# How Fuel Cells Could Impact Vehicles, Buildings & Utilities

May 23, 2019

Carnegie Mellon University
Wilton E. Scott Institute
for Energy Innovation

Alfred P. Sloan
Foundation

**The Wilton E. Scott Institute for Energy Innovation at Carnegie Mellon University** addresses the world's most important energy-related challenges by enabling collaborative research, strategic partnerships, public policy outreach, entrepreneurship, and education.

As one of CMU's only university-wide institutes, we seek to optimize energy resources, reduce the environmental impacts of energy production and use, and develop breakthrough technologies and solutions that will have meaningful global impact.

# What we do

## Support and Promote Faculty Research

- More than 145 faculty
- CMU Energy Fellows program
- Fund Seed Grants & Faculty Fellowships

## Foster Entrepreneurship

- CMU Energy + Cleantech Investor Forum & Startup Showcase
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- CMU VentureWell Energy Hackathon

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- 2019 CMU Energy Consortium for industry

## Engage with Industry and the Public Sector

- Collaborations with NETL, NREL, City of Pittsburgh, DOE

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- District-scale Pilots
- House Centers for specific interest areas

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# CMU Energy Areas of Expertise

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- High-Performance Renewables
- Transportation Energy, EVs, Infrastructure, and Electrification
- Energy Storage, Batteries, Fuel Cells, and Internet of Things
- Decarbonization, Carbon Capture, Sequestration and Utilization

## Resource Efficiency, Policy, and Analysis

- Efficiency of Traditional Fuels and Resource Recovery
- Environmental Monitoring, Sensing and Treatment
- Energy Policy, Economics and Community
- Enhanced Water Resources

## High-Tech Energy and Computational Solutions

- Grid Modernization, Energy Planning, System Reliability, and Resiliency
- Building Performance, Urban Planning, Design and Analytics
- Machine Learning, AI, Autonomous Vehicles, and Robotics for Energy Systems
- High-Performance Computing and Data Centers

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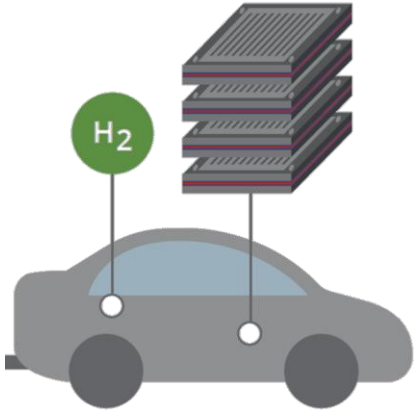
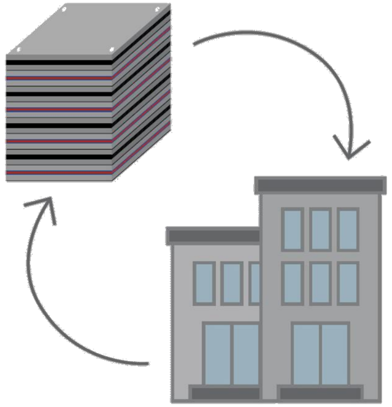
# Expert Assessments of Fuel Cell Cost, Durability, and Viability



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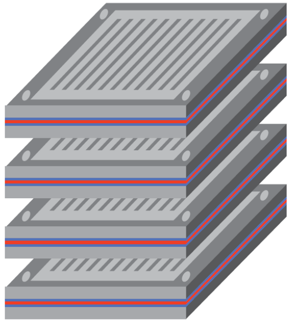
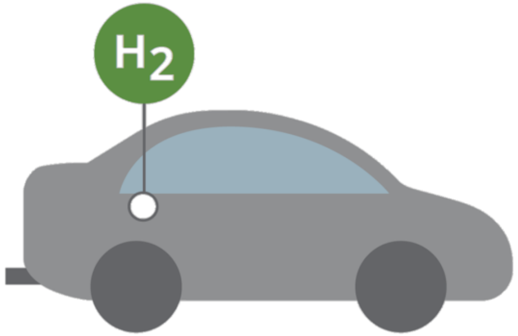
# Outline

Fuel cells and DOE targets

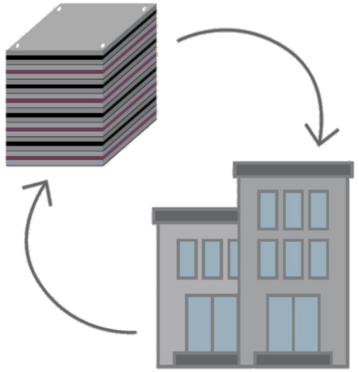


Expert Elicitation


Fuel Cell Vehicle Assessments




Solid Oxide Fuel Cell Assessments



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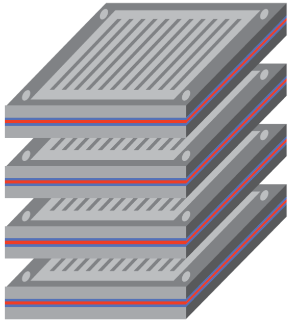

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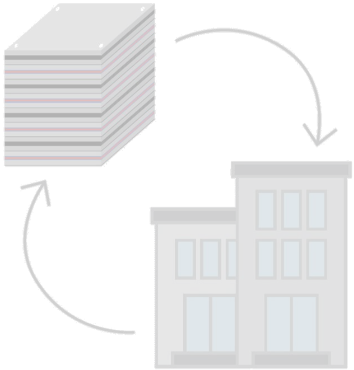
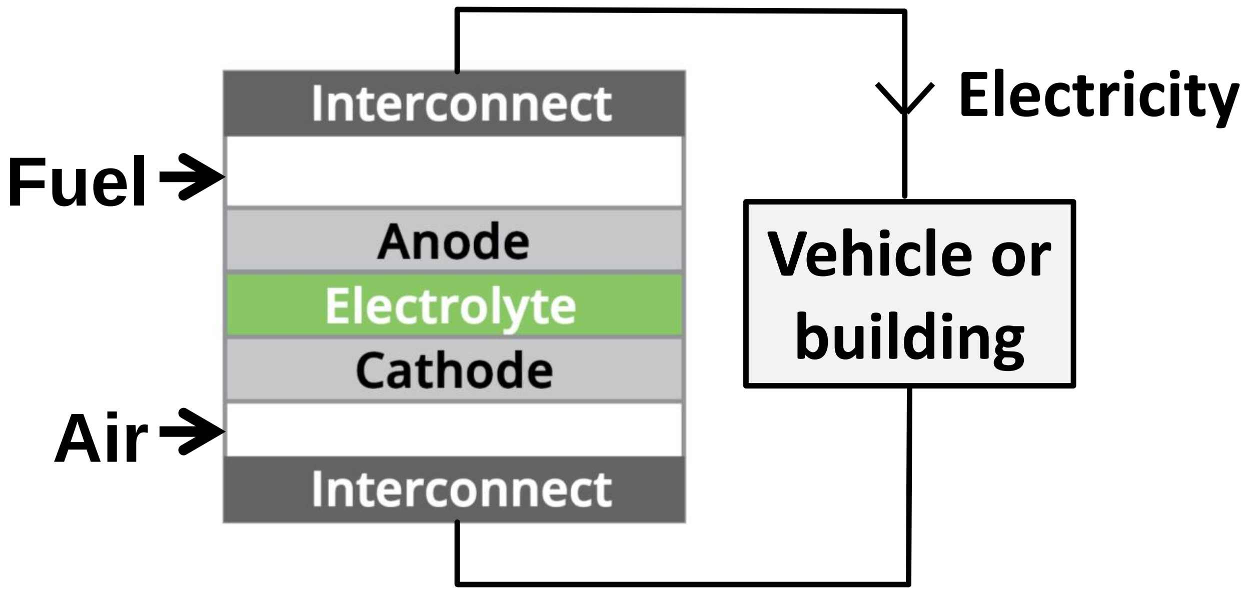
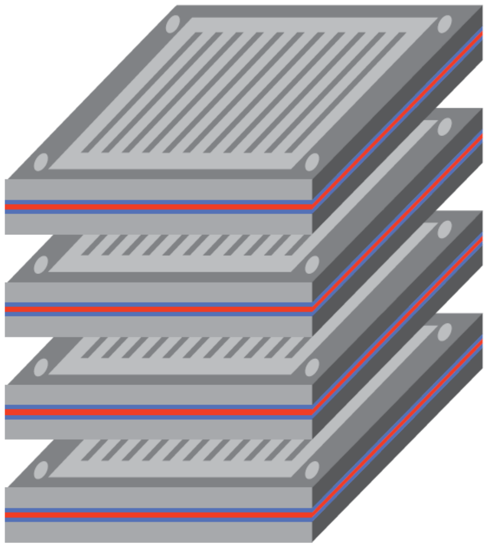


# What is a fuel cell?

**Fuel cells generate electricity**

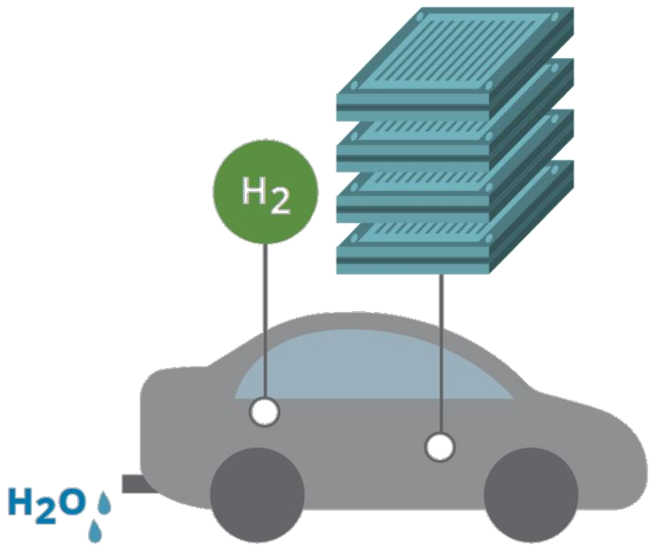



**"Stack"**

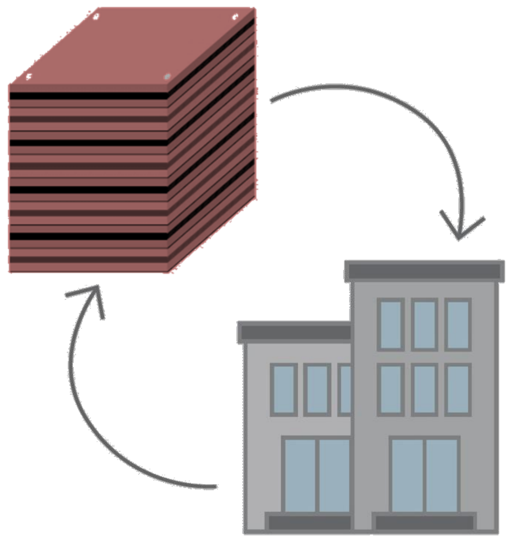


- **Efficient, quiet**: No combustion or moving parts (uses an electrochemical reaction)
- **Scalable**: Produce energy for small and large applications

# Research focus: PEMFCs and SOFCs



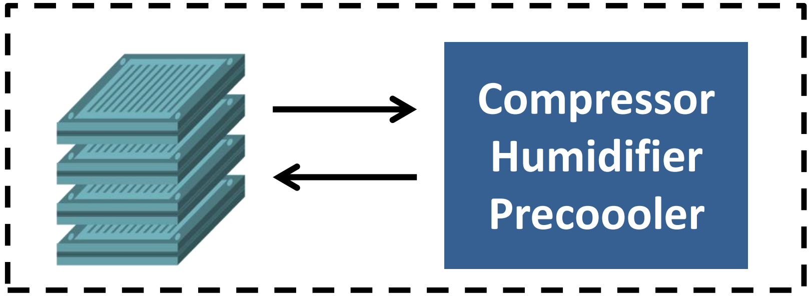

- **Proton exchange membrane fuel cells** (PEMFCs) Low-temperature (<100 °C), fast start-up, compact
- **Energy security** and **environment** (hydrogen)
- **Market for FCEVs:** Toyota, Honda, Hyundai (3–5 minute refueling, 350+ mile range) (Honda, 2019)



- **Solid oxide fuel cells (SOFCs):** Temperatures > 600 °C, power and heat, fuel-flexible
- **Continuous, clean, distributed** power (Bloom Energy)
- **“Bridge”** from **fossil** to **low-carbon fuels**; new jobs

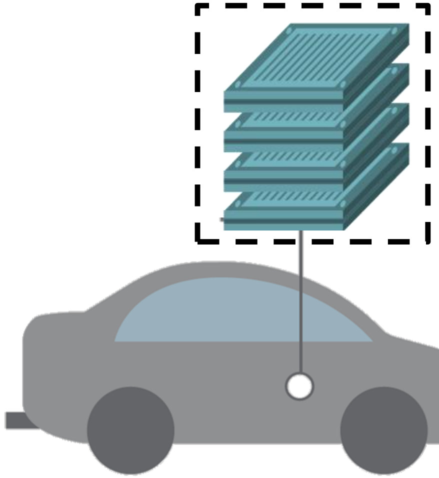
# PEMFC challenges: Cost and durability

"**Cost** and **durability** are the major challenges to fuel cell commercialization." (DOE, MYRD&D Plan, 2017)




*Excludes $H_2$ storage, power electronics, electric drive, battery*

- **Cost** = System cost/power output ($/kW)
- **Status (2017)** = $53/kW (James et al., 2017)
- **Target** = $30/kW (compete with ICEVs) (DOE, 2017)

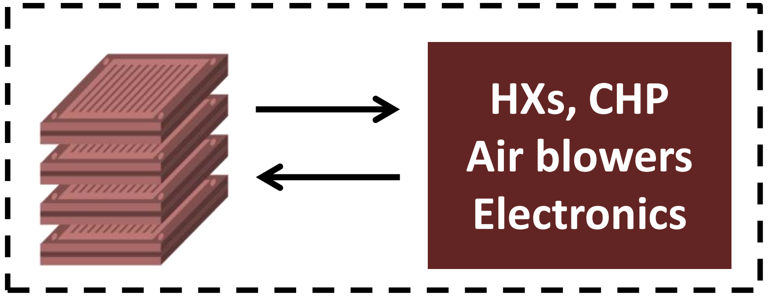


*Stack testing*

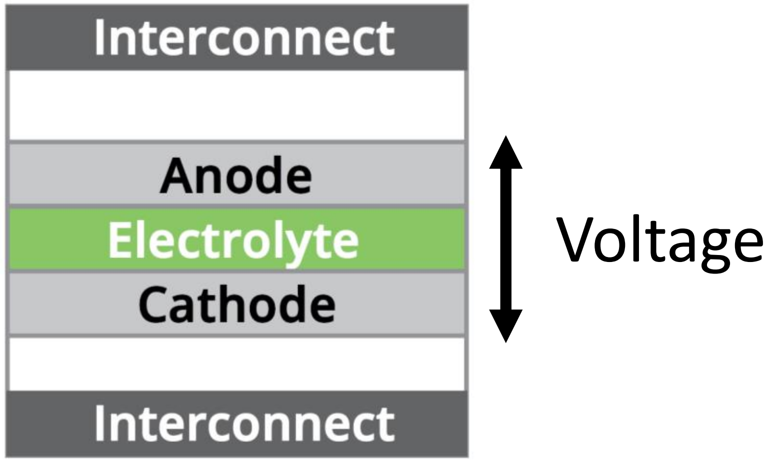
- **Durability**= Time until 10% power reduction
- **Status (2015)**= 2,500 hrs (DOE, 2017)
- **Target** = 8,000 hrs (150,000 miles) (DOE, 2017)

# SOFC challenges: Cost and degradation rate

"...efficient, **low-cost** electricity with intrinsic carbon capture capabilities...." (Vora, SOFC Project Review Meeting, 2018)




- **Cost** = system cost/power output ($/kW)
- **Status (2013) =** $12,000/kW (Iyengar et al., 2013)
- **Target** = $900/kW (compete with internal combustion engines and microturbines) (Vora, 2018)




- **Degradation rate** = Reduction in stack voltage
- **Status (2017)** = 1–1.5%/1.000 hrs (Vora, 2018)
- **Target** = 0.2%/1,000 hrs (Vora, 2018)

# Outline

Fuel cells and DOE targets

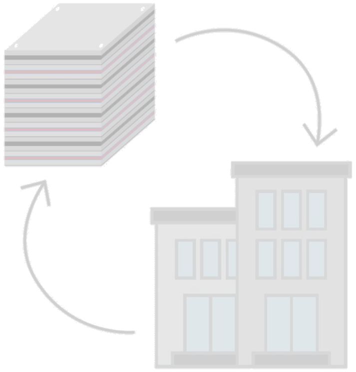


Expert Elicitation

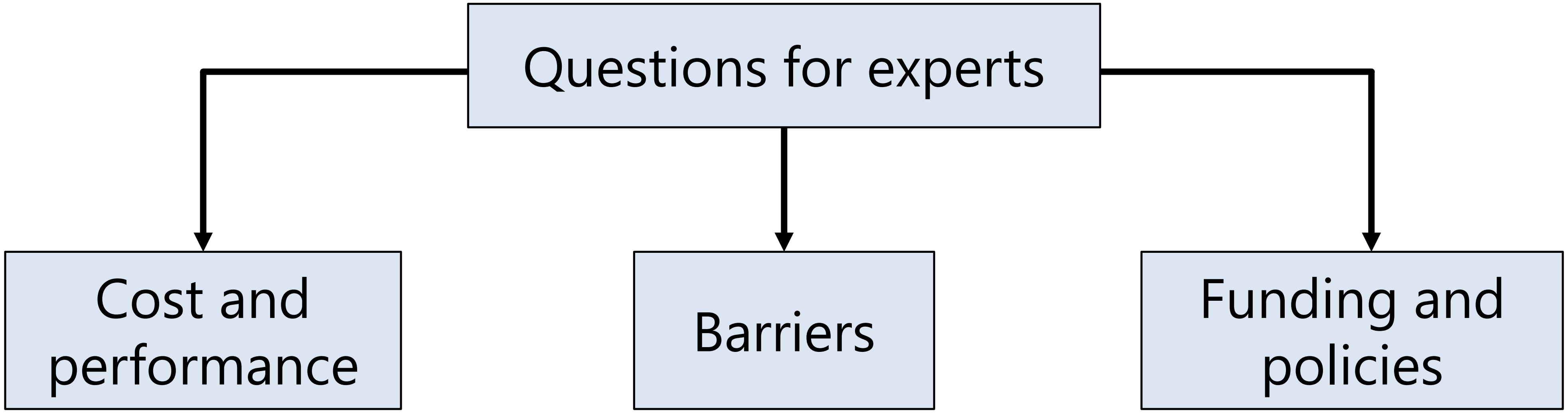

Fuel Cell Vehicle Assessments




Solid Oxide Fuel Cell Assessments



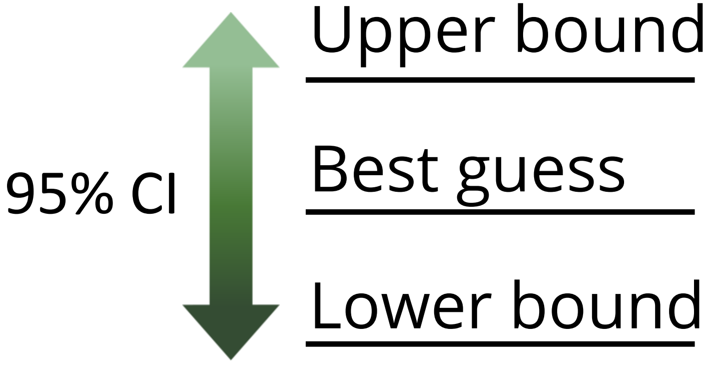
# Research questions




- What are the current and anticipated **future costs** and **durability** of fuel cell technologies?
- What are the **major barriers** to improving cost and performance?
- How much **RD&D funding** and what **policies** are needed?

# Expert elicitation

- **Formal** and **systematic** procedure for gathering experts' assessments




Mitigate **biases** and **heuristics**

- **Previous studies** used expert elicitation to assess:

| | | |
|---|---|---|
| Solar (Curtright et al., 2008) | Wind (Wiser et al., 2016) | Carbon capture (Baker et al., 2009) |
| Biofuels (Fiorese et al., 2013) | Gas turbines (Bistline et al, 2014) | Nuclear (Abdulla et al.,, 2013) |

# Project timeline

**2016**
*Project launch*
Literature review
Protocol development

**2017**
*Individual interviews*
64 interviews (in-person, phone)
PEMFC: 18 yrs experience
SOFC: 19 yrs experience

**2018**
*Elicitation workshops*
Group discussion
16 PEMFC experts
21 SOFC experts

**2019**
*Dissemination*
CMU Energy Week
Policy Briefing

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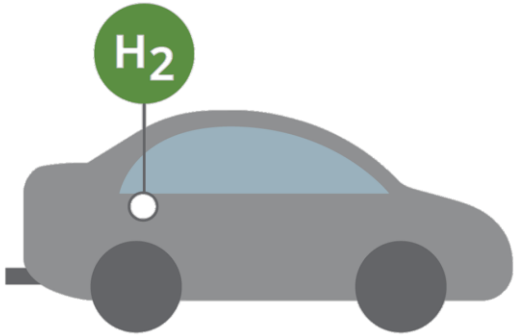
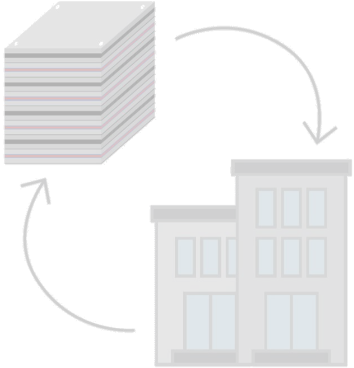
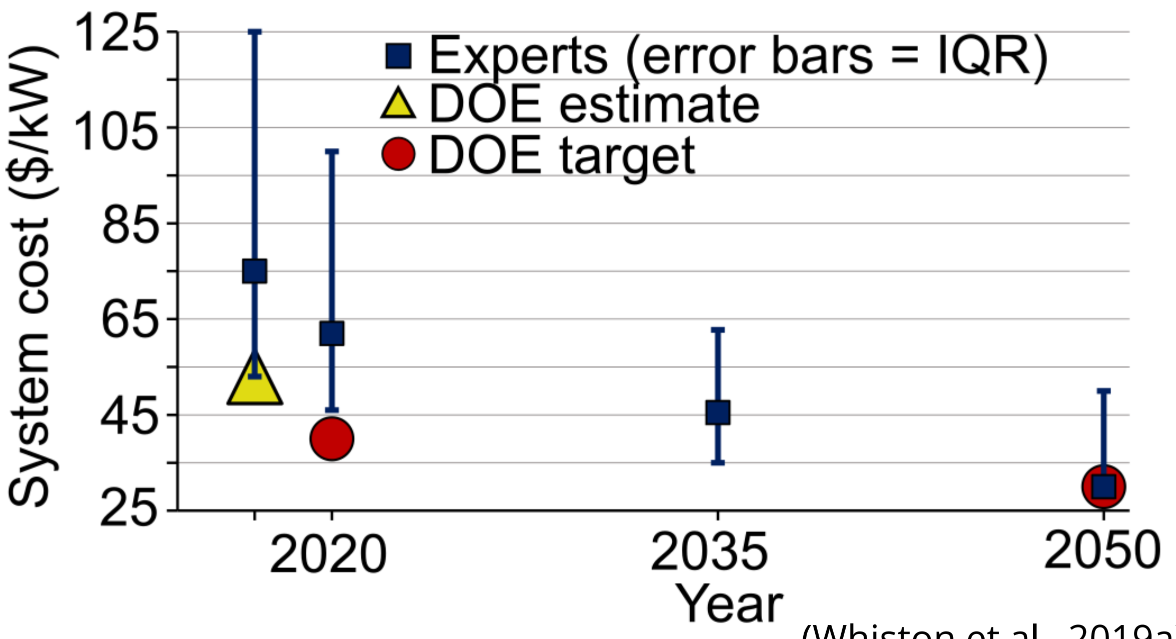


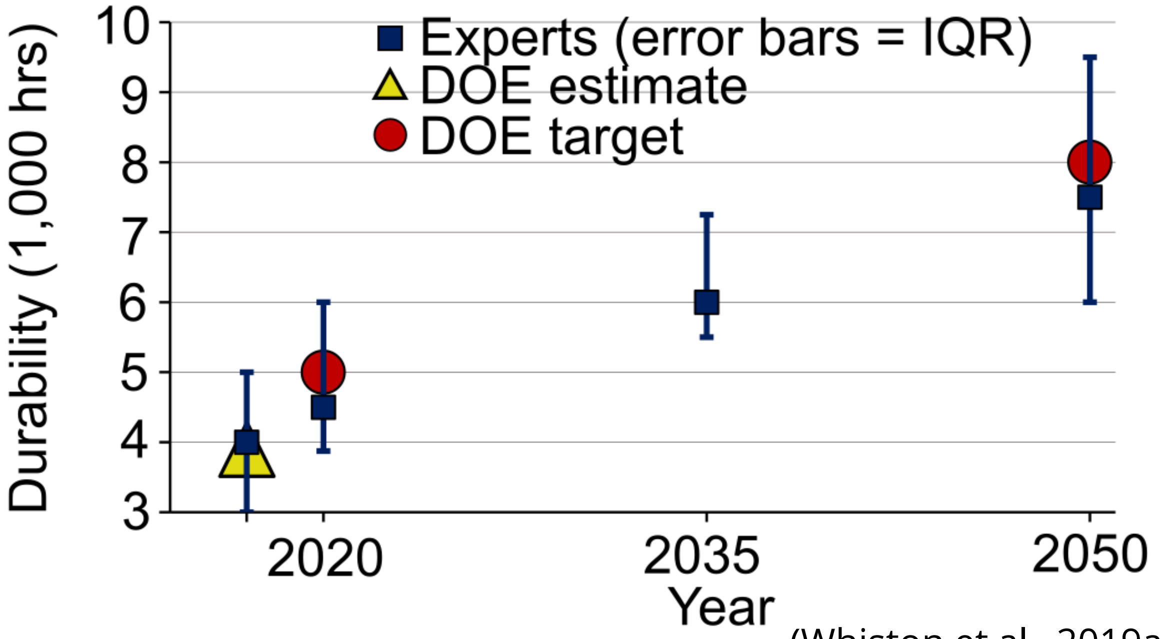

Solid Oxide Fuel Cell Assessments



# Cost and durability targets met by 2035–2050




(Whiston et al., 2019a)




(Whiston et al., 2019a)

- **Cost:** 51% of experts said target met by 2050 (median = $30/kW)
- **Durability:** 48% said target met by 2050 (median = 7,500 hrs)

# Pt loading, instability, and sintering are barriers

| | Ranking 1st | 2nd | 3rd |
|---|---|---|---|
| Platinum loading | 26 | 4 | 2 |
| Bipolar plate cost | 4 | 7 | 12 |
| Membrane cost | 1 | 14 | 8 |
| Air compressor cost | 1 | 7 | 3 |
| Gas diffusion layer cost | 1 | 3 | 5 |

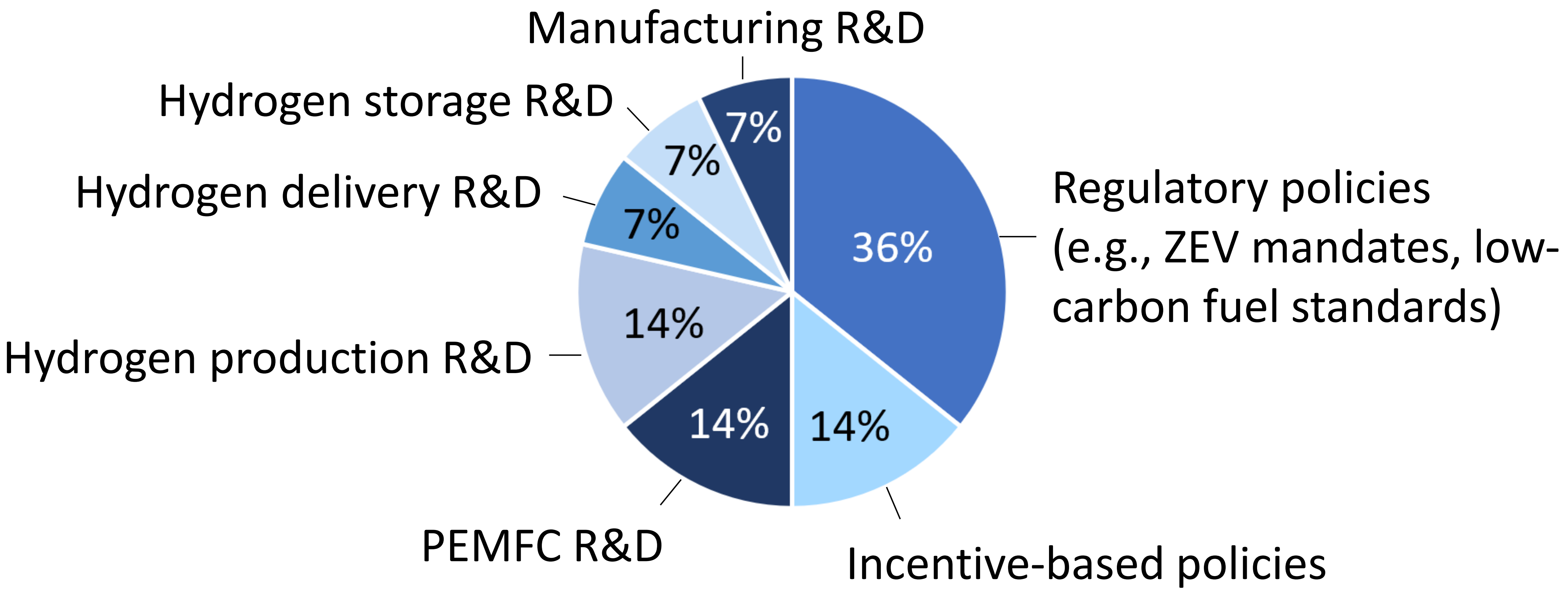
(Whiston et al., 2019a)

| | Ranking 1st | 2nd | 3rd |
|---|---|---|---|
| Catalyst instability | 14 | 2 | 5 |
| Pt sintering | 13 | | 1 |
| Pt dissolution | 9 | 8 | |
| Carbon support corrosion | 5 | 10 | 5 |
| Membrane chemical degradation | 1 | 4 | 6 |

(Whiston et al., 2019a)

- **Reducing cost:** Platinum loading, bipolar plate manufacturing, coating cost
- **Improving durability:** Pre-leaching, annealing, particle size

# Governmental actions to advance FCEV viability




- **Hydrogen storage:** Compressed gas viable in 2035; 44% experts anticipated material storage by 2050
- **Refueling stations:** 500 stations by 2030 and 10,000 by 2050

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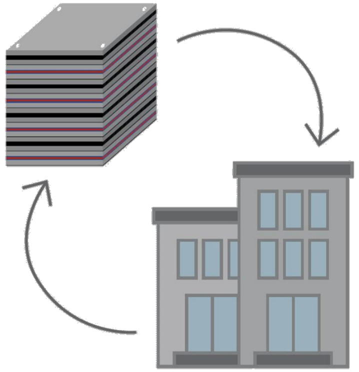
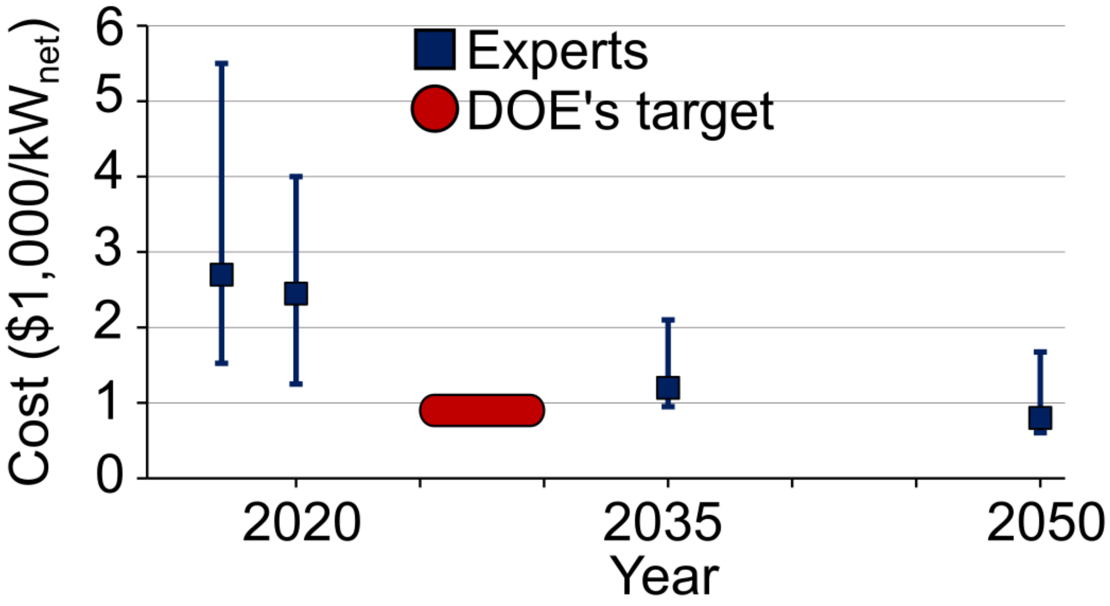
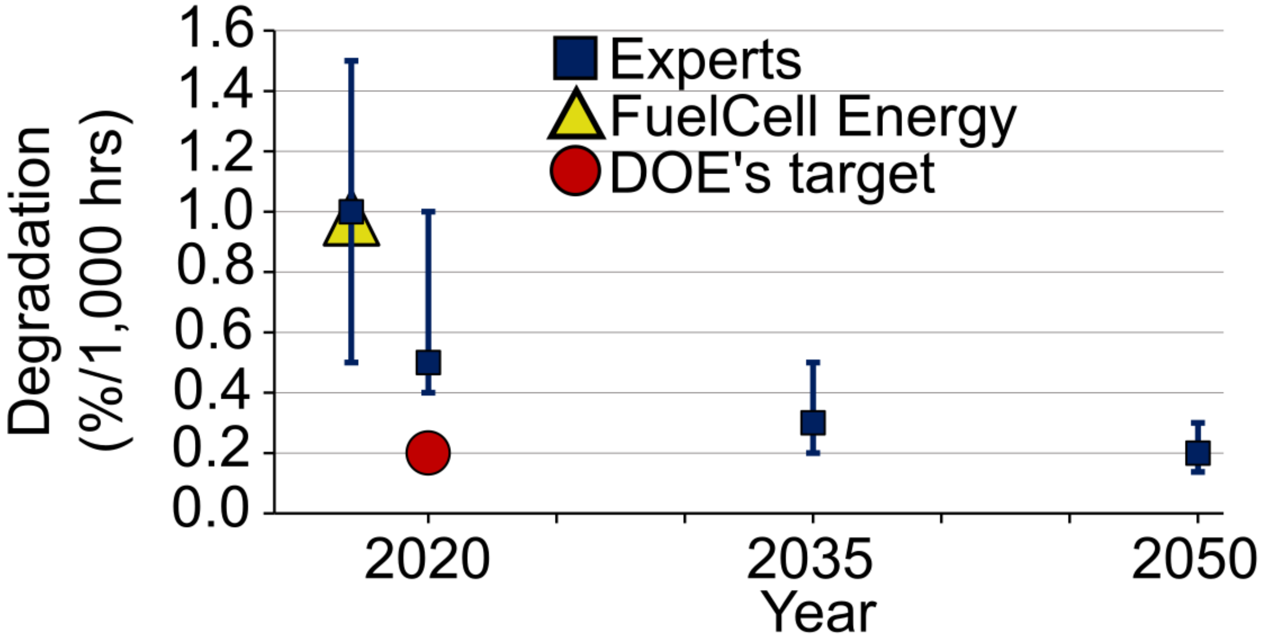
**Solid Oxide Fuel Cell Assessments**



# Cost and degradation rate targets met by 2035–2050




(Whiston et al., 2019b)




(Whiston et al., 2019b; Ghezel-Ayagh, 2011)

- **Cost:** 25% of experts said target met by 2035; 52% said target met by 2050 (median = $800/kW)
- **Degradation:** 36% said target met by 2035; 58% said target met by 2050 (median = 0.2%/1,000 hrs)

# Stack cost and chromium poisoning considerable

| | Ranking 1st | 2nd | 3rd |
|---|---|---|---|
| Cost of material | 13 | 8 | 5 |
| Cost of machinery | 7 | 8 | 7 |
| Cost of labor | 5 | 5 | 7 |
| Cost of scrap | 1 | 3 | 3 |
| Cost of tooling | 1 | 3 | 1 |

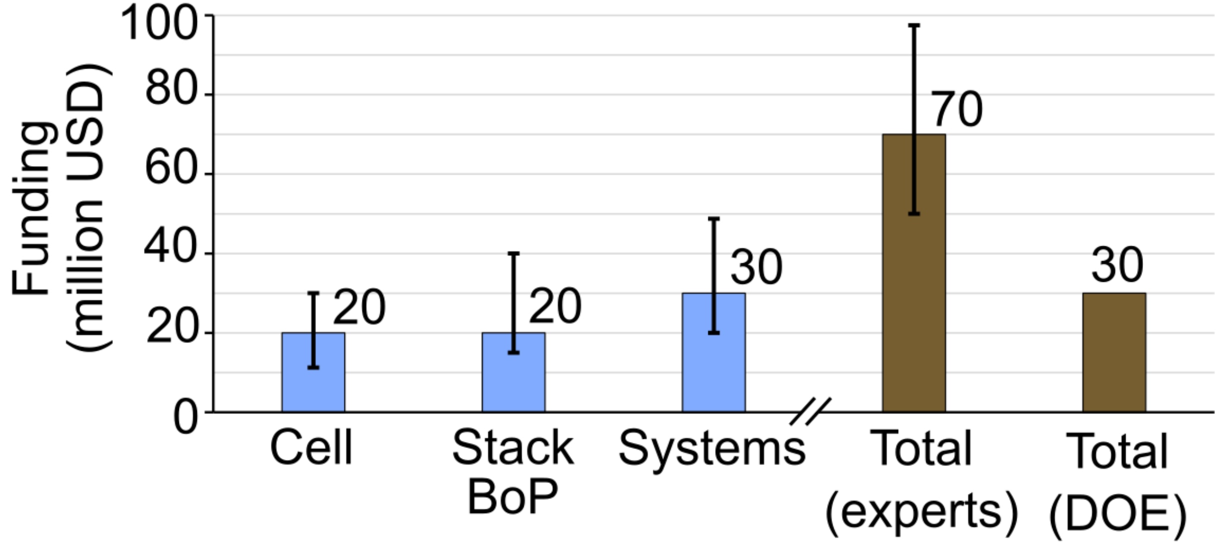
(Whiston et al., 2019b)

| | Ranking 1st | 2nd | 3rd |
|---|---|---|---|
| Chromium poisoning | 14 | 6 | 3 |
| Ni particle coarsening | 3 | 6 | 3 |
| Secondary phase formation | 3 | 2 | 4 |
| Ni particle agglomeration | 2 | 2 | 4 |
| Sulfur poisoning | 2 | 1 | 1 |

(Whiston et al., 2019b)

- **Reducing stack cost:** Operating temperature, production volume
- **Chromium poisoning:** Chromium getters, interconnect coatings

# RD&D funding needed, entry-level markets kW-scale




(Whiston et al., 2019b; Vora, 2016)

| | Ranking | |
|---|---|---|
| | 1st | 2nd |
| Medium (5–500 kW) | 11 | 9 |
| Small (0.5–5 kW) | 8 | 9 |
| Large (500 kW–10 MW) | 3 | 2 |
| Grid support (>10 MW) | 1 | 2 |

(Whiston et al., 2019b; Vora, 2016)

- Experts recommended **$70 million (median)** in total funding for FY 2018
- Experts identified **medium** and **small-scale** applications as the most favorable entry-level markets

# Conclusions

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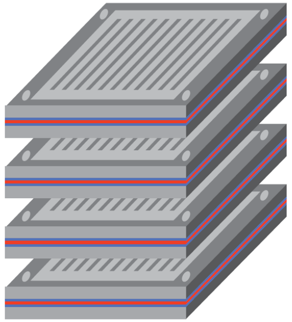
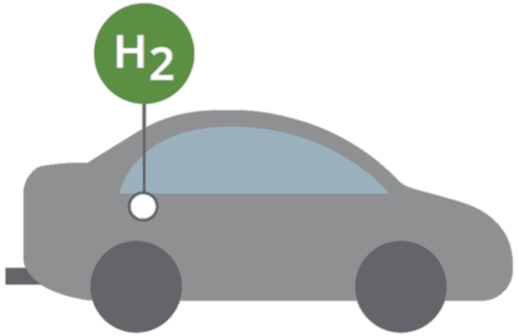
## Fuel cells and DOE targets



## Expert Elicitation


## Fuel Cell Vehicle Assessments

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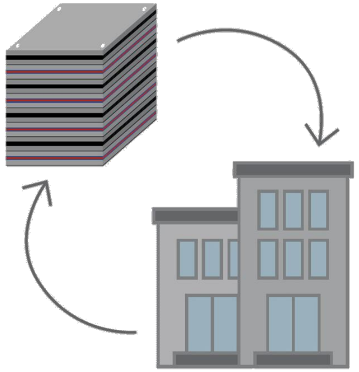

# How Fuel Cells Could Impact Vehicles, Buildings & Utilities

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