LOW-CARBON ELECTROFUEL SYNTHESIS FOR AVIATION AND FREIGHT TRANSPORTATION: A TECHNO-ECONOMIC ANALYSIS

USAEE 2018
By Evan D. Sherwin
PhD Candidate, Engineering and Public Policy
MS Student, Machine Learning
esherwin@cmu.edu
Carnegie Mellon University
With: Inês M. L. Azevedo and W. Michael Griffin
The challenge: Decarbonization of aviation and heavy freight transportation

~2.4% of global GHG emissions

~3.1% of global GHG emissions

~0.8% of global GHG emissions

Energy density:
Jet fuel: 37.4 MJ/L
Diesel: 35.8 MJ/L
Li-ion battery: 2.64 MJ/L

Sources: 1, 2
Images: pxhere.com, maxpixel.com
Can biofuels, electrofuels, or direct air capture with sequestration economically reduce GHGs by 80+%?

• Biofuels: Substantial land use and life-cycle emissions concerns [3]
• Electrofuels: Synthetic hydrocarbons from renewably-sourced carbon dioxide and hydrogen
• Conventional fuels with direct air capture and CO\textsubscript{2} sequestration
  • Average pre-tax fossil jet fuel price is \sim$2/GGE [4]
    • Diesel is \sim$2.5/GGE [4]
• Techno-economic analysis
WHAT ARE ELECTROFUELS?

Image: svgsilg.com
THE WHOLE PROCESS

Direct air carbon capture → Reverse water-gas shift → Fischer-Tropsch fuel synthesis

Electrolyzer
Direct air capture of CO$_2$

$9M$ pilot plant, $1t$CO$_2$/day ($\sim100$ cars) [20]

Source: carbonengineering.com
THE WHOLE PROCESS

174 kWh electricity
694 kWh heat
2000 kg(H₂O)

Direct air carbon capture

Electrolyzer

480 kg(CO₂)

CO₂: 400ppm

CO₂: 100ppm

CₙHₙ(2n+2) + nH₂O
1 barrel of oil equivalent
(Jet fuel, diesel, gasoline, naphtha, tar, methane)

(1 barrel of oil equivalent is ~60 gallon of gasoline equivalent)

Image: pngimg.com, flickr.com, Wikimedia.org, pixabay.com, pxhere.com
**ELECTROLYSIS OF WATER**

$$\text{H}_2\text{O} + e^- \rightarrow \text{H}_2 + \text{O}_2$$
The Whole Process

Direct air carbon capture

- 170 kWh electricity
- 690 kWh heat
- 2000 kg(H₂O)

Electrolyzer

- 480 kg(CO₂)
- CO₂: 100ppm

- 68 kg(H₂)
- 2270 kWh(H₂)
- 540 kg(O₂)
- At 70% efficiency

CO₂: 400ppm

CₙH(2n+2) + nH₂O
1 barrel of oil equivalent (Jet fuel, diesel, gasoline, naphtha, tar, methane)

540 kg(O₂)
610 kg(H₂O)

Image: pngimg.com

(1 barrel of oil equivalent is ~60 gallon of gasoline equivalent)
THE WHOLE PROCESS

Direct air carbon capture

- 170 kWh electricity
- 690 kWh heat
- 2000 kg(H₂O)

Electrolyzer

- 3240 kWh electricity
- 610 kg(H₂O)

Reverse water-gas shift

- 480 kg(CO₂)

CO₂: 400ppm

CO₂: 100ppm

- 68 kg(H₂)
  (2270 kWh(H₂))
- 540 kg(O₂)
  At 70% efficiency

CₙHₙ(2n+2) + nH₂O
1 barrel of oil equivalent
(Jet fuel, diesel, gasoline, naphtha, tar, methane)

(1 barrel of oil equivalent is ~60 gallon of gasoline equivalent)

Image: pngimg.com
REVERSE WATER GAS SHIFT

\[ \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{CO}_3 \]
THE WHOLE PROCESS

Direct air carbon capture:
- 170 kWh electricity
- 690 kWh heat
- 2000 kg(H₂O)

Electrolyzer:
- 3240 kWh electricity
- 610 kg(H₂O)
- 480 kg(CO₂)
- CO₂: 400ppm
- CO₂: 100ppm

Reverse water-gas shift:
- 68 kg(H₂)
- (2270 kWh(H₂))
- 540 kg(O₂)
- At 70% efficiency

Fischer-Tropsch fuel synthesis:
- CₙHₙ(2n+2) + nH₂O
- 1 barrel of oil equivalent
- (Jet fuel, diesel, gasoline, naphtha, tar, methane)

75% combined efficiency

Image: pngimg.com

(1 barrel of oil equivalent is ~60 gallon of gasoline equivalent)
FISCHER-TROPSCH PROCESS

\[ \text{O} \quad \text{C} \quad \text{H} + \quad \rightarrow \quad nC_2(n+1)H + \quad \text{O}_2 \quad \text{O} \quad \text{OH} \]
THE WHOLE PROCESS

170 kWh electricity
690 kWh heat
2000 kg(H₂O)

Direct air carbon capture

480 kg(CO₂)

Reverse water-gas shift

75% combined efficiency

Fischer-Tropsch fuel synthesis

CᵣH_(2n+2) + nH₂O
1 barrel of oil equivalent
(Jet fuel, diesel, gasoline, naphtha, tar, methane)

Image: pngimg.com
EXISTING TECHNO-ECONOMIC ANALYSES

• Zeman & Keith (2008): Cost ranges overlap for electrofuels, biofuels, conventional fuels + DACS [28]
  • $3.4-4.5/GGE

• Graves et al. (2011): Electrolyzer capital costs dominate in many cases, particularly with low capacity factors [29]
  • Electrofuels competitive with $2/gal gasoline at 1-2¢/kWh

• Brynolf et al. (2018): Review of electrofuel production cost studies, finds costs high compared to biofuels
  • ~$4-$15/GGE [21]

• Fasihi et al. (2015-2017): Hybrid wind-PV, $3.3-3.8/GGE [27, 30]
Feasibility of Electricity Options

- Industrial electricity rates are generally ~6¢/kWh [31]
  - Similar for low-end cost estimates of nuclear [32]
- Electricity for hydrogen would cost ~$3.40/GGE for an electrolyzer with 70% efficiency
- Thus, if conventional fuel is cheaper than that, it is cheaper to just bury the captured CO$_2$
- Even with 65% renewables on the grid, only ~20% curtailment estimated, probably highly seasonal [33]
- This study: Dedicated solar or wind
# Main Sources of Uncertainty

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Optimistic</th>
<th>Reference</th>
<th>Pessimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer capex [21]</td>
<td>$/kW(e)</td>
<td>350</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td>Electrolyzer efficiency [21]</td>
<td>%</td>
<td>80%</td>
<td>70%</td>
<td>60%</td>
</tr>
<tr>
<td>System integration cost</td>
<td>% of capex</td>
<td>0%</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>Electricity price</td>
<td>$/kWh</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>%</td>
<td>40%</td>
<td>30%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Very large economies of scale: 2GW(fuel), 30k bbl/d (Average US oil refinery is 120k bbl/d)
## Direct Air Capture Input Parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capex</td>
<td>$/(t(CO_2))/yr</td>
<td>694</td>
<td>1046</td>
<td>2250</td>
</tr>
<tr>
<td>O&amp;M cost</td>
<td>$/(t(CO_2))/yr</td>
<td>26</td>
<td>42</td>
<td>100</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Years</td>
<td>25</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Electricity demand</td>
<td>kWh/(t(CO_2))/yr</td>
<td>366</td>
<td>366</td>
<td>300</td>
</tr>
<tr>
<td>Heat demand</td>
<td>GJ/(t(CO_2))/yr</td>
<td>5.25</td>
<td>5.25</td>
<td>6</td>
</tr>
<tr>
<td>$/t(CO_2) @90% CF</td>
<td>$/t(CO_2)</td>
<td>136</td>
<td>204</td>
<td>360</td>
</tr>
</tbody>
</table>
ELECTROFUEL COST BREAKDOWN

Electrofuel cost component:
- Water
- DAC energy
- Electrolyzer electricity
- Fischer-Tropsch: O&M
- Electrolyzer: O&M
- DAC: O&M
- System: Capital
- Fischer-Tropsch: Capital
- Electrolyzer: Capital
- DAC: Capital

Optimism scenario:
- Reference
- Optimistic
- Pessimistic

Electrofuel cost ($2017/GGE)
REFERENCE CASE COSTS BY COMPONENT

- Direct air carbon capture: $4.82/GGE
- Electrolyzer: $3.41/GGE
- Reverse water-gas shift: $0.70/GGE
- Fischer-Tropsch fuel synthesis: $9.03/GGE

\[ C_n H_{(2n+2)} \]
**Carbon Mitigation Costs in \$/t(CO_2)\)**

- EPA estimates social cost of carbon substantially below $100/t(CO_2)
- ~$40/t(CO_2) commonly used in policy analysis [39]
- EPA’s 95\textsuperscript{th} percentile estimate for 2050 is $212.

<table>
<thead>
<tr>
<th>$/t(CO_2)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrofuel GHG price v. $2/GGE</td>
<td>1003</td>
</tr>
<tr>
<td>Electrofuel GHG price v. $3/GGE</td>
<td></td>
</tr>
<tr>
<td>Sequestration cost (same assumptions)</td>
<td></td>
</tr>
<tr>
<td>Sequestration cost (NG firing)</td>
<td></td>
</tr>
</tbody>
</table>
NO EASY OPTIONS

• Using dedicated solar electricity in the modeled configuration will cost at best ~$4/GGE, possibly much higher

• Offsetting conventional fuels with direct air carbon capture and sequestration is less expensive except under highly favorable circumstances

• Nuclear and grid electricity are likely better used for direct air capture with sequestration than electrofuels
(Very preliminary) Policy implications

• Direct air carbon capture RD&D may be a high priority for decarbonization of aviation
• Although potentially expensive, electrofuels allow deep GHG emissions reductions and do not require CO2 sequestration
• Still, jet fuel prices could rise 3.7x, to ~$7/GGE, before airplane tickets reach 1980 levels [4, 40]
  • Could this become socially acceptable?
ACKNOWLEDGMENTS

- Max Henrion
- M. Granger Morgan
- David Keith
- Nathan Lewis
- Geoffrey Holmes
- Carbon Engineering
- Jennifer Wilcox
- Hadi Dowlatabadi
- Lonnie Chrisman
- National Science Foundation
  - Graduate Research Fellowship
  - Center for Climate and Energy Decision Making

Evan D. Sherwin
PhD Candidate, Engineering and Public Policy
MS Student, Machine Learning
esherwin@cmu.edu
WORKS CITED


WORKS CITED


18. Carbonengineering.com

19. Climeworks.com


WORKS CITED


WORKS CITED


32. Electric Power Annual: Table 2.7. Average Price of Electricity to Ultimate Customers (2017) Available at: https://www.eia.gov/electricity/annual/.


FUTURE WORK

• Optimal operation with realistic renewable generation profiles and heat and H₂ storage
• Vary electricity prices as capacity factor decreases
• Fuel product distributions and coproduct markets
• Natural gas firing of DAC
• Other DAC technologies, process heat recycling
• Biogenic CO₂
• Concentrating solar for process heat
• Potential for DAC cost reductions through heat recycling in electrofuel production
• Feasibility of sequestration (siting, leakage, earthquakes)
## Other Sources of Uncertainty

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Optimistic</th>
<th>Reference</th>
<th>Pessimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer lifetime [21]</td>
<td>Years</td>
<td>30</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Electrolyzer O&amp;M [21]</td>
<td>% of capex/yr</td>
<td>1%</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td>Fischer-Tropsch capital [21]</td>
<td>$/kW(fuel)</td>
<td>350</td>
<td>500</td>
<td>650</td>
</tr>
<tr>
<td>Fischer-Tropsch O&amp;M [21]</td>
<td>% of capex/yr</td>
<td>1%</td>
<td>3%</td>
<td>5%</td>
</tr>
<tr>
<td>Fischer-Tropsch lifetime [21]</td>
<td>Years</td>
<td>30</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Fischer-Tropsch energy efficiency [21]</td>
<td>%</td>
<td>80%</td>
<td>75%</td>
<td>70%</td>
</tr>
<tr>
<td>Fischer-Tropsch O&amp;M [21]</td>
<td>% of capex/yr</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>WACC (~discount rate)</td>
<td>%</td>
<td>6%</td>
<td>8%</td>
<td>10%</td>
</tr>
<tr>
<td>Desalinated water price [21]</td>
<td>$/t(H2O)</td>
<td>0.50</td>
<td>1.15</td>
<td>2</td>
</tr>
</tbody>
</table>
OTHER PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fischer-Tropsch CO₂ requirement [21]</td>
<td>t(CO₂)/MWh(fuel)</td>
<td>0.28</td>
</tr>
<tr>
<td>Sequestration cost [28]</td>
<td>$/t(CO₂)</td>
<td>12</td>
</tr>
<tr>
<td>Shipping cost [27]</td>
<td>$/GGE</td>
<td>0.03</td>
</tr>
</tbody>
</table>
REFERENCE CASE SENSITIVITY: ±20%

Range sensitivity of Levelized electrofuel costs ($(2017)/GGE)
REFERENCE CASE SENSITIVITY: RANGE PARAMETERS

- Capacity factor
- DAC capital cost
- System integration cost
- DAC O&M
- WACC (~discount rate)
- Electricity price
- Electrolyzer capital cost
- Electrolyzer efficiency (LHV)
- Fuel synthesis capital cost
- Fuel synthesis efficiency (LHV)
- Electrolyzer O&M
- Fuel synthesis O&M cost
- DAC lifetime
- Electrolyzer lifetime
- Fuel synthesis lifetime
- DAC heat demand
- DAC electricity demand

Range sensitivity of Levelized electrofuel costs ($/(2017)/GGE)

1. Low
2. High
DIRECT-AIR CAPTURE OF CO$_2$

Source: carbonengineering.com
DEDICATED RENEWABLES HAVE ADVANTAGES

- Low and declining costs of wind and solar
  - ~4¢/kWh unsubsidized in US [33, 34]
- No need for DC-AC conversion
- No grid interconnection costs (potentially)
- Lower capacity factors are a drawback
  - Solar is <30% or so [33]
  - Wind is <50% or so [34]
HOW I BECAME THE RESEARCHER I AM TODAY

• From near Santa Barbara, CA
• UC Berkeley: Physics and Applied Mathematics
• Wildfire modeling at UC Santa Barbara
• Energy analyst, Lumina Decision Systems
• PhD in Engineering and Public Policy at Carnegie Mellon University with Inês Azevedo & Max Henrion
  • Uncertainty in long-term energy forecasting (Nature Energy, featured in News and Views, 55 media outlets)
  • Residential utility program evaluation using smart meter data
  • One class away from an MS in Machine Learning
• Interests: Improvisational theater, songwriting, biking, yoga, Ultimate Frisbee, board games