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Meeting Solid Oxide Fuel Cell Cost and Degradation Rate Targets

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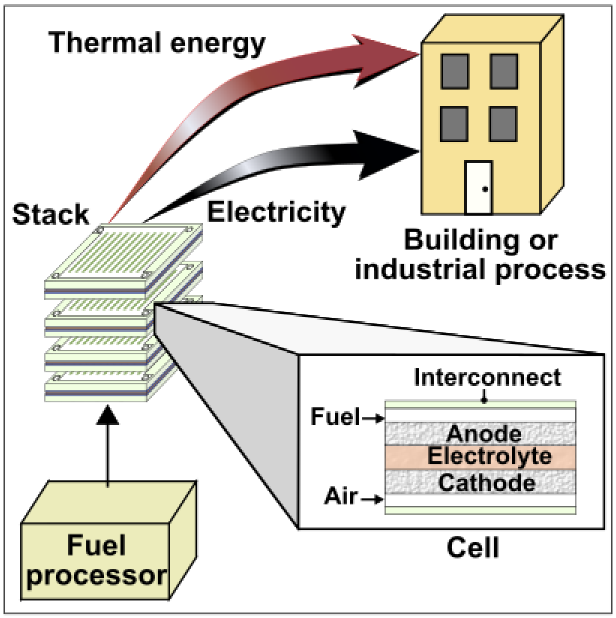
Graphical Abstract



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Abstract and Keywords

Solid oxide fuel cells (SOFCs) are highly efficient, scalable devices capable of operating on hydrogen and hydrocarbon fuels and can co-generate power and thermal energy. However, SOFCs lack wide market adoption. To prioritize RD&D areas, the U.S. Department of Energy (DOE) established system capital cost and stack degradation rate targets. Here, we present an expert elicitation of current and expected future SOFC system costs, stack costs, and stack durability. Based on 27 experts' assessments, we found that meeting DOE targets by 2020–2030 could require considerable cost reductions and improvements in stack durability. Assuming hypothetical, high-volume manufacturing, experts assessed a 2020 median system cost of $1,200/kW_{net}$. Seventy-five percent and 92% of respondents assessed higher 2035 system costs and 2020 degradation rates, respectively, than DOE targets. Reducing the SOFC stack's manufacturing cost, mitigating chromium poisoning of the cathode and chemical and microstructural changes in the electrodes, and increasing government RD&D funding could significantly accelerate progress toward meeting DOE targets.

Keywords: solid oxide fuel cell; expert elicitation; cost; degradation; research, development, and demonstration; policy; funding

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Introduction

Solid oxide fuel cells (SOFCs) are highly efficient, scalable, high-temperature (typically greater than 600 °C), solid-state devices that, through an electrochemical reaction, convert hydrocarbon or hydrogen fuels into electricity and thermal energy. Without compromising efficiency, SOFCs can be connected, and interconnects electrically joined, to form stacks that meet demand. Commercial SOFC systems are capable of operating on hydrogen, natural gas, propane, and biogas and produce nearly zero criteria air pollutant emissions, including NO_x and SO_x [1,2]. Due to their scalability, high efficiency, clean emissions, and quiet operation, SOFC systems are alternative sources of continuous, distributed, uninterruptible power and thermal energy for residential, commercial, and remote applications [1–3]. In the future, SOFCs could switch from fossil to low-carbon fuels, without modifying the cell, as these fuels and infrastructure become available [4]. When operating on low-carbon fuels, such as hydrogen produced by the renewable electrolysis of water or biofuels derived from low-impact biomass, SOFC systems have the potential to produce zero net carbon emissions.

Despite these advantages, the majority of SOFC system installations rely on government subsidies and less than 100 MW of SOFC power (less than 30,000 systems) were shipped in 2018 [3]. Barriers to widely commercializing SOFC systems include high capital costs and high operating expenses due to degradation over time. To inform RD&D priorities and direction, the U.S. Department of Energy (DOE) established a 2025–2030 system capital cost target of \$900/kW [5], 2020 stack degradation target of 0.2%/1,000 hrs, and 2030 stack cost target of \$225/kW_{net} [6], which we adjusted to \$206/kW_{DC}. Meeting these targets would enable SOFC systems to be cost-competitive, per kWh, with incumbent technologies, including small-scale generators, microturbines, and renewables.

Based on expert assessments that we collected using a detailed elicitation protocol, we found that meeting DOE targets by 2020–2030 could require considerable reductions in stack and system costs, better understanding and strategies for mitigating cell and stack degradation, and increased government RD&D funding with an emphasis on systems development. Expert elicitation is a formal and systematic procedure for interviewing experts and encoding their assessments into subjective probability distributions [7]. We elicited 27 experts' assessments, in the form of best estimates (most likely values) banded by 95% confidence intervals (CIs), of current and expected future system costs, stack costs, and stack degradation rates. Our experts had an average experience of 19 years and a cumulative experience of over 500 years working with SOFCs. Eleven of our experts worked in academia, eight experts worked in government, and eight experts worked in industry. We further describe our materials and methods, including cost target adjustments, in the Supplemental Experimental Procedures section of our Supplemental Information (see Table S1 for a summary of experts' background information).

When Will SOFCs Meet DOE Targets?

The experts we interviewed anticipated that, based on current trajectories, stacks and systems in 2030 would likely be more expensive than DOE targets. We asked our experts to assess the costs of a 100 kW_{net} combined heat and power (CHP) system and 30 kW_{DC} stack under hypothetical production volumes of 50,000 systems/year and 500,000 stacks/year. Figure 1 presents experts' assessments. Experts anticipated 2017, 2020, 2035, and 2050 median system costs of \$2,700/kW_{net}, \$2,450/kW_{net}, \$1,200/kW_{net}, and \$800/kW_{net}, respectively (Figure 1A).

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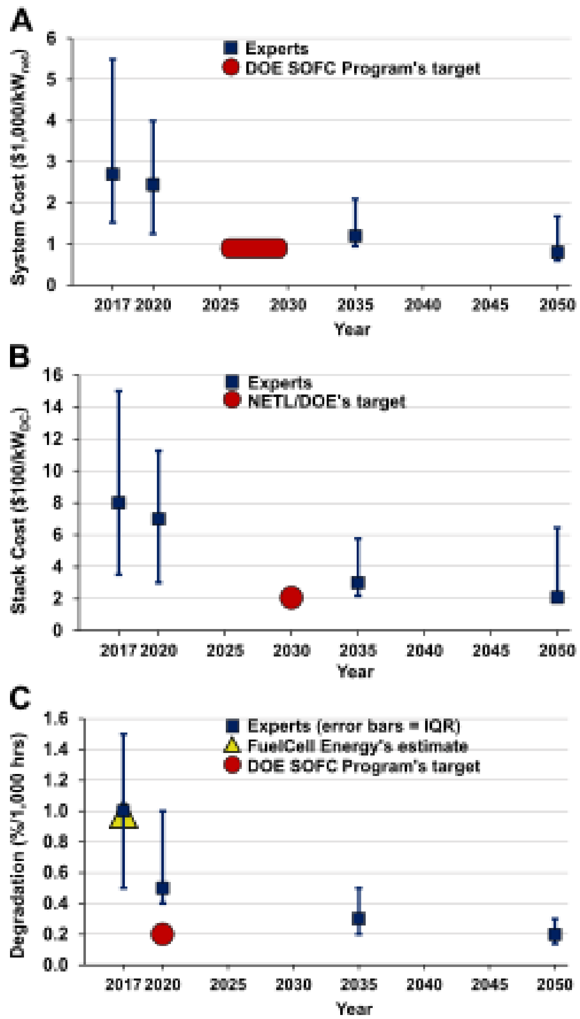

Figure 1. Experts' Assessments of SOFC System Cost and Stack Degradation
The medians of experts' best estimates are denoted by squares, and the IQRs are denoted by error bars. Experts anticipated higher 2017 and 2020 costs and degradation rates than DOE targets. By 2035 and 2050, the targets could be met. All costs are expressed in 2017 USD.
(A) SOFC CHP system cost assessments. DOE's 2025–2030 target is $900/kW_{net}$.
(B) SOFC stack cost assessments. DOE's adjusted 2030 target is $206/kW_{DC}$.
(C) SOFC stack degradation rate assessments. DOE's 2020 target is 0.2%/1,000 hrs.

While a considerable reduction in system cost could occur between 2020 and 2035, seventy-five percent of experts anticipated that system costs in 2035 would be higher than DOE's 2025–2030 target. Like system costs, the DOE stack cost target could be met by 2035–2050, and a considerable improvement could occur between 2020 and 2035. Experts anticipated 2017, 2020,

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A

	Ranking (from list) 1st	2nd	3rd
Cost of SOFC stacks	17	7	2
Cost of power electronics, control, and instrumentation	5	5	8
Cost of fuel processor*	2	8	9
Cost of air preheater	2	4	3
Cost of start-up air blower and cathode air blower		5	4

*The fuel processor includes the burner, ejector, reformer and fuel preheater, and tail gas

B

	Ranking (from list) 1st	2nd	3rd
Cost of material	13	8	5
Cost of machinery (including operation)	7	8	7
Cost of labor	5	5	7
Cost of scrap	1	3	3
Cost of tooling	1	3	1

Figure 2. Experts' Rankings of Barriers to Reducing SOFC Stack and System Cost
Each box indicates the number of experts who selected each barrier and the corresponding ranking (most, second most, and third most considerable) assigned by experts. The barriers shown were selected from a list.
(A) Barriers to reducing system cost. Experts identified the SOFC stack, power electronics, and fuel processor costs as considerable.
(B) Barriers to reducing stack cost. Experts identified material and machinery costs as considerable.

2035, and 2050 stack costs of \$800/kW_{DC}, \$700/ kW_{DC}, \$300/kW_{DC}, and \$207/kW_{DC}, respectively (Figure 1B). Seventy-five percent of respondents anticipated higher 2035 stack costs than DOE's 2030 target.

The durability of SOFC stacks will likely require considerable improvement to meet DOE's 2020 degradation rate target. We asked experts to assess the degradation rate of a reformate-fed, planar stack tested in a furnace maintained at 715°C. Experts estimated the degradation rate of a stack manufactured in 2017 to be 1%/1,000 hrs (Figure 1C), which agrees with FuelCell Energy's estimate of 0.98%/1,000 hrs, also shown in Figure 1C [8]. Experts

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anticipated 2020, 2035, and 2050 median degradation rates of 0.5%/1,000 hrs, 0.3%/1,000 hrs, and 0.2%/1,000 hrs, respectively. Ninety-two percent of respondents anticipated higher 2020 best estimates than DOE's 2020 target of 0.2%/1,000 hrs.

There is large uncertainty in future costs and degradation. Experts' 2020 best estimates of system cost ranged from \$720 to \$10,000/kW_{net} [confidence intervals (CIs): \$400 to \$15,000/kW_{net}; see Figures S1–S3 and Tables S2–S4 for experts' disaggregated assessments of system cost, stack cost, and stack degradation]. During their interviews, three experts referenced a 2010 Bloom Energy estimate of \$7,000–\$8,000/kW_{net}, and one expert referenced a 2015 Japanese ENE-FARM estimate of \$15,000/kW_{net}. Experts also commented on factors contributing to cost uncertainty; these factors included the system's operating temperature, companies' manufacturing capability, and the degree of market penetration. Experts' 2020 best estimates of stack cost ranged from \$100 to \$15,000/kW_{DC} (CIs: \$60 to \$100,000/kW_{DC}). Several experts assessed 2035 stack costs greater than \$1,000/kW_{DC}. Two of these experts mentioned that the stack cost would equal half the system cost.

Variation in system design and operation could contribute to future uncertainty. Experts' 2020 best estimates of stack degradation ranged from 0.15% to 2.5%/1,000 hrs (CIs: 0.02% to 5%/1,000 hrs). Several experts assessed 2020 degradation rates greater than or equal to 2.5%/1,000 hrs. One of these experts explained that the degradation rate depends on the stack's operating temperature and material set, both of which vary by the stack manufacturer. Another of these experts mentioned that the balance-of-stack components, including the stack housing, sealing, and interconnects, posed more severe limitations to achieving degradation targets than the cell (anode, cathode, and electrolyte) materials.

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Advancing the Viability of SOFCs

Identifying barriers to improving SOFC costs and performance is essential to prioritizing RD&D areas. Figure 2 displays experts' rankings of barriers to reducing system and stack costs. Most respondents identified the stack as the most considerable barrier to reducing system cost (Figure 2A; see Figure S4 for additional remarks made by experts). Reducing the stack's operating temperature would permit the use of less expensive interconnects, seals, and balance-of-plant (BoP) components [9]. Avenues being pursued to improve low-temperature SOFC performance include (i) improving electrolyte conductivity by fabricating stable, bilayer electrolyte materials [10], and (ii) improving the oxygen reduction reaction kinetics by developing nanostructured, infiltrated cathodes and perovskite-related cathode materials [11]. Experts wrote-in barriers (Figure S5) related to short stack lifetimes and the costs of BoP components (e.g., fuel processor, air and recirculation blowers, and heat exchangers). Improving stack lifetime would reduce the frequency of stack replacements.

Experts identified the costs of material and machinery, including operation, as the most considerable barriers to reducing stack cost (Figure 2B; see Figure S6 for additional remarks made by experts). Experts emphasized the cost of electricity and heating during cell manufacturing, and one expert mentioned that SOFCs, as a niche industry, require custom-built tooling and machinery. Another expert estimated the cost of balance-of-stack components (seals, assembly and housing, current collectors, and interconnects) to be twice as high as cell material costs. Experts wrote-in barriers related to low production volumes, the cost of stack replacements, and the cost of stack conditioning (Figure S7). One expert, who worked in industry, commented on the intensity of labor and energy required to condition the stack, which involves heating-up, testing, and cooling-down the stack prior to shipment.

Mitigating chromium (Cr) poisoning, chemical and microstructural changes in the electrodes, and seal and interconnect degradation could significantly improve the stack's durability. Most experts identified Cr poisoning of the cathode as the most considerable barrier to reducing stack degradation (Figures S8A and S9). One expert explained that Cr poisoning is problematic for both lanthanum strontium cobalt ferrite (LSCF) and lanthanum strontium manganite cathodes but more problematic for LSCF. A different expert mentioned that Cr poisoning could originate from interconnects and upstream BoP components. Experts wrote-in challenges related to chemical and microstructural changes in the electrodes, degradation of metallic interconnects, and seal degradation (Figure S8B).

Recommended RD&D Funding

Improving the viability of SOFCs requires a focused RD&D portfolio to address the biggest challenges. We asked experts to recommend the minimum amount of government RD&D funding that they thought would be necessary to achieve future (2020 and onward) technical and economic milestones established by the DOE. Figure 3 presents experts' funding recommendations, organized by RD&D area, and the DOE SOFC Program's FY 2018 appropriation. From FY 2015–2018, DOE appropriated $30 million USD per annum [5]. Experts recommended $70 million (median) in total FY 2018 funding. The middle 50% of experts recommended $50–$97.5 million in total funding, which is 2–3 times more funding than DOE's

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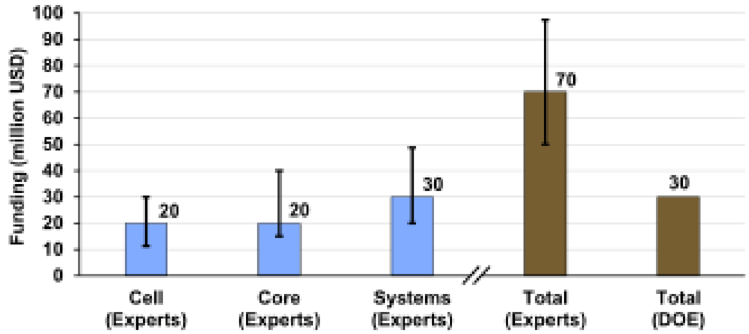

Figure 3. Experts' Recommended Government RD&D Funding Levels
Experts recommended a funding increase relative to DOE's FY 2018 appropriation. To the left of the axis break, we present the medians of experts' recommended funding levels in FY 2018 for each RD&D area: "cell development," "core technology," and "systems development." To the right of the axis break, we present the median of experts' total funding recommendations and the DOE SOFC Program's FY 2018 appropriation. "Cell development" refers to the improvement of the fuel cell's durability, performance, and cost. "Core technology" is the reduction of the cost and improvement of the durability of stack and BoP components. "Systems development" is the integration, manufacturing, and deployment of systems to accelerate market penetration, as well as cell and stack design and scale-up [12].

FY 2018 appropriation. Figure S10 disaggregate experts' funding recommendations by expert number. Experts ranged in total funding from $30–$550 million.

Figure 3 indicates that experts allocated the most median funding to "systems development," followed in equal amounts by "cell development" and "core technology." This trend applied after controlling for affiliation (Figure S11 and Table S5). Experts who provided 2050 system cost estimates greater than the DOE target recommended 2.5 times more funding for "systems development" than experts who thought the target would be met by 2050 (Figure S12).

We conducted a simple check for the possible influence of motivational bias. We separated experts into two groups based on experts' funding source: DOE vs. non-DOE. As presented in Figure S13 and Table S6, DOE-funded experts recommended $75 million (median) in total funding, whereas non-DOE-funded experts recommended $55 million (median) in total funding. However, both groups of experts recommended considerably more funding than DOE's FY 2018 appropriation, and both groups allocated the most median funding to "systems development."

Conclusions

A transition to a sustainable energy system will require new technologies, such as SOFCs, to provide key low-carbon and environmentally sustainable energy services. While further analysis is required to determine how SOFCs and solid oxide electrolysis cells (or reversible SOFCs) fit into a future, decarbonized energy system, based on formal interviews with 27 experts, we found that SOFC costs and degradation could potentially meet DOE targets by 2035–2050. Uncertain market demand, low manufacturing capacity, and variations in system design and operation contribute to future uncertainty.

Experts indicated that balance-of-stack component (e.g., seals and housing) and manufacturing machinery (including operation) costs, as well as chromium poisoning, chemical and microstructural changes in the electrodes, and seal and interconnect degradation, are major barriers to improving the cost and durability of SOFCs. Our findings suggest that an increase in RD&D spending, with an emphasis on systems integration and deployment, will substantially accelerate progress toward meeting DOE targets.

Our findings could inform decision-makers about key opportunities facing SOFCs, and shape policies, research agendas, and funding levels needed to advance SOFC viability. In the engineering and scientific communities, our assessments could be used to understand and benchmark industry progress and develop scenario analyses and process-based cost models for

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low-carbon technology deployment. Our assessments may be especially insightful to funding agencies in developing SOFC technology roadmaps, and fuel cell companies who are evaluating the deployment of CHP systems.

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Declaration of Interests

The authors declare no competing interests.

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