Bridging Renewable Electricity with Transportation Fuels

Grigorii Soloveichik

ARPA-E workshop
August 27, Denver, CO
Imperative: reducing greenhouse gases emission while preserving energy security

• Fossil fuels used for power generation emit CO₂ and other GHG that leads to dramatic climate change
• Burning fossil fuels in internal combustion engines for transportation is responsible for about 1/3 of GHG emission
• Replacement coal for natural gas reduced GHG emissions for grid scale power generation but replacement of liquid transportation fuels with NG is currently not viable due to low energy density of methane
• Market penetration of electric vehicles is lower than anticipated due to high cost of batteries, long charge time and range anxiety
Solution: replace fossil fuels with zero-emission regenerable fuels

• More than 95% vehicles use liquid fuels, infrastructure in place
• ICEs emit CO₂ and other GHGs (hard to capture)
• Electricity from renewable sources is clean and can be used directly (batteries) or to generate hydrogen to power fuel cells
• Batteries are expensive; recharging time and range anxiety lead to low public acceptance
• Hydrogen fuel cell vehicles are considered to be ultimate solution for long range transportation and dense urban areas
Vehicle energy consumption and emissions (full energy cycle)

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Energy consumption, kWh/mile</th>
<th>CO₂ emissions, g/mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average gasoline car</td>
<td>1.55</td>
<td>411</td>
</tr>
<tr>
<td>Gasoline car (Honda Accord)</td>
<td>1.08</td>
<td>286</td>
</tr>
<tr>
<td>Diesel car (FW Jetta)</td>
<td>1.11</td>
<td>299</td>
</tr>
<tr>
<td>Hybrid car (Prius)</td>
<td>0.79</td>
<td>212</td>
</tr>
<tr>
<td>BEV (Tesla)</td>
<td>1.09 (0.40 battery)</td>
<td>375 (248 CA)*</td>
</tr>
<tr>
<td>BEV (Leaf)</td>
<td>1.32 (0.48 battery)</td>
<td>419 (267 CA)*</td>
</tr>
<tr>
<td>HFCEV (Toyota Mirai)</td>
<td>1.52 (el), 1.20 (SMR)</td>
<td>510 (el), 118 (SMR)</td>
</tr>
</tbody>
</table>

* - Electricity from fossil fuels, 153 g CO₂/mile estimated from battery manufacturing

Only renewable energy sources can decrease carbon emissions
Critical needs

- Renewable power generation (remote) separated from liquid transportation fuel consumption (local)
- Wide spread of intermittent renewables requires bulk energy storage
- Infrastructure for renewable power transmission and distribution needs to be build
Problems

1. Energy transport
   • Long distance
   • Capital cost
   • Efficiency (losses)
   • Safety, other risks

2. Energy storage for intermittent sources
   • Capital cost/duration
   • Efficiency (losses)
   • Lifetime (LCOE)
   • Safety, other risks

3. Infrastructure
   • Geography (terrain, local codes)
   • Capital cost
   • Capacity
   • High entry cost
Program concept

1) Reduce transportation and storage costs of energy from remote renewable intermittent sources to consumers and
2) Enable the use of existing infrastructure via
   i) energy conversion into hydrogen-rich liquid fuels,
   ii) transportation of liquids, and
   iii) energy generation at the end point using direct (combustion or electrochemical) or indirect (via intermediate hydrogen extraction) oxidation
Why does it matter?

- **Direct conversion of renewable electricity/solar to fuels:**
  - closes gap between production and use
  - increases well-to-wheel efficiency

- **Use of extractable hydrogen in fuel cells:**
  - decreases GHG emissions
  - reduces energy demand compared to ICEs

- **Transportation fuels from renewables:**
  - reduce dependence on fossil fuels
  - increase energy security of the US
  - allow using of existing infrastructure
Program targets

- Develop **scalable, preferably direct** electrochemical or photochemical conversion of renewable energy to high energy density **liquid** hydrogenated fuels via water splitting
- Develop cost effective methods for **direct** (electrochemical) and **indirect** (thermal) extraction of hydrogen and demonstrate their use in fuel cells
Program outcome

• Zero emission liquid transportation fuels from remote renewable energy sources
• Use of existing infrastructure for fuel delivery/distribution
• No need for compressed/liquid hydrogen storage, no flammability/explosion hazards of hydrogen fuel
• Public acceptance (safety, range anxiety eliminated)
• Increase of US energy security
• Creation of new jobs in fuel production and transportation
Problem: How to convert renewable power to transportation fuels

• Major renewable energy sources (hydro, solar, wind) generate electricity in remote locations

• Transportation fuels (gasoline, diesel, jet fuel) mostly produced by oil refining are inexpensive and energy dense – hard to compete

• Gas-to-liquid process is capital, water and energy intensive, GHG emissions similar to refinery

• Synthetic liquid fuels produced from renewable biomass (corn, sugar cane, switchgrass, algae) demand energy to produce and have net positive CO₂ emission
Possible solution: replace ICE propulsion with zero-emission electric drives

Option 1 (short term) to provide on-board mobile power: batteries

Batteries advantages:
- Mature technology, simple to operate
- Competition drives price down

Batteries issues:
- High cost (on a track to meet $150/kWh)
- Power and energy coupled (two types of batteries may be needed)
- Low conformability (limited design options)
- Intrinsically unsafe (active materials in close proximity to each other)
- Long recharge time (limited by heat rejection)
- No infrastructure designed for high market penetration of EVs (especially in urban environment)
- Difficult to reach needed 300 miles range (range anxiety)
Possible solution: replace ICE propulsion with zero-emission electric drives

Option 2 (long term) to provide on-board power: fuel cells

Fuel cell systems advantages:
- 300 miles range proven, short refueling time
- Power and energy decoupled, fuel cell and storage tank separated
- Less well-to-wheel emissions

Fuel cell systems issues:
- High fuel cell cost (on a track to meet $55/kW)
- Lower efficiency (slow oxygen reduction reaction requires PGM catalysts)
- On-board hydrogen storage (compressed H₂ is the only current option)
- No infrastructure/high cost for hydrogen transportation and delivery (hydrogen has to be produced on site)
- High entry barrier for refueling stations (high price/low capacity)
Current energy delivery systems

Remote production

Electricity production – water electrolysis – hydrogen transportation and storage – FCEV
- Compression losses
- High cost of hydrogen transportation
- Flammability/explosion hazard

Electricity production – transmission and distribution – battery storage – BEV
- Transmission and delivery losses
- Low battery energy density
- Long charge time
Possible solution: Transportation of liquid fuels

- Physicochemical properties of fuels dictate the mode of transport
  - Pipeline - hydrocarbons
  - Rail/truck – alcohols, liquefiable gases, gases
- Mode of shipment is directly influencing economics
  - Pipeline is order of magnitude cheaper than rail/truck
    - Pipeline is more efficient as well
    - Barge is the most economical but geographically limited
- Cost scales as a function of fuel density and energy density
  \[ P \left( \frac{\$}{E} \right) \propto \rho^{-1} E^{-1}_{\text{density}} \]

Transportation cost is small compared to fuel production costs
Cost of energy transportation (electricity)

Electricity transmission and distribution
- Average US electricity losses in T&D 5.5%
- Energy losses 5.5% per 1000 km (OHVAC)
- Average cost $0.01/kWh (transmission) and $0.028/kWh (distribution)
- Transportation of electricity for 2000 km increases the cost by 42%
- Capital power line cost $7.9M/mile (OHVAC) or $21.5M/mile (HVDC)

Energy storage
- Battery storage $0.10/kWh (Tesla) - $0.05/kWh (projected)
Cost of energy transportation (liquid fuels)

- Average cost $0.025/gal (gasoline) or $0.00075/kWh
- Pipeline capital cost $4.2M/mile

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Cost of Shipping per kWh 1000km</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTG</td>
<td>$0.00036</td>
</tr>
<tr>
<td>FTD</td>
<td>$0.00034</td>
</tr>
<tr>
<td>methanol</td>
<td>$0.011</td>
</tr>
<tr>
<td>ethanol</td>
<td>$0.0082</td>
</tr>
<tr>
<td>DME</td>
<td>$0.011</td>
</tr>
<tr>
<td>NH3</td>
<td>$0.0048</td>
</tr>
<tr>
<td>electricity</td>
<td>$0.053</td>
</tr>
</tbody>
</table>

**Case study**

Solar PV array 500 MW
- 8 hrs active, storage capacity 50%
- 4 GWh electricity or 50,000 kg H₂ or 280 ton NH₃
- Delivery from Utah to East Coast (2000 miles)
- Daily energy delivery cost:
  - Electricity $249,000
  - Hydrogen $268,000
  - Ammonia $134,000
Projected global hydrogen storage and transportation systems using liquid organic hydrogen carriers (LOHC)

- Toluene/methylcyclohexane system: Chiyoda Corp., Hitachi Ltd. (Japan), HydroCreatives (India)
- N-ethylcarbazole/dodecahydro-N-ethylcarbazole: Areva, H2- Industries (Germany)
- Hydrogenated dibenzyltoluene: Hydrogenious Technologies (Germany)
- Hydrnol (C₅H₁₂S/ C₅H₆S): Asemblon (USA)

J. von Wild et al., Proceedings of the 2010 WHEC  
http://www.h2-industries.com/
Projected global hydrogen storage and transportation systems using liquid organic hydrogen carriers (LOHC)

Fukushima Renewable Energy Institute (FREA)

A hydrogen supply center by 2016

*Japan Times*, July 14, 2015
# Main parameters of promising LOHC

<table>
<thead>
<tr>
<th>LOHC couple</th>
<th>B.p., deg C</th>
<th>Wt. % H</th>
<th>T dehydro, deg C</th>
<th>Dehydrogenation $\Delta H$, k J/mol H$_2$</th>
<th>Energy density, Wh/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methylcyclohexane/toluene</td>
<td>101</td>
<td>6.5</td>
<td>280</td>
<td>-67.4</td>
<td>1345</td>
</tr>
<tr>
<td>Perhydrodibenzyltoluenes/dibenzyltoluenes</td>
<td>390</td>
<td>6.2</td>
<td></td>
<td></td>
<td>1735</td>
</tr>
<tr>
<td>Decalin/naphtalene</td>
<td>186</td>
<td>7.2</td>
<td>274</td>
<td>-59.0</td>
<td>1893</td>
</tr>
<tr>
<td>$C_{14}H_{25}N/N$-ethylcarbazole</td>
<td>281</td>
<td>5.8</td>
<td>128</td>
<td>-51.9</td>
<td>2010</td>
</tr>
<tr>
<td>Perhydroquinaldine/quinaldine</td>
<td>214</td>
<td>6.5</td>
<td></td>
<td></td>
<td>1715</td>
</tr>
<tr>
<td>$C_5H_{12}S/C_5H_6S$</td>
<td>113</td>
<td>5.8</td>
<td></td>
<td></td>
<td>1370</td>
</tr>
<tr>
<td>Propanol-2/acetone</td>
<td>56</td>
<td>3.4</td>
<td>170</td>
<td>-68.8</td>
<td>750</td>
</tr>
<tr>
<td>1,4-butanediol/$\gamma$-butyrolactone</td>
<td>204</td>
<td>4.5</td>
<td>84</td>
<td>-42.2</td>
<td>1371</td>
</tr>
<tr>
<td>2,4-pentanediol/valerolactone</td>
<td>140</td>
<td>3.8</td>
<td></td>
<td>--45.6</td>
<td>1105</td>
</tr>
<tr>
<td>Ammonia</td>
<td>-33</td>
<td>17.8</td>
<td></td>
<td></td>
<td>3170</td>
</tr>
<tr>
<td>Liquid hydrogen</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2340 (1640)</td>
</tr>
</tbody>
</table>
LOHC safety requirements

**Handling:**
- Non-explosive
- Non-(easily) flammable
- Non(low)-volatile
- Non-sensitive to oxygen and water
- Non-corrosive
- Non-toxic
- Non-irritant

**Environmental:**
- Biodegradable
- Non-toxic
- Non-accumulative
Current energy delivery systems

On-site production
Future energy delivery system

Off-board use

On-board use
## Vehicle refueling options comparison

<table>
<thead>
<tr>
<th>Car type</th>
<th>Refueling place</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Central station</td>
</tr>
<tr>
<td></td>
<td>Fast refueling</td>
</tr>
<tr>
<td>Gasoline car</td>
<td>Green</td>
</tr>
<tr>
<td>BEV</td>
<td>Yellow</td>
</tr>
<tr>
<td>HFCEV</td>
<td>Green</td>
</tr>
<tr>
<td>Liquid Fuel Cell EV</td>
<td>Green</td>
</tr>
</tbody>
</table>
Levelized cost of hydrogen and competing ES technologies

Ranges of Levelized Cost of Output Electricity from Storage

The levelized cost is the total annualized cost of capital and operating expenses throughout the life of the facility divided by the total yearly energy output.

NREL National Hydrogen Association Conference, 2010
Grids interactions

- Power plant
- Renewable generation
- Gas-to-Liquid

Electricity → Natural gas

New program

Liquid fuels
Liquid Hydrogen Carriers, Carbon free program
white space

CO2 release (g/mile)

- FCs based on gaseous H₂
- EVs (BEEST, RANGE)
- Natural gas (MOVE)
- Biofuels, PETRO (Billion tons = 30% of US oil)

Scalability (infrastructure, fast “charge”, customer acceptance)

- Oil with efficient powertrains (HEV), TRANSNET

New program white space
Program framing

- Zero carbon emissions
- Energy dense fuels, liquid at ambient conditions
- Fuel production tolerable to intermittent character of renewables
- Scale match between energy production and fuel generation
- Onboard power delivery sufficient for mobile applications
- Stationary applications possible
- Use of existing infrastructure with minimal modifications
- Cost competitive with electricity energy delivery (T&D)

- Technologies satisfying these criteria wanted
- Performance matrix needs to be developed
Thank you!