ME 432 Fundamentals of Modern Photovoltaics

Discussion 43: The Grid and Energy Storage
9 December 2020
Review Article
Hydrogen is essential for sustainability
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Current Opinion in Electrochemistry 2018, 12:166–181

Prof. Jack Brouwer, Mechanical and Aerospace Engineering, UC Irvine.
Director, National Fuel Cell Research Center
Popular Thinking & Arguments

Main Strategy:
• 100% renewable (solar, wind, geothermal, ...) power generation
• Electrify all end-uses
• Use batteries to handle intermittency on grid & for end-uses

Arguments against hydrogen & fuel cells:
• Most hydrogen today is made from fossil fuels (natural gas)
• Making hydrogen from water & electricity is less efficient than charging a battery
• Making electricity from hydrogen in a fuel cell is less efficient than a battery (i.e., round-trip efficiency is lower than a battery)
• Hydrogen is difficult to store & transport in society

I agree with most of this!
Subtly untruthful - Not the whole story
Popular Thinking & Arguments

**Main Strategy:**
- 100% renewable (solar, wind, geothermal, ...) power generation
- Electrify all end-uses (some)
- Use batteries to handle intermittency on grid & for end-uses (some)

**Arguments against hydrogen & fuel cells:**
- Most hydrogen today is made from fossil fuels (natural gas)
- Making hydrogen from water & electricity is less efficient than charging a battery
- Making electricity from hydrogen in a fuel cell is less efficient than a battery (i.e., round-trip efficiency is lower than a battery except for long duration storage!)
- Hydrogen is difficult to store & transport in society, but more energy dense than batteries!

I agree with most of this! Subtly untruthful - Not the whole story
Main Points

• Solar and wind are the key, but challenges remain to manage electrical grid dynamics and to meet end-use requirements for energy dense fuels and chemicals
• Renewable hydrogen (via “P2G”, power-to-gas technology) provides the best opportunity for a zero emissions fuel and is the best feedstock for production of zero emissions liquid fuels and some chemical and heat end-uses
  – Renewable hydrogen can be made at high efficiency using electrolysis systems that are dynamically operated to complement renewable wind and solar power dynamics
  – Hydrogen can be stored within the existing natural gas system to provide a low-cost, massive storage capacity that could enable a 100% renewable grid
Depiction of U.S. primary energy consumption and electricity penetration shares for different energy subsectors in 2015. 
Source: Reproduced from Ref. [86], with permission from National Renewable Energy Laboratory.
Challenges with Electrification

• Some end uses are easy to electrify. But doing so with wind & solar will require a viable storage option. Batteries and pumped hydro are not sufficient.

• Some end uses like aviation, long-haul trucking, shipping, heavy industry (cement and steel production), fertilizer industry – which account for 30% of global carbon emissions -- are difficult to electrify. So, we will need clean chemical fuels.
  – e.g. Electrification of light-duty vehicles is occurring now, but electrification of heavy-duty transportation faces challenges in upfront costs, range limitations, and infrastructure development
Batteries

- Viable for small, isolated power systems to store small amounts of excess renewable electricity for short durations (hours or days).
- But for larger scale duration, Li-ion batteries are limited:
  - Insufficient global reserves of lithium and cobalt
  - Challenges with self-discharge, that make seasonal storage impossible
  - Challenges with recycling and waste
  - Energy density not sufficient to meet some end uses

Davis et al., Science 360, 1419 (2018)
From Prof. Brouwer’s Presentation

Amount of Storage Required for 100% Renewable – CA

- Wind dominant case (37 GW solar capacity, 80 GW wind capacity)

* Nissan Leaf Equiv. – 62 kWh

Saeedmanesh, A., Mac Kinnon, M., Brouwer, J., Current Opinion in Electrochemistry, Vol. 12, pp.166–181, 2018
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What is P2G?

• “Power to gas”: Conversion of electricity into a gaseous energy carrier
• Integrating solar and wind requires a storage capacity which can be provided by hydrogen production by P2G. Excess electricity is used to cleanly produce H2, which can be stored as a clean-burning chemical fuel for later.
  – Current methods of H2 production are not renewable, and release CO2 into the atmosphere
  – The idea here is to cleanly produce H2 using electrolysis. Electrolysis is the use of excess electricity to split water and produce H2.
  – 100s of GWh of energy can be stored
  – The cleanly produced H2 can be used in fuel-cell vehicles including heavy-duty fleet, can be methanated with CO2 to produce fuels like methane and methanol as alternative fuels for cargo ships/airplanes
• Hydrogen is the only option that can technically balance renewable power and energy with load on an annual basis
• H2 can be transported using the existing natural gas pipeline infrastructure
Net-zero Emissions Energy Systems

Davis et al., Science 360, 1419 (2018)
Table 1. Key energy carriers and the processes for interconversion. Processes listed in each cell convert the row energy carrier to the column energy carrier. Further details about costs and efficiencies of these interconversions are available in the supplementary materials.

<table>
<thead>
<tr>
<th>From</th>
<th>e⁻</th>
<th>H₂</th>
<th>C₂O₄H₂</th>
<th>NH₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻</td>
<td>Electrolysis ($5 to 6/kg H₂)</td>
<td>Electrolysis + methanation</td>
<td>Electrolysis + Haber-Bosch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrolysis + Fischer-Tropsch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂</td>
<td>Combustion</td>
<td>Methanation ($0.07 to 0.57/m³ CH₄)</td>
<td>Haber-Bosch ($0.50 to 0.60/kg NH₃)</td>
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</tr>
<tr>
<td></td>
<td>Oxidation via fuel cell</td>
<td>Fischer-Tropsch ($4.40 to $15.00/gallon of gasoline-equivalent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂O₄H₂</td>
<td>Combustion</td>
<td>Steam reforming ($1.29 to 1.50/kg H₂)</td>
<td>Steam reforming + Haber-Bosch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biomass gasification ($4.80 to 5.40/kg H₂)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₃</td>
<td>Combustion</td>
<td>Metal catalysts (~$3/kg H₂)</td>
<td>Metal catalysts + methanation/Fischer-Tropsch</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sodium amide</td>
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</tbody>
</table>
Solid Oxide Electrolysis for H₂ Production

- High temperatures result in high round-trip efficiencies (don’t need expensive or rare catalysts)
Reversible Solid Oxide Cells

- Electricity storage at large scales to sustain transition of electricity generation to intermittent renewable energy sources
- Reversible solid oxide electrochemical cells (ReSOCs) combined with sub-surface gas storage
- SOC switched between fuel cell and electrolysis
- System modeling shows desirable cost & efficiency

Reversible Solid Oxide Cells

- **Oxygen Ion Conductors**

  - **Solid Oxide Fuel Cell (SOFC)**
    - Anode: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$
    - Electroyte: $O^{2-}$
    - Cathode: $\frac{1}{2} O_2 + 2e^- \rightarrow O^{2-}$

  - **Solid Oxide Electrolysis Cell (SOEC)**
    - Anode: $O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$
    - Electroyte: $O^{2-}$
    - Cathode: $H_2 O + 2e^- \rightarrow H_2 + O^{2-}$

- **Excellent energy conversion efficiencies**
- **Novel materials for electrodes and electrolytes**
- **Electrolysis mode puts cells materials under extreme conditions different from fuel cell mode, introducing new degradation mechanisms and materials challenges**
Reversible Solid Oxide Cells

- Intermediate temperature operation
- Relatively less well understood compared to oxide ion conducting systems
- Novel materials for electrodes and electrolytes

**Proton Conductors**

**Solid Oxide Fuel Cell (SOFC)**

- Anode: $H_2 \rightarrow 2H^+ + 2e^-$
- Electrolyte: $H^+$
- Cathode: $2H^+ + \frac{1}{2} O_2 + 2e^- \rightarrow H_2O$

**Solid Oxide Electrolysis Cell (SOEC)**

- Anode: $H_2O \rightarrow 2H^+ + \frac{1}{2} O_2 + 2e^-$
- Electrolyte: $H^+$
- Cathode: $2H^+ + 2e^- \rightarrow H_2$
Current State of the Art

- R-SOCs benefit from improvement and cost reduction of SOFCs
- Fuel flexibility
- Critical issues to be addressed
  - materials selection: properties, costs, mechanical strength, electrode stability, delamination (esp. oxygen electrode)
  - cell-stack designs
  - operating parameters suitable for reversible operation
  - system design and integration

Mermelstein and Posdziech, Fuel Cells 17 562 (2017)

ReSOC energy storage system at Boeing Huntington Beach, connected to the Southern California Edison Grid
Challenges:

- Conductivity
- Surface exchange kinetics
- Novel compositions

Efficiency:

- Surface stability
- Materials stability
- Interface stability
Improving Interface Stability

**Need:** understand air electrode-electrolyte delamination in SOEC mode

Finite element simulations demonstrate oxygen vacancy profiles and corresponding stress

P. Sofronis et al. (in preparation)

Cell micrograph: Hughes et al, PCCP (2013)

\[
\begin{align*}
\Phi^s - \Phi^i &= V^s - V^i + \frac{RT}{F} \ln \left( \frac{c^s}{c^i} \right) \\
V^R - V^L &= 0.5 \text{ V or } 1.5 \text{ V}
\end{align*}
\]

Initial vacancy concentration = \(c^0_v = 0.1\)
How To Get Involved

• Expose yourself to new ideas and learn how the system works
  – Intern at the DOE
    • Advanced Research Projects Agency – Energy (ARPA-E)
    • Solar Energy Technologies Program (DOE-EERE)
  – Undergraduates: REU
  – Intern at a company

• Advice
  – Know the fundamentals
  – Choose meaningful, use-inspired scientific projects
  – Develop an interest, and excel at something you are passionate about