Fuel Cell Powered Vehicles – Opportunities and Challenges
Forever Technology of the Future?

MIT Mobility Forum, November 10, 2023

Progress in extending life of fuel/electrolysis cells by markedly reducing susceptibility to “poisoning”
Outline

• **CO₂ induced global warming** - *how did we get there?*

• **Transportation** – *hooked on oil.*

• **Electric vehicle options**: *battery vs fuel cell*
  • Battery vehicles - *how fast can they grow?*
  • Fuel cell vehicles –
    • *Hydrogen* generation and distribution challenges
    • *Electrolyzers* are the answer and *here’s why!*

• **And now for something different** - *Fundamentals:*
  • Breakthroughs in our lab promising:
    • Fuel/electrolyzer cells with *improved performance,*
      *extended life* and less reliance on *critical materials*
Rapid increase in energy use with improved living conditions

Energy use per person vs. GDP per capita, 2021

Focus on impact of vehicle consumption and use

https://ourworldindata.org/grapher/energy-use-per-person-vs-gdp-per-capita

$10^3$-$10^5$ kWh - Factor or ~100!
Growth of GDP and Vehicle Sales

GDP and population growth has led to explosive increase in fossil fuel consumption and CO₂ emissions generally!


https://carsalesbase.com/china-car-sales-data-market/
Vehicle Energy Consumption & Impact on Emissions

Percentage share of total primary energy consumption by U.S. energy use sectors, 2022

Total = 100.41 quadrillion British thermal units

- Electric power: 38%
- Transportation: 27%
- Industrial: 23%
- Residential: 7%
- Commercial: 5%

Energy (largely fossil) consumption:
- 27% by vehicles (EVs)
- 38% by electric power generation (coal and gas)
- Renewables – intermittent PV and Wind (H₂?)

Note: Sum of individual percentages may not equal 100 because of independent rounding.
**Fossil fuels pack big punch:** high stored chemical energy, including cleaner alternatives like natural gas (largely methane).

- **Installed infrastructure** – USA
  - 145,000 filling stations (Am. Petroleum Inst.)
  - 278 million *registered* passenger vehicles (*Forbes*)
- **Rapid refueling & extended range** to 400 miles, low cost

**Challenges:**
- Non-renewable resource
- Strategic fuel
- Contamination (fracking, oil spills)
- Emissions
  - Health
  - Global warming

**Handwriting on the wall:** Government regulations/incentives to drive combustion-engined vehicles to extinction between 2035-2050

The future is here! EV Adoption Grew by 55% to 10.1 M in 2022

• Mainland China: 5.9 million units ~ 60% of EVs sold worldwide. Represents 29% of all light vehicles sold in region, up from 15% in 2021.

• Europe has 26% share and 2.6 million units sold.

• US has 9% share, but rapid growth, with 920,000 EVs sold, up 72%.

What are Electric Vehicle Options?

Fuel use by vehicle type

- Petroleum, natural gas, and biofuels
- Electricity
- Hydrogen

- Internal combustion engine vehicle
- Plug-in hybrid electric vehicle
- Battery electric vehicle
- Fuel cell electric vehicles

Source: U.S. Energy Information Administration

Tesla S

Toyota Mirai
EV Sales Breakdown by Type & Location

- Light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs)

- Battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell electric vehicles (FCEVs).

- EVs hit milestone in 2022 with **10 million** in annual **EV sales**, 54% increase from 2021.

US Transportation Energy Use

U.S. transportation energy use by mode and type, 2022

- light trucks 32%
- cars and motorcycles 21%
- other trucks 25%
- aircraft 10%
- boats and ships 5%
- pipeline fuel 3%
- trains and buses 3%
- military (all modes) 2%
- lubricants <1%

Note:
- Passenger vehicles consume ~ 20% of total
- Light trucks consume ~ 32% of total
- Heavy duty vehicles (minus aircraft) ~ 35%

Data source: U.S. Energy Information Administration, Annual Energy Outlook 2023, Reference case, Table 35, estimates for 2022

https://www.eia.gov/energyexplained/use-of-energy/transportation.php
Electric LDVs comprised 99% of global EV sales for the year, with the other 1% were electric HDVs.

HDVs however consume large fraction of transportation in Energy sector

FCEV opportunities lie most strongly with HDVs – *let’s see why*

Transportation - Specific Energy/Power – Why so difficult to get off alcohol wagon?

Energy density – extended *range* with fuel cells
Power density - increased *acceleration* with batteries

High Energy Density Batteries – Self Contained

Key parameters:
- Open circuit voltage $V_{OC}$
- Capacity mAh/g *(Range)*
- Maximum discharge rates *(Acceleration)*
- Maximum charge rates *(Charging times)*
- Resistance to dendrite formation *(life)*
- Electrolyte chemical stability *(Safety?)*
- Critical materials content (e.g. Co, Ni, Li)

$$V_{OC} = \Delta G / nF$$

Moving towards all solid-state batteries
Polymer Electrolyte Membrane (PEM) Fuel Cell

Note:
In contrast to battery, FC doesn’t carry both “reactants”

$H_2 \rightarrow 2H^+ + 2e^-$

$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O$

Why PEMFC?

Polymer Electrolyte Membrane - PEM

Advantages:
• High power density – *long range*
• Good start – stop capabilities
• Low temperature operation – suitable for portable applications
• *Scalable to large vehicles*

Disadvantages:
• Costly platinum catalysts/degrades
• Costly polymer membrane
• Active water management required
• Poor CO and S tolerance of Pt catalyst.
• *Require hydrogen refueling stations!*
Anatomy of Fuel Cell Vehicle

https://ssl.toyota.com/mirai/fcv.html
Toyota Mirai Fuel Cell Powered Car

- 800 km range
- 3 min refueling time
- -30°C cold-start

Roughly 2100 Mirai’s sold in 2022 in US

Lack of hydrogen Refueling Infrastructure!
Hydrogen - Electric Grid Infrastructure

Image: H₂@Scale, U.S. Department of Energy

Global Hydrogen Demand Estimation 2050

Hyundai Motor Group 2020
Hydrogen Sourcing & Distribution Channels

Generally, sources other than Electrochemical, while efficient and readily transported, lead to high CO$_2$ emissions

- **SMR**: CO$_2$ emissions of around 8-10 kg CO$_2$ per kg of H$_2$ produced
- **Coal gasification**: CO$_2$ emissions of around 14-15 kg CO$_2$ per kg of H$_2$ produced

Green Hydrogen Generation
International Renewable Energy Agency (IRENA)

• Hydrogen: low carbon and ultimately **green from outset**. **Electrolysis** of water using renewable electricity. Key for **long-haul transport, shipping and aviation**, green steel & chemicals.

• **Low-cost electricity essential** for producing competitive green hydrogen;

• **Major reductions in costs of electrolysis plants** needed with 40% reductions in the short term to 80% in the long term.

• **Fundamental breakthroughs needed** in addition to standardization, economies of size and scale-up.

Doesn’t address hydrogen transport challenges!

On-site hydrogen generation at refueling stations

Hi-T Solid Oxide Electrolysis/Fuel Cells

- Reduced electrical energy demand
- No need for costly and sensitive noble metal catalysts
- Resistant to CO & SO$_2$
- No water management issues
- Reversible operation – key for energy storage of intermittent sources

Fig. 2 Concept diagram of applications of a sustainable energy system based on SOEC/SOFC technology.

“On site generation”
Projected $H_2$ Production Cost Reductions - Electrolyzers

**Challenge – reduce costs 5-fold!**

[Bar chart showing projected reduction in hydrogen production costs from today to future, with 80% reduction in electrolyser cost, 65% to 76% efficiency, 53 to 20 USD/MWh electricity cost, full load hours from 3200 to 4200, 10 to 20 years lifetime of electrolyzers, and a weighted average cost of capital (WACC) from 10% to 6%.

Note: ‘Today’ captures best and average conditions. ‘Average’ signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). ‘Best’ signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

- **Efficiency** depends on:
  - Low overpotentials - losses at electrodes – susceptible to poisons.
  - Low ohmic resistance of solid electrolyte.

- **Device lifetime** depends on sensitivity to electrode “poisons”:

- **Device cost** depends on component materials criticality

\[
\frac{1}{2} O_2 + V_0^{\text{ads}} + 2e^- \leftrightarrow O_o^X
\]

\[j_0 = -k_0(C_{O,\text{atmosphere}} - C_{O,\text{surface}})\]

**DOE Targets on SOFCs**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Current</th>
<th>2020 Target</th>
<th>2025/2030 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Cost (100 kW- IMW)</td>
<td>&gt;$12,000/kWe</td>
<td>$6,000/kWe</td>
<td>$900/kWe</td>
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<tr>
<td>Single Cell Degradation</td>
<td>0.2 - 0.5% per 1,000 hrs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Manufacturing Approach</td>
<td>Batch</td>
<td>Semi- Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>System Degradation</td>
<td>1 - 1.5% per 1,000 hrs</td>
<td>0.5 - 1.0% per 1,000 hrs</td>
<td>&lt;0.2% per 1,000 hrs</td>
</tr>
<tr>
<td>Fuel Reformation</td>
<td>Primarily external natural gas conditioning/reforming</td>
<td>100% integrated natural gas reforming inside cell stack</td>
<td></td>
</tr>
<tr>
<td>Durability</td>
<td>10 hrs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platform</td>
<td></td>
<td>Commercial pilot</td>
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<tr>
<td>Configuration</td>
<td>Breadboard/Integrated system</td>
<td>Fully packaged</td>
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<tr>
<td>Fuel</td>
<td>Natural gas</td>
<td>Natural gas</td>
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<tr>
<td>Demonstration Scale</td>
<td>50 kWe – 5,000 kWe</td>
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<tr>
<td></td>
<td>DG:</td>
<td>MWe-class</td>
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<tr>
<td></td>
<td>Utility-scale:</td>
<td>10 – 50 MWe</td>
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</table>

If not resolved, high degradation rates are potentially show stoppers for SOFC technology to be broadly accepted. But also, need to minimize use of critical materials to reduce costs and insure reliable supply. How to address these problems in a novel way?

Identified Descriptor Controlling Oxygen Exchange Rate: Acidity of Surface Additives

Can it be reactivated?

Pristine

Basic (e.g. Li)

Acidic (e.g. Cr)

$k_{chem}$ (cm$^{-1}$)

$1,000/T$ (K$^{-1}$)

Smith, Journal of Chemical Education, 1987, 64, 480-481.


Patent Pending
**Approach**

- Demonstrate ability to recover Cr-driven degradation in surface activity with serial infiltration of basic additives

- Conductivity relaxation measurements
  - Porous bar ($\sigma \propto P_{O_2}^{\pm 1}$)

- Electrochemical impedance spectroscopy (EIS)
  - Distribution of relaxation time (DRT)
  - Screen-printed symmetric cells

- Current-Voltage-Power curves (I-V-P)
  - Anode-supported single cells
Demonstration of Cell Performance with Controlled Acidity

Measurement conditions
- Humidified H₂ at anode
- Synthetic air at cathode
- Temperature: 650-550°C

✓ More than 35% recovery of degraded power density!

H. G. Seo, H.L. Tuller, et al., J. Power Sources., 2022
Hydrogen Powered Vehicles – Forever Technology of the Future?

On-site generation (one man’s vision!)

Long range heavy vehicles
Acknowledgements – Acidity/Basicity Research

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Dr. Seo

Tuller group

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Questions?
Solid Oxide Fuel Cells (SOFCs) and Cr-poisoning

\[ \frac{1}{2} O_2 + V_o^- + 2e^- \leftrightarrow O_0^X \]

- Cr-containing interconnects
- Chemical degradation by Cr-impurities
- Largest source of degradation in SOFCs

To date, the main source of Cr-induced degradation remains controversial.

Keep in mind: 1. initial performance, 2. rate of performance degradation, 3. critical materials
Cr-Poisoning & Recovery: Serial Infiltration with Li

Normalized conductivity vs. time at 400°C and pO₂ = 0.1 to 0.2 atm.

Flush time limit and accelerated degradation.

H. G. Seo, H.L. Tuller et al., Energy Environ. Sci., 2022, 15, 4038

Patent Pending
Surface Additive-Induced ORR Activity

Basic additives can lead to enhanced performance!

Non-serial infiltration

- $Z'(\Omega)$
- Total ASR / $\Omega \text{cm}^2$

Can Ca-Additives Reactivate Cr-Poisoned Surface?

Cr-additives significantly impeded rate of oxygen reduction, leading to increases in ASR. Remarkably, degraded ASR can be recovered by addition of Ca-additives.

H. G. Seo, H.L. Tuller, et al., J. Power Sources., 2022
Conclusions

Demonstrated with controlled acidity:
• Enhanced performance
• Extended life
• Reduced dependence on critical materials

“IMPACT”: Accelerate ability to bring wide range of technologies to market!