.

1	Most significant
2	2nd most significant
3	3rd most significant

A: Cost of platinum due to high platinum group metal (PGM) total loading on both electrodes
B: Cost of cathode humidifier
C: Cost of heat exchangers for thermal management
D: Cost of bipolar plates
E: Cost of air compression system (air compressor, expander, and motor controller)
F: Cost of membrane
G: Cost of gas diffusion layers

Fig. S8. Experts' rankings of barriers to reducing PEMFC system cost. The barriers shown were selected from a list.

Table S5. Experts' rankings of barriers to reducing PEMFC system cost. The barriers shown were written-in by experts.

Barrier	Ranking	Expert
Cost of membrane electrode assembly	1	36
Cost of system integration	1	33
Maintaining high voltages at high current densities	1	26
Cost of assembling the stack	2	33
Cost of assembling the stack components	3	33
Lack of automation to mass produce fuel cell systems	3	36

Expert

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
A	2	3	3	3	2			2	2	2	1	2		4		2		1					2	1	2				1	1	2		3		3		
B						1		3						5			2	3							2					3*			10	3	2	3	
C			2	3														2	2									3	2			3	6	1			3
D	3			3	3	2	2							2	3													3					7				1
E										3	2	3							3				3			3		2			3	2	8			2	1
F																									3			2					9				1
G						3	3		3								3								3	3							5				
H		1	1	1	1		1	1		1		1		1			1								1			1	3				4			1	
I		2	1	2						1		1	1	1	2		1						1	2	1	2		1		2	2		2				
J	1		3	3					1	1	3	1	3	3	1	1	4		1						1	1		1	4		1	1	1	2	1		2

* Expert 30 expanded barrier B to include ionomer poisoning due to fuel and air impurities.

1 Most significant
2 2nd most significant
3 3rd most significant

A: Carbon support corrosion
B: Catalyst poisoning due to fuel and air impurities
C: Membrane mechanical failure due to humidity and temperature variation
D: Membrane mechanical failure due to pinholes or foreign matter from manufacturing
E: Membrane chemical degradation due to reaction with free radicals
F: Membrane chemical degradation due to ionic contamination
G: Bipolar plate corrosion
H: Platinum sintering
I: Platinum dissolution
J: Instability of alloyed catalysts

Fig. S9. Experts' rankings of barriers to improving PEMFC stack durability. The barriers shown were selected from a list.

Table S6. Experts' rankings of barriers to improving PEMFC stack durability. The barriers shown were written-in by experts.

Barrier	Ranking	Expert
Membrane degradation (mechanism unspecified)	1	20
Membrane chemical degradation (mechanism not specified)	2	29
Manufacturing defects in PEMFC components (e.g., sharp pieces in electrodes, membranes, or gas diffusion layers)	2	13
Combined membrane mechanical and chemical degradation accelerated by contamination	3	16
Membrane mechanical failure due to carbon support corrosion and/or platinum dissolution	3	24

Expert

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
A		2	2		2		2			2			3	2*				2						1	2			2					3†				
B	3	1	1		1		1	2	3	1		1	2		1	1	1		1	1			1		2	2		3	1			3	1		1	3	2
C					3					2														2					3		1		6	3	3		1
D																																	5				1
E			3						1										2						3							2	4				1
F	2	3															2							3							1		7	2			
G	1						3	1	2	3		2	1		2	2		3					3		1	1		1			1				2		
H				1				3				3					3																8	1			

* Expert 14 emphasized low electrolyte ionic conductivity at low relative humidity in barrier A.

† Expert 33 emphasized electrolyte ionic conductivity losses in the membrane and catalyst layers in barrier A.

1 Most significant
2 2nd most significant
3 3rd most significant

A: Low electrolyte ionic conductivity
B: High cathode activation loss
C: High electrical contact resistance between the electrodes and electrolyte
D: High oxygen crossover through the electrolyte
E: High hydrogen crossover through the electrolyte
F: Low bipolar plate electrical conductivity
G: High local platinum-electrolyte O_2 transport resistance
H: Large bipolar plates

Fig. S10. Experts' rankings of barriers to improving PEMFC stack power density. The barriers shown were selected from a list.

Table S7. Experts' rankings of barriers to improving PEMFC stack power density. The barriers shown were written-in by experts.

Barrier	Ranking	Expert
High O_2 transport resistance in gas diffusion layers	1	36
	2	23
	2	29
	3	16
Bipolar plate thickness	1	14
Bipolar plate thickness and active area underutilization	1	37
Low operating temperature	1	18
Membrane resistance at low relative humidity or water vapor pressure	1	32
Large cooling system inside fuel cell stack enclosure (e.g., heat spreaders or cooling channels)	2	4
Losses in the catalyst layer due to oxygen, proton, and/or water transport	2	33
Overall fuel cell stack design	2	36
Electrical contact resistance between the bipolar plates and gas diffusion layers	3	26
High local proton-Pt transport resistance	3	15
Mechanical robustness of fuel cell components	3	19
Thick gas diffusion layers due to low thermal and electrical conductivities of gas diffusion layers	3	4

Figs. S11 and S12 presents experts' recommended funding levels and funding prioritizations, respectively. As shown in Fig. S11, experts 3 and 32 recommended funding levels significantly higher than the FCTO's FY 2017 appropriation. Expert 3 recommended 11 times the FY 2017 appropriation for "catalysts and electrodes" and 18 times the FY 2017 appropriation for "fuel cell performance and durability." During their interview, expert 3 highlighted cost and durability as major issues. Expert 32 recommended 16 times the FY 2017 appropriation for "membranes and electrolytes" and 25 times the FY 2017 appropriation for "testing and technical assessment." Expert 32 recommended the same funding amount for each R&D area: $50 million. During their interview, expert 32 used previous funding opportunity announcements as a reference but chose not to look at the previous year FCTO funding levels when given the opportunity to do so. As shown in Fig. S12, most experts prioritized "catalysts and electrodes" and "fuel cell performance and durability" before "membranes and electrolytes" and "testing and technical assessment."

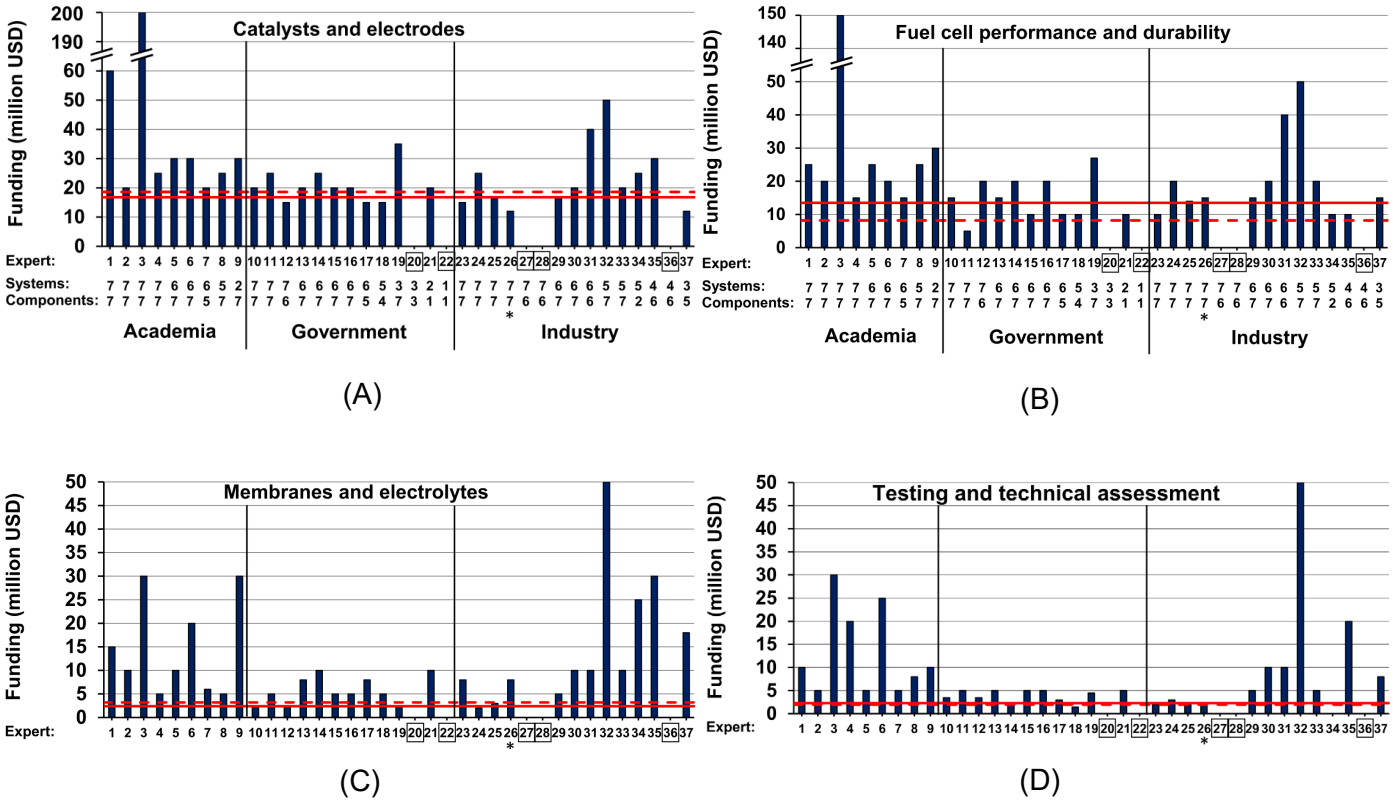


Fig. S11. Experts' recommended funding levels in FY 2018. Experts' assessments are organized by affiliation and self-assessed expertise (0 = not familiar, 7 = very familiar). For each PEMFC R&D area, we show the DOE's FY 2017 appropriation (horizontal solid line) and FY 2017 request (horizontal dashed line). An expert whose number is boxed did not respond to the question. The group interview is marked by an asterisk. (*A*) Catalysts and electrodes. (*B*) Fuel cell performance and durability. (*C*) Membranes and electrolytes. (*D*) Testing and technical assessment.

Expert

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
A	4	4	4	2	4	4	1	3	4	3	4	3	4	4	4	4	4	4	3	4	4		4	4	3	4	4		4	3	3	4	4	4	3		3
B	1	2	1	3	1	1	2	2	1	2	1	2	1	1	1	1	2	1	1	2	1		1	1	1	2	3		1	1	2	2	2	1	1		4
C	2	1	2	1	2	3	2	1	2	1	3	1	2	2	2	2	1	3	2	3	2		3	2	2	1	1		3	2	1	1	1	3	4		2
D	3	3	3	4	3	2	2	4	3	4	2	4	3	3	3	3	3	2	4	1	3		2	3	4	3	2		2	4	3	3	3	2	2		1

1 Highest priority
2 2nd highest priority
3 3rd highest priority
4 4th highest priority

A: Testing and technical assessment
B: Catalysts and electrodes
C: Fuel cell performance and durability
D: Membranes/electrolytes

Fig. S12. Experts' rankings of PEMFC R&D areas in order of government funding priority in FY 2018.

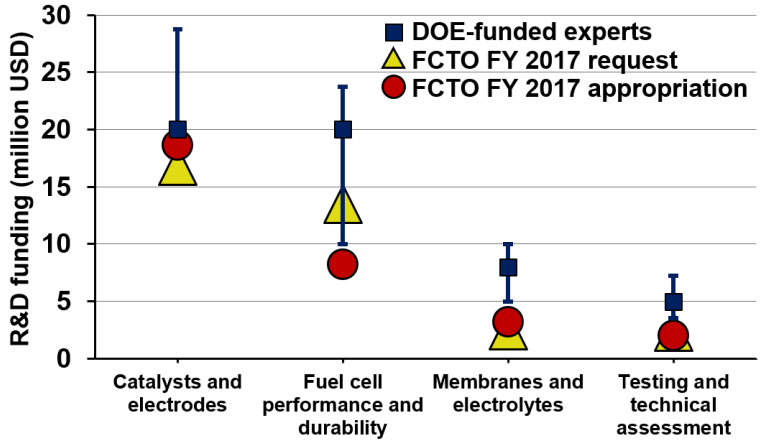
Supporting Information

Section S6

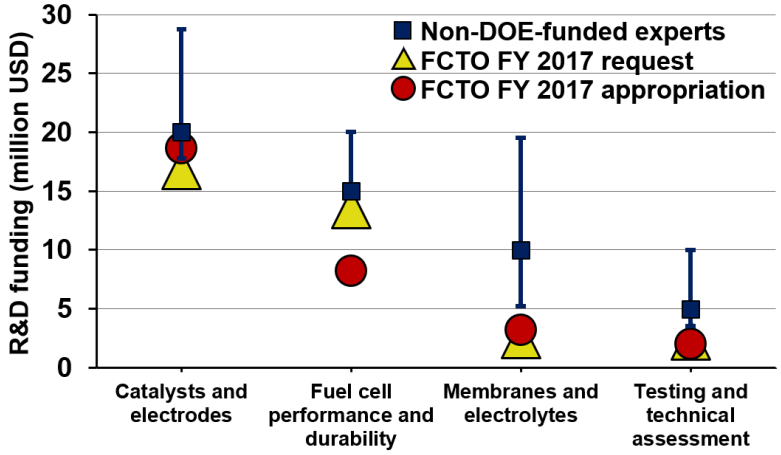
Test for Motivational Bias

To test for motivational bias in experts' funding recommendations, we organized experts' recommendations by funding source. Fig. S13 and Table S8 present our results. U.S. Department of Energy (DOE)-funded experts include experts who work in a DOE National Laboratory or received DOE Fuel Cell Technologies Office (FCTO) funding in FY 2016 or FY 2017 (1, 2).[*] Both DOE and non-DOE-funded experts allocated the most median funding to "catalysts and electrodes" and "fuel cell performance and durability," followed by "membranes and electrolytes" and "testing and technical assessment." DOE-funded experts recommended $50 million (median) in total funding (range: $31.5 to $200 million), and non-DOE-funded experts recommended $55 million (median) in total funding (range: $35 to $410 million). Thus, we did not detect motivational bias associated with experts' funding affiliations.

[*] Recipients of FCTO funding include Principal Investigators and collaborators on FCTO-funded projects.



(A)



(B)

Fig. S13. Experts' recommended government R&D funding levels, separated by funding source, 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' recommendations. (*A*) DOE-funded experts. (*B*) Non-DOE-funded experts.

Table S8. Summary statistics of experts' R&D funding recommendations, separated by funding source.

	R&D Funding (million 2017 USD)				
	Minimum	25th percentile	Median	75th percentile	Maximum
DOE-funded experts *					
Catalysts and electrodes	12	20	20	28.75	60
Fuel cell performance and durability	5	10	20	23.75	50
Membranes and electrolytes	2.5	5	8	10	50
Testing and technical assessment	1.5	3.5	5	7.25	50
Non-DOE-funded experts †					
Catalysts and electrodes	12	17.75	5	28.75	200
Fuel cell performance and durability	10	15	20	20	150
Membranes and electrolytes	2	5.25	15	19.5	30
Testing and technical assessment	0	3.5	10	10	30

* DOE-funded experts include experts who work in a DOE National Laboratory or received FCTO funding in FY 2016 or FY 2017. Recipients of FCTO funding include Principal Investigators and collaborators on FCTO-funded projects (1, 2).
† Non-DOE-funded experts include all other experts (i.e., experts not included in the footnote above).

References

1. Fuel cells. In: Annual Merit Review Proceedings [Internet]. Washington, D.C.: U.S. Department of Energy; 2016. Available from: https://www.hydrogen.energy.gov/annual_review16_fuelcells.html

2. Fuel cells. In: Annual Merit Review Proceedings [Internet]. Washington, D.C.: U.S. Department of Energy; 2017. Available from: https://www.hydrogen.energy.gov/annual_review17_fuelcells.html

Supporting Information

Section S7

Barriers to Reducing Cost, Improving Durability, and Improving Power Density

System Cost

Fig. S14 presents experts' rankings of barriers to reducing proton exchange membrane fuel cell (PEMFC) system cost. These barriers were written-in by experts. Experts highlighted stack manufacturing and system integration as significant barriers. In 2017, General Motors and Ford announced their agreement to invest a combined total of $85 million to mass produce fuel cell systems beginning in 2020 (1). Europe's Fuel Cells and Hydrogen Joint Undertaking (FCH JU) supports the FIT-4-AMandA project to automate PEMFC stack manufacturing (2). The U.S. Department of Energy has supported projects to expand PEMFCs' supply chain (3, 4). One expert commented on the importance of maintaining high voltage (i.e., high power density) at high current density. This expert explained that improving power density reduces the stack materials, and thus, the stack cost.

Stack Durability

Fig. S15*A* presents experts' rankings of barriers to improving PEMFC stack durability. These barriers were selected from a list. Many experts identified the instability of alloyed catalysts as the most significant barrier. Pre-leaching, or dealloying, which is the removal of surface accessible, unalloyed transition metal via acid treatment, improves retention of the catalyst's base metal (5). In addition, experts identified Pt sintering, Pt dissolution, and carbon support corrosion as significant barriers. Recent work suggests that that zirconia nanocages (6) and silica coatings (7) could inhibit Pt migration. Pt dissolution is mitigated by annealing the catalyst (8) and reducing the Pt particle size (9). Catalyst supports composed of mesoporous carbon spheres (10), hybrid graphene-carbon nanotubes (11), SiC (12), or TiC (13) could mitigate Pt electrochemical surface area loss.

Several experts wrote in barriers related to membrane degradation (Fig. S15*B*). Free radical scavengers, particularly Ce^{3+}, are known to enhance PEMFCs' chemical durability (14–17). Baker et al. (18) incorporated $Ce_{0.85}Zr_{0.15}O_2$ (CZO) into the cathode. Compared to the CZO-free MEA, the MEA with a CZO loading of 10 μg/cm^2 exhibited slower open circuit voltage (OCV) decay during and better polarization performance after accelerated chemical stress testing. Baker, Wang, Johnson, Prasad, and Advani (19) incorporated CeO_2-coated multiwall carbon nanotubes (CeO_2/MWNTs) into the Nafion membrane. Compared to pure Nafion, the CeO_2/MWNT Nafion membrane exhibited a lower OCV decay rate during testing and better mechanical strength prior to testing. Incorporating ePTFE can improve the membrane's mechanical strength and dimensional stability (20). Prior studies have also investigated membrane durability under combined mechanical and chemical stresses (21, 22).

Stack Power Density

Fig. S16 presents experts' rankings of barriers to improving PEMFC stack power density. Fig. S16*A* indicates the number of experts who selected each barrier from a list. Many experts identified the high cathode activation loss as the most significant barrier. Li et al.'s (23) jagged Pt nanowires exhibited an ex-situ mass activity 52 times greater than that of Pt/C. Numerous other catalysts, including Pt_3Ni nanoframes (24), Pt nanocages (25), $Pt_{2.5}Ni$ octahedra (26), Pt alloy nanowires (27, 28), Pd-Pt core-shell icosahedra (29), and Mo-Pt_3Ni octahedra (30), have exhibited higher ex-situ catalytic activities than that of Pt/C. Several experts identified the local Pt-electrolyte O_2 transport resistance as a significant barrier. The local Pt-electrolyte O_2 transport resistance accounts for PEMFC voltage loss at high current densities and low Pt loadings. Developing electrode ionomers that are highly O_2 permeable and acid groups less prone to adsorb on Pt could reduce the local O_2-ionomer resistance (31).

Several experts wrote in barriers related to the stack's structural design (Fig. S16*B*). These barriers included bipolar plate (BPP) active area underutilization, overall fuel cell stack design, and the size of the stack's cooling system. Toyota improved their stack power density from 1.4 to 3.1 kW/L through several design modifications. Toyota incorporated a 3-D fine mesh flow field that facilitated O_2 diffusion to the cathode and the removal of water from the membrane electrode assembly and gas diffusion layer (GDL). In addition, Toyota reduced the membrane thickness by two-thirds relative to their 2008 model, removed the stack's external compression springs, and increased the stack's catalyst activity (32, 33). Intelligent Energy's evaporative cooling mechanism eliminated liquid cooling channels between the fuel cells. The company's automotive stack operates at an impressive 3.5 kW/L (34). Modifying BPP design provides another avenue for improving stack power density. It is well-known that flow field geometry impacts power density (35, 36). Lastly, several experts identified O_2 transport resistance in the GDLs as a major barrier to improving power density. Recent work modified the composition (37) and porosity (38) of GDLs to improve O_2 transport.

	Ranking (written-in)		
	1st	2nd	3rd
Cost of MEA	1		
Cost of system integration	1		
Maintaining high voltage at high current density	1		
Cost of assembling stack		1	
Cost of assembling stack components (e.g., unitized electrode assemblies)			1
Lack of automation to mass produce fuel cell systems			1

Fig. S14. Experts' rankings of barriers reducing PEMFC system cost. The number of experts who selected each barrier is indicated. The barriers shown were written-in by experts.

	Ranking (from list)		
	1st	2nd	3rd
Instability of alloyed catalysts	14	2	5
Pt sintering	13		1
Pt dissolution	9	8	
Carbon support corrosion	5	10	5
Membrane chemical degradation (reaction with free radicals)	1	4	6
Membrane mechanical failure (humidity and temperature variation)	1	4	4
Catalyst poisoning (fuel and air impurities)	1	3	5
Membrane mechanical failure (pinholes or foreign matter from manufacturing)	1	3	5
Membrane chemical degradation (ionic contamination)	1	1	1
BPP corrosion			6

(A)

	Ranking (written-in)		
	1st	2nd	3rd
Membrane degradation (mechanism unspecified)	1		
Manufacturing defects in PEMFC components (e.g., sharp pieces in electrodes, membranes, or GDLs)		1	
Membrane chemical degradation (mechanism unspecified)		1	
Combined membrane mechanical and chemical degradation accelerated by contamination			1
Membrane mechanical failure due to carbon support corrosion and/or Pt dissolution			1

(B)

Fig. S15. Experts' rankings of barriers to improving PEMFC stack durability. The number of experts who selected each barrier is indicated (darker cells indicate more experts). (*A*) Barriers selected from a list. (*B*) Barriers written-in by experts.

	Ranking (from list)		
	1st	2nd	3rd
High cathode activation loss	15	5	5
High local Pt-electrolyte O_2 transport resistance	7	5	4
High electrical contact resistance between electrodes/electrolyte	2	2	4
High H_2 crossover through the electrolyte	2	2	2
Large BPPs	2		3
Low electrolyte ionic conductivity	1	9	2
Low BPP electrical conductivity	1	3	2
High O_2 crossover through the electrolyte	1		

(A)

	Ranking (written-in)		
	1st	2nd	3rd
High O_2 transport resistance in GDLs	1	2	1
BPP thickness	1		
BPP thickness and active area underutilization	1		
Low operating temperature	1		
Membrane resistance at low relative humidity or water vapor pressure	1		
Large cooling system in stack enclosure*		1	
Losses in the catalyst layer due to oxygen, proton, and/or water transport		1	
Overall fuel cell stack design		1	
Electrical contact resistance between BPPs and GDLs			1
High local proton-platinum transport resistance			1
Mechanical robustness of fuel cell components			1
Thick GDLs due to low thermal and electrical conductivities of GDLs			1

*For example, heat spreaders or cooling channels.

(B)

Fig. S16. Experts' rankings of barriers to improving PEMFC stack power density. The number of experts who selected each barrier is indicated (darker cells indicate more experts). (*A*) Barriers selected from a list. (*B*) Barriers written-in by experts.

References

1. General Motors (2017) GM and Honda to establish industry-first joint fuel cell system manufacturing operation in Michigan. Available at: http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2017/jan/0130-tunein.html [Accessed August 1, 2018].

2. Fuel Cells anad Hydrogen Joint Undertaking (2017) FIT-4-AMANDA. Available at: http://www.fch.europa.eu/project/future-european-fuel-cell-technology-fit-automatic-manufacturing-and-assembly [Accessed August 1, 2018].

3. Valente P (2016) *FY 2016 progress report for the DOE Hydrogen and Fuel Cells Program (Report No. DOE/GO-102017-4891): Clean energy supply chain and manufacturing competitiveness analysis for hydrogen and fuel cell technolodies* Available at: https://www.hydrogen.energy.gov/pdfs/progress16/vi_2_valente_2016.pdf.

4. Harned A (2016) *FY 2016 progress report for the DOE Hydrogen and Fuel Cells Program (Report No. DOE/GO-102017-4891): Fuel cell and hydrogen opportunity center* Available at: https://www.hydrogen.energy.gov/pdfs/progress16/vi_3_harned_2016.pdf.

5. Gasteiger HA, Kocha SS, Sompalli B, Wagner FT (2005) Activity benchmarks and requirements for Pt, Pt-alloy, and non-Pt oxygen reduction catalysts for PEMFCs. *Appl Catal B Environ* 56(1–2):9–35.

6. Cheng N, et al. (2015) Extremely stable platinum nanoparticles encapsulated in a zirconia nanocage by area-selective atomic layer deposition for the oxygen reduction reaction. *Adv Mater* 27(2):277–281.

7. Lu P, Campbell CT, Xia Y (2013) A sinter-resistant catalytic system fabricated by maneuvering the selectivity of SiO_2 deposition onto the TiO_2 surface versus the Pt nanoparticle surface. *Nano Lett* 13(10):4957–4962.

8. Makharia R, et al. (2006) Durable PEM fuel cell electrode materials: Requirements and benchmarking methodologies. *ECS Trans* 1(8):3–18.

9. Yu K, et al. (2014) Degradation mechanisms of platinum nanoparticle catalysts in proton exchange membrane fuel cells: The role of particle size. *Chem Mater* 26(19):5540–5548.

10. Zhang C, et al. (2014) Enhanced electrocatalytic activity and durability of Pt particles supported on ordered mesoporous carbon spheres. *ACS Catal* 4(6):1926–1930.

11. Pham K-C, McPhail DS, Mattevi C, Wee ATS, Chua DHC (2016) Graphene-carbon nanotube hybrids as robust catalyst supports in proton exchange membrane fuel cells. *J Electrochem Soc* 163(3):F255–F263.

12. Stamatin SN, Speder J, Dhiman R, Arenz M, Skou EM (2015) Electrochemical stability and postmortem studies of Pt/SiC catalysts for polymer electrolyte membrane fuel cells. *Appl Mater Interfaces* 7(11):6153–6161.

13. Chiwata M, et al. (2015) Oxygen reduction reaction activity and durability of Pt catalysts supported on titanium carbide. *Catalysts* 5(2):966–980.

14. Endoh E (2008) Development of highly durable PFSA membrane and MEA for PEMFC under high temperature and low humidity conditions. *ECS Trans* 16(2):1229–1240.

15. Coms FD, Liu H, Owejan JE (2008) Mitigation of perfluorosulfonic acid membrane chemical degradation using cerium and manganese ions. *ECS Trans* 16(2):1735–1747.

16. Trogadas P, Parrondo J, Ramani V (2008) Degradation mitigation in polymer electrolyte membranes using cerium oxide as a regenerative free-radical scavanger. *Electrochem Solid-State Lett* 11(7):B113–B116.

17. Wang L, Advani SG, Prasad AK (2013) Degradation reduction of polymer electrolyte membranes using CeO_2 as a free-radical scavenger in catalyst layer. *Electrochim Acta* 109:775–780.

18. Baker AM, et al. (2017) Zr-doped ceria additives for enhanced PEM fuel cell durability and radical scavenger stability. *J Mater Chem A* 5(29):15073–15079.

19. Baker AM, Wang L, Johnson WB, Prasad AK, Advani SG (2014) Nafion membranes reinforced with ceria-coated multiwall carbon nanotubes for improved mechanical and chemical durability in polymer electrolyte membrane fuel cells. *J Phys Chem* 118(46):26796–26802.

20. Cleghorn S, Kolde J, Liu W (2003) Catalyst coated composite membranes. *Handbook of Fuel Cells*, eds Vielstich W, Lamm A, Gasteiger HA (John Wiley and Sons, Chichester), pp 566–575.

21. Lim C, et al. (2015) Fuel cell durability enhancement with cerium oxide under combined chemical and mechanical membrane degradation. *ECS Electrochem Lett* 4(4):F29–F31.

22. Park J, Wang L, Advani SG, Prasad AK (2012) Durability analysis of Nafion/hydrophilic pretreated PTFE membranes for PEMFCs. *J Electrochem Soc* 159(12):F864–F870.

23. Li M, et al. (2016) Ultrafine jagged platinum nanowires enable ultrahigh mass activity for the oxygen reduction reaction. *Science (80-)* 354(6318):1414–1419.

24. Chen C, et al. (2014) Highly crystalline multimetallic nanoframes with three-dimensional electrocatalytic surfaces. *Science (80-)* 343(6177):1339–1343.

25. Zhang L, et al. (2015) Platinum-based nanocages with subnanometer-thick walls and well-defined, conrollable facets. *Science (80-)* 349(6246):412–416.

26. Choi S-I, et al. (2013) Synthesis and characterization of 9 nm Pt-Ni octahedra with a record high activity of 3.3 A/mgPt for the oxygen reduction reaction. *Nano Lett* 13(7):3420–3425.

27. Guo S, et al. (2013) FePt and CoPt nanowires as efficient catalysts for the oxygen reduction reaction. *Angew Chemie* 52(12):3465–3458.

28. Higgins DC, et al. (2014) Morphology and composition controlled platinum-cobalt alloy nanowires prepared by electrospinning as oxygen reduction catalyst. *Nano Energy* 10:135–143.

29. Wang X, et al. (2015) Palladium-platinum core-shell icosahedra with substantially enhanced activity and durability towards oxygen reduction. *Nat Commun* 6:1–8.

30. Huang X, et al. (2015) High-performance transition metal-doped Pt3Ni octrahedra for oxygen reduction reaction. *Science (80-)* 348(6240):1230–1234.

31. Kongkanand A, Mathias MF (2016) The priority and challenge of high-power performance of low-platinum proton-exchange membrane fuel cells. *J Phys Chem Lett* 7(7):1127–1137.

32. Yoshida T, Kojima K (2015) Toyota MIRAI fuel cell vehicle and progress toward a future hydrogen society. *Electrochem Soc Interface* 24(2):45–49.

33. Konno N, Mizuno S, Nakaji H, Ishikawa Y (2015) Development of compact and high-performance fuel cell stack. *SAE Int J Altern Power* 4(1):123–129.

34. Intelligent Energy (2015) Intelligent Energy for high-performance 100 kW automotive fuel cell architecture. *Fuel Cells Bull*:4.

35. Cooper NJ, Smith T, Santamaria AD, Park JW (2016) Experimental optimization of parallel and interdigitated PEMFC flow-field channel geometry. *Int J Hydrogen Energy* 41(2):1213–1223.

36. Taccani R, Zuliani N (2011) Effect of flow field design on performances of high temperature PEM fuel cells: Experimental analysis. *Int J Hydrogen Energy* 36(16):10282–10287.

37. Koresawa R, Utaka Y (2014) Improvement of oxygen diffusion characteristic in gas diffusion layer with planar-distributed wettability for polymer electrolyte fuel cell. *J Power Sources* 271:16–24.

38. Zhang Y, Verma A, Pitchumani R (2016) Optimum design of polymer electrolyte membrane fuel cell with graded porosity gas diffusion layer. *Int J Hydrogen Energy* 41(20):8412–8426.