Hydrogen & Fuel Cells for Zero Emissions Electricity

Jack Brouwer

November 2, 2021
Outline

• Electric sector decarbonization opportunities for hydrogen & fuel cells
  • Fuel for dispatchable resources
  • Long-duration and massive energy storage
  • Resilience & reliability via pipelines & wires

• Air quality improvements of hydrogen & fuel cells
  • Fuel cells vs. backup diesel generator AQ impacts

• Hydrogen production pathways

• Emissions and air quality impacts of hydrogen blends with natural gas
  • Appliances
  • Industrial Burners
  • Power Plants
Renewable Energy Conversion (Solar & Wind)

We must increasingly adopt energy conversion that is sustainable & naturally replenished quickly

Good News!

- Widely available around world
- Now typically cheapest form of primary energy

Renewable Curtailment in California

Challenges of Dynamics already being realized – slowing pace of adoption

California ISO

NATIONAL FUEL CELL RESEARCH CENTER

Megawatt hour (MWh)

10,000
125,000
150,000
175,000
200,000
225,000
250,000
275,000
300,000
325,000
350,000

341,959
223,195
94,778
85,760
45,763
4,444

Dynamics of Renewable Future are Challenging

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

Deficit
Surplus

Current Gas Storage converted to H₂
21 million EVs

Pumped Hydro
We Must Transform the Gas System

- Northwestern U.S. Energy Dynamics

Magnitude Comparison

**Annual Hourly Demand - 2016**

- Gas Demand (MWh)
- Electricity Demand (MWh)

Gas Peak ~ 70 GWh
Electric Peak ~ 30 GWh

120000

Full Electrification? Must TRIPLE Electric Infrastructure Double again for Transportation
Gas System – Resource for Zero Emissions & Resilience

- First mix X% – HUGE Resource for grid renewables & transportation electrification
- Then piecewise convert to pure hydrogen

Solar Here!

Close valves Here!
Gas System – Resource for Zero Emissions & Resilience

- 40% of all electric demand – 20 sq. miles of solar, only gas system use for H₂ storage AND all T&D for resilience


20 X 20 miles solar, H2 in gas system adds 40% renewables to electric grid!
Hydrogen Energy Storage Dynamics

- Hydrogen Storage complements Texas Wind & Power Dynamics

- Load shifting from high wind days to low wind days
- Hydrogen stored in adjacent salt cavern

Hydrogen Energy Storage Dynamics

- Weekly and seasonal storage w/ H$_2$, fuel cells, electrolyzers


But what can we do if we don’t have a salt cavern?
Resilient Storage & Transmission/Distribution/Resource

- Natural Gas Transmission, Distribution & Storage System

<table>
<thead>
<tr>
<th></th>
<th>Annual Tuition &amp; Fees</th>
<th>Total OC Population</th>
<th>4 years for entire population</th>
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<tr>
<td>U.C. Irvine</td>
<td>$17,331</td>
<td>2,246,000</td>
<td>$39 billion</td>
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<table>
<thead>
<tr>
<th></th>
<th>Average Annual Tuition &amp; Fees</th>
<th>Total Student Population</th>
<th>4 years for entire population</th>
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</thead>
<tbody>
<tr>
<td>All University of California Schools</td>
<td>$17,800</td>
<td>265,000</td>
<td>$4.7 billion</td>
</tr>
</tbody>
</table>

> 99.999% available

Gas Technology Institute, Assessment of Natural Gas ... Service Reliability, 2018.

Carmona, Adrian, M.S. Thesis Project, UC Irvine, J. Brouwer advisor, 2014.
Demonstrated Resilience of Fuel Cells and Gas System

San Diego Blackout, 9/28/11
Winter Storm Alfred, 10/29/11
Hurricane Sandy, 10/29/12
CA Earthquake, 8/24/14

Data Center Utility Outage, 4/16/15
Hurricane Joaquin, 10/15/15
Napa Fire, 10/9/17
Japanese Super-Typhoon, 10/23/17

Hurricane Michael, 10/15/18
Ridgecrest Earthquakes, 7/4-5/19
Manhattan Blackout, 7/13/19
Grid dispatch modeling using CPUC RESOLVE model shows that use of renewable hydrogen for VER firming becomes cost optimal in some hours beginning at a cost of $24/MMBtu (just over $3/kg).

Source: UCI APEP
U.S. DOE “Hydrogen Energy Earthshot”

- Accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade

Office of Energy Efficiency & Renewable Energy » Hydrogen Shot

- Reduce RH₂ cost from ~$5/kg to $1/kg to unlock new markets for hydrogen, including steel manufacturing, ammonia, energy storage, and heavy-duty trucks
Example: Renewable H₂ Production & Use by LADWP

• Salt Caverns & other facilities proven to safely store massive amounts of hydrogen
• Magnum working with LADWP to adopt similar salt cavern H₂ storage in Utah
• Gas turbines – colleagues & competitors
  • state-of-the-art for large scale power generation
• All gas turbine manufacturers evolving H₂-use
  • GE, Mitsubishi, Siemens, Solar, others
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• Emissions and air quality impacts of hydrogen blends with natural gas
  • Appliances
  • Industrial Burners
  • Power Plants
Recent Increase in Fossil Back-up Generator Deployment

- 34% increase in Bay Area from 2018 - 2021
- > 8,700 deployed
- Capable of > 4.8 GW
- Disproportionately located in disadvantaged communities (CalEnviroScreen 3.0 percentiles shown)

Recent Increase in Fossil Back-up Generator Deployment

- 22% increase in SoCAB
- > 14,000 deployed
- Capable of > 7.3 GW
- Disproportionately located in disadvantaged communities (CalEnviroScreen 3.0 percentiles shown)

Recent Increase in Fossil Back-up Generator Deployment

M.Cubed study found significant health & economic impacts of BUGs

- Used U.S. EPA’s CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)

- Estimated annual economic benefits of reducing BUG emissions
  - $3.5 to $7.9 million annually for a 25% reduction
  - $7.0 to $15.9 million for a 50% reduction
  - $14.1 to $31.8 million for a 100% reduction

Air Quality Impacts of H₂ & Fuel Cell Alternatives

• The only alternative to H₂ & Fuel Cells that is currently available and being widely implemented to deal with reliability and resilience (e.g., for wildfires & PSPS events) is diesel backup generation

• Recent APEP study

Overview of study methodology

Air Quality Impacts of H₂ & Fuel Cell Alternatives

- Total increases of NOx and PM$_{2.5}$ and spatial location of NOx emissions increases of the Grid Disruption Scenario

[Graph showing total increase in SoCAB emissions and spatial distribution of NOx increases]

[Hyperlink: http://apep.uci.edu/PDF/Potential_Public_Health_Costs_from_Air_Quality_Degradation_During_Grid_Disruption_Events_070921.pdf]
Air Quality Impacts of H₂ & Fuel Cell Alternatives

• Changes in ground-level ozone (O₃) due to grid disruption scenario

Air Quality Impacts of H₂ & Fuel Cell Alternatives

- Increases in ground level MD24H PM$_{2.5}$ from the widespread use of fossil backup generators during a grid disruption for winter (a) and summer (b) with units in μg/m$^3$
Air Quality Impacts of H₂ & Fuel Cell Alternatives

- Public health costs estimated from increased short-term exposure to ozone and PM$_{2.5}$ that results from fossil back-up generators operating during a grid disruption

Air Quality Impacts of H₂ & Fuel Cell Alternatives

- Spatial distribution of public health costs from AQ degradation in (a) winter and (b) summer
- Boundaries for socially disadvantaged communities (DAC) according to CalEnviroScreen 3.0 are outlined
- DACs are disproportionately impacted

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Renewable and Zero-carbon Gaseous Fuel Pathways

- Organics Conversion
- Power-to-Gas
- Artificial Photosynthesis

- Anaerobic Digestion
- Thermo-chemical
- Electrolysis

- CO2

- Renewable Natural Gas
- Renewable Hydrogen

- Reformation
- Methanation
Hydrogen Supply-chain Costs Forecast to Decline Rapidly

Increased station network use & economies of scale are most significant

Source: UCI APEP using HDSAM 3.1
Build-out to Serve High-demand Case

- ~500 new facilities needed – more than 25 new facilities in peak year
- Aggregate investment of $30 - $50 billion

Source: UCI APEP, CEC Renewable H2 Roadmap, 2020
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Appliances

Summary

• Hydrogen addition improves emissions for most un-modified burners
  • Those using ~80% NG / 20% H₂
• Understanding established to propose modifications to accommodate even more hydrogen

<table>
<thead>
<tr>
<th>Appliances</th>
<th>Fuel Mixture</th>
<th>NOₓ</th>
<th>CO</th>
<th>Upper Limit</th>
<th>NOₓ</th>
<th>CO</th>
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<th>NOₓ</th>
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<tbody>
<tr>
<td>Cooktop</td>
<td>CH₄ - H₂</td>
<td>-23%</td>
<td>-14%</td>
<td>55%</td>
<td>0%</td>
<td>-38%</td>
<td>30%</td>
<td>3966%</td>
<td>-100%</td>
<td>100%</td>
<td>0%</td>
<td>+27%</td>
<td>10%</td>
<td>-20%</td>
<td>-10%</td>
<td>&gt;20%</td>
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<tr>
<td></td>
<td>CH₄ - CO₂</td>
<td>-51%</td>
<td>+58%</td>
<td>35%</td>
<td>-92%</td>
<td>+114%</td>
<td>15%</td>
<td>-76%</td>
<td>-99.9%</td>
<td>45%</td>
<td>46%</td>
<td>+334%</td>
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<td>-45%</td>
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<td>Oven</td>
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<td>4. Low NOₓ SWH</td>
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<td>5. Tankless WH</td>
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<td>Space Heater</td>
<td>CH₄ - H₂</td>
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<td>-14%</td>
<td>45%</td>
<td>-96%</td>
<td>+762%</td>
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<td>&gt;40%</td>
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<td>Pool Heater</td>
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<td>Outdoor Grill</td>
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<td>Laundry Dryer</td>
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Key (NOₓ/CO)

% Increase
% Decrease
No Change

Burner Performance Reports Available for each—Appendices for Final Report
**Industrial Burners**

Quantified NO\textsubscript{x} and CO emissions relative to operation on 100% Natural Gas (CH\textsubscript{4})

- Variation for burners, pollutants, and fuels

<table>
<thead>
<tr>
<th>Fuel Mixture</th>
<th>1. LSB</th>
<th>2. SSB</th>
<th>3. MTC</th>
<th>4. Oxygas</th>
<th>5. HSJ</th>
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<tbody>
<tr>
<td>76% CH\textsubscript{4} - 24% H\textsubscript{2}</td>
<td>-111%</td>
<td>-40%</td>
<td>-64%</td>
<td>-40%</td>
<td>200%</td>
</tr>
<tr>
<td>98% CH\textsubscript{4} - 2% CO\textsubscript{2}</td>
<td>-5%</td>
<td>11%</td>
<td>-3%</td>
<td>3%</td>
<td>-17%</td>
</tr>
<tr>
<td>94% CH\textsubscript{4} - 6% C\textsubscript{2}H\textsubscript{6}</td>
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<td>8%</td>
<td>2%</td>
<td>3%</td>
<td>3%</td>
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<td>95% CH\textsubscript{4} - 5% C\textsubscript{3}H\textsubscript{8}</td>
<td>9%</td>
<td>3%</td>
<td>3%</td>
<td>6%</td>
<td>5%</td>
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<td>-50%</td>
<td>233%</td>
<td>-35%</td>
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<td>98% CH\textsubscript{4} - 2% CO\textsubscript{2}</td>
<td>-3%</td>
<td>0%</td>
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<td>94% CH\textsubscript{4} - 6% C\textsubscript{2}H\textsubscript{6}</td>
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<td>4%</td>
</tr>
</tbody>
</table>

**Key (NO\textsubscript{x}/CO)**

- **% Increase**
- **% Decrease**
- **No Change**

Gas Turbines

• OEMs are conservative in their developments and targets
  • “Slight increase in NOx may result”
  • This has been the case for decades
    • Original NOx limits were 42 ppm, then 25 ppm, then 9 ppm and now 2.3 ppm
      • ~20x reduction attained through technology development
  • Combustion science guides the development
    • Well established
    • Optimization of local combustion temperatures via flow split adjustments
  • UCI measurements on commercial 60kW engine illustrate that NOx can actually be reduced when adding hydrogen
    • Modification of air distribution within the combustion system can take advantage of the wider flammability limits offered by hydrogen
  • UCI currently testing a 200kW version
Gas Turbines

- Hydrogen faster flame speed allows more lean operation
- Micro-mixing full-scale GT design

https://www.osti.gov/servlets/purl/1030641
Air Quality Implications

- Example: Adaptation of preferred equipment @ 20% hydrogen addition, summer
  - Using measured/simulated changes in NOx emissions from Appliances, Industrial burners and Gas turbines

![Change in Ozone, ppb](image1)

![Change in PM2.5, μg/m³](image2)