Prospects for Producing Low Carbon Transportation Fuels from Captured CO$_2$ in a Climate Constrained World

Tom Kreutz
Princeton Environmental Institute
Princeton University, Princeton, New Jersey 08544

10th Annual Conference on Carbon Capture & Sequestration
Session: Beneficial Uses of CO$_2$
Pittsburgh, PA, 4 May 2011
Outline

1. Background and Motivation
2. Methods and Assumptions
3. Features of Microalgae Biodiesel and S2P FTL
4. Bifurcated Climate Regime
5. Anticipated and Calculated Climate Benefits
6. Economic Considerations
7. Discussion and Conclusion
Concerns about climate change, and growth of CCS has spawned schemes for “CCR”, CO$_2$ Capture and Reuse.

CCR converts a CO$_2$ storage liability into an economic opportunity.

Significant DOE support (107 M$) for CCR.

The most numerous and significant CCR systems produce transportation fuels, labeled here “CCTF”, CO$_2$ Capture to produce Transportation Fuels.

Two exemplars of CCTF studied here:
1. Microalgae-based Biodiesel
2. S2P FTL (Sunshine-to-Petrol Fischer-Tropsch liquids)
   (Also, the Joint Center for Artificial Photosynthesis, JCAP)

Both use solar energy to “upconvert” CO$_2$ to transportation fuel precursors.
Microalgae - Photobioreactor
Microalgae Variants
• High temperature heat from concentrated sunlight drives a novel thermochemical cycle that can reduce \( \text{CO}_2 \rightarrow \text{CO} + \frac{1}{2} \text{O}_2 \) (and/or \( \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2 \)) for FTL synthesis.
Magnetite / wüstite redox cycle:

1. Fe$_3$O$_4$ $\rightarrow$ FeO + $\frac{1}{2}$ O$_2$ (endothermic thermal reduction; >1600 K)
2. FeO + CO$_2$ $\rightarrow$ Fe$_3$O$_4$ + CO (exothermic oxidation; < 1200 K)
S2P – Generic Solar Field
Background and Motivation

• CCTF has the potential to improve energy security by producing large amounts of domestic transportation fuels.

• In CCTF, the carbon in power plant exhaust is “used twice” before reaching the atmosphere, displacing GHG emissions from petroleum-based fuels.

• In the U.S., the fuel carbon consumed by the transportation sector (500 Mtonne C in 2008) is well matched to that in CO$_2$ vented by pulverized coal (PC) power plants (540 Mtonne C in 2008).
Critical Questions

• In what scenarios can CCTF play a significant role in reducing the GHG emissions of the US transportation sector?

• Can/should CCTF significantly replace CCS?

• How does CCTF compare with “XTL” plants previously studied by our group and others?
**CCTF vs. CCBF**

- **CCBF:** “CO$_2$ Capture to produce Boiler Fuel”,

- For example, anaerobic digestion of algae to produce oil and methane.

- Carbon can be recycled *many times* before eventually leaking into the atmosphere:
  - burn boiler fuel,
  - capture the CO$_2$,
  - solar upgrade CO$_2$ to boiler fuel,
  - repeat...

- Low carbon energy, but not a solution for hydrocarbon-based transportation, which has a huge carbon “leak” to the atmosphere.
Assumptions

• Focus on U.S.: lots of land, coal, cars, and GHG emissions.

• U.S. challenge: reduce GHG emissions by ~80% by 2050 (e.g. “Waxman Markey” and IPCC stabilization: 500 ppm CO$_2$eq).

• Assume rising cost of CO$_2$ emissions (“CO$_2$ price”).

• Assume large scale reductions in emissions will occur first in the power sector (41% of total emissions), via CCS or replacing fossil fuels (esp. coal) with nuclear power and/or renewables.

• For simplicity, focus on CO$_2$ emissions from US coal power:
  1. 84% of power sector emissions,
  2. large, concentrated (~13%) point sources of CO$_2$, and
  3. well matched to carbon needs of the transportation sector.

• Assume CCS is a viable large scale GHG mitigation option.

• Transportation sector (33% of total emissions) must be deeply decarbonized, i.e. ~80% reduction in GHG emissions.
Methodology

• Avoid convolving the power and transportation sectors.

• CCTF is evaluated separately as a means of reducing transportation GHG emissions, set in the context of a power sector undergoing decarbonization.
  – CCTF is a perturbation on the power sector

• If CCTF becomes economical, it can be built by a power plant or external entrepreneur.
  – The economics are identical.
  – Close integration will provide some advantages.

• Conceptual plants studied here are “bolted together”:
  – Not optimized nor integrated nor entirely self-consistent.
Important Caveats

- This work is only a preliminary scoping study, a back-of-the-envelope assessment designed to sketch out the rough outlines of each system’s prospective performance and economics as related primarily to GHG emissions.

- The burgeoning field of algae-to-energy is far too dynamic and diverse to attempt here anything more than a generic characterization, and S2P technology and systems design are still under active development with few details available in the open literature.

- The results of these schematic representations should be interpreted only as crude generic estimates, in no way comparable to the detailed (Aspen Plus-based) techno-economic investigations of novel low carbon synfuels production plants described in our other research at PEI.
Bifurcated Climate Regime

- Imagine a future characterized by two distinct temporal regimes, labeled: "Pre-CCS" and "Post-CCS"

- Shorthand for pre- and post- decarbonization of the electric power sector - not necessarily via CCS.

- Transition from Pre-CCS to Post-CCS will occur within a band of "crossover" CO₂ prices, e.g. 60-100 $/t CO₂
  - [During decarbonization, some “fuel switching” from PC to NGCC will occur, roughly halving CO₂ emissions; however, to meet US GHG emission goals, the CO₂ price will rise enough to decarbonize even NGCC.]

- Adopt a single crossover CO₂ price, 60 $/tonne, above which it is more profitable for a PC plant to adopt CCS than vent CO₂.
Cost of Coal Power – Old Plants

- Cost of Electricity ($/MWh)
- CO2 Emissions Price ($/tonne CO2)

85% Capacity Factor
Add CCS Retrofit

CO2 Emissions Price ($/tonne CO2)

Cost of Electricity ($/MWh)

PC - CO2 venting
PC - CCS retrofit

85% Capacity Factor
Crossover CO₂ Price

"Crossover" CO₂ Price

PC - CO₂ venting

PC - CCS retrofit

85% Capacity Factor
• It is still profitable to vent CO₂ above the crossover price.
Fuel Switching to Natural Gas

- Decarbonizing NGCC requires higher CO₂ emissions prices

Nat. Gas: 6 $/GJ HHV

85% Capacity Factor
When biomass power is deployed, CCS is most profitable design.
Bifurcated Climate Regime

- **Pre-CCS regime (CO₂ price < crossover price):**
  - Power sector CO₂ is vented as usual
  - Fees for emitting CO₂ are passed on to consumers.
  - Large point sources of concentrated (4-13%) CO₂ are common.
  - CO₂ capture provides negative carbon emissions
Bifurcated Climate Regime

• *Post-CCS regime (CO₂ price > crossover price):*
  – Fossil-based power plants either employ CCS or have been replaced by nuclear power and/or renewable generators.
  – Large point sources of vented fossil CO₂ are relatively rare.
  – Point sources of vented CO₂ from biomass-fired plants may exist, but CCS is more profitable than CO₂ venting.
  – Large supplies of CO₂ are generally available only as supercritical CO₂ in pipelines destined for geologic storage (or natural sources of CO₂).
  – The amount of pipeline CO₂ available depends on competition between fossil plants with CCS (or CCFT) and non-carbon generators.
  – We assume here that CCS is competitive: pipeline CO₂ is plentiful.

[Note: high oil prices will bias this competition toward fossil-based power with CCFT.]
Anticipated Climate Benefits of CCTF

• **Pre-CCS regime** (CO₂ captured from flue gases):
  – Roughly C-neutral.

• **Post-CCS regime** (CO₂ from CCS pipelines):
  – Similar to petroleum-based fuels.
  – Comparable to new reservoir of domestic crude oil.

  [This result is independent of CO₂ origin, e.g. fossil fuels vs. biomass.]

• If CO₂ can be captured directly from the air, CCTF fuels are roughly C-neutral (both regimes).
  – [We assume here that air capture is uneconomical, and do not consider this option further.]
CO₂ Requirements

• Both algae and S2P require relatively concentrated sources of CO₂ for economical operation.

• S2P requires fairly pure CO₂.

• Microalgae can grow on pure CO₂ or extract CO₂ from flue gases injected directly into raceway sumps or photobioreactors.
  – We consider here only flue gas injection for algae.

• Pre-CCS era:
  – Assume CO₂ is captured from PC plant exhaust gases.

• Post-CCS era:
  – Assume CO₂ is available at zero cost from CCS pipelines.
  – Both S2P and algae: we employ high carbon utilization designs (for high CO₂ prices) to capture ~90% of CO₂ normally vented during fuel production and recycle it back to the precursor synthesis unit.
  – Algae: the CO₂ capture efficiency of initial flue gas is also increased.
### Algae & S2P – Common Processes

<table>
<thead>
<tr>
<th>Common Process</th>
<th>Algae Biodiesel</th>
<th>S2P FTL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ capture</td>
<td>CO₂ sparging / absorption in carbonation sump</td>
<td>MEA CO₂ capture from coal power plant flue gases</td>
</tr>
<tr>
<td>Synthesis of fuel precursors</td>
<td>Cultivation of <em>microalgae</em> in raceways</td>
<td>Reduction of CO₂ to CO in CR5 reactors</td>
</tr>
<tr>
<td>Fuel production, refining</td>
<td>Lipid extraction and transesterification</td>
<td>FT synthesis (with internal recycle) and subsequent refining</td>
</tr>
<tr>
<td>(integrated heat and power)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*CR5 reactors*
General Plant Characteristics

• Solar-driven fuel precursor synthesis units:
  – Assume 34.2% availability (12 hr/day x 250 days/yr).
  – Scaled up to supply the fuel production units.

• Assume 90% capacity factor of the fuel production, via buffer storage of the fuel precursors.

• All plants scaled to produce:
  – 50,000 bbl_{eq}/day fuel, and
  – modest export power (~10 of plant output).
Microalgae
Microalgae Advantages

• Many strains rich in oils - readily converted to biodiesel via transesterification.

• High growth rates and photosynthetic efficiency - potential for:
  – higher yields per acre than terrestrial biodiesel feedstocks,
  – greatly reduced land requirements.

• Can be cultivated on land unsuited to traditional agriculture:
  – in brackish or saline water
  – significantly reduced competition with food crops (and thus indirect land use change)

• Several strains successfully cultivated on power plant flue gas.

• Potential exists for using wastewater for additional nutrients.

• Algae composition, esp. the oil content, can be significantly altered by varying the growth conditions.

• Amenable to strain selection and genetic modification.
Microalgae Biodiesel System

• Specific configuration (Stephenson, et al., 2010):
  – two-stage (i.e. nutrient sufficient/starved) cultivation of *Chlorella vulgaris*,
  – 30 dry g/m²/day (110 tonne/ha/yr) in open raceways,
  – PC flue gas (12.5% vol. CO₂) injected into carbon sumps,
  – aluminum sulfate flocculation + decanter centrifuging,
  – countercurrent oil extraction with hexane - 5-stage cascade,
  – oil transesterification to biodiesel and glycerol,
  – anaerobic digestion of the non-oil fraction to methane to provide process heat and (excess) power.

• Adopt capital cost estimates of Benemann and Oswald (1996), and Huntley and Redalje (2006).
S2P
S2P FTL System

• Specific configuration studied:
  – MEA post-combustion CO$_2$ capture from coal power plants,
  – networked array of CR5 heat engine reactors,
  – centralized cobalt-based FT synthesis (with internal recycle of unconverted synthesis gas),
  – refining of FT products to synthetic diesel fuel,
  – integrated heat recovery steam cycle for power production.

• FTL production design and capital costs taken from Liu, et al. (2010).

• Note: S2P is a novel technology, and the system design studied here is only a very crude estimate.
## Plant Inputs and Outputs

<table>
<thead>
<tr>
<th>Input $\text{CO}_2$, tonne/hr:</th>
<th>Pre-CCS</th>
<th>Post-CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microalgae biodiesel</td>
<td>2,058</td>
<td>943</td>
</tr>
<tr>
<td>S2P FTL</td>
<td>1,010</td>
<td>824</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output fuel, $\text{MW}_{th}^{a}$</th>
<th>Pre-CCS</th>
<th>Post-CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3,174</td>
<td>3,174</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Export Power, $\text{MW}_e$:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Microalgae biodiesel</td>
<td>324</td>
<td>250</td>
</tr>
<tr>
<td>S2P FTL</td>
<td>241</td>
<td>347</td>
</tr>
</tbody>
</table>

$^{a}$ Microalgae biodiesel: 50,000 bbl$_{eq}$.

S2P FTL: 30,171 bbl$_{eq}$ (2,004 MW$_{th}$) diesel + 19,829 bbl$_{eq}$ (1,155 MW$_{th}$) gasoline.
Anticipated Climate Benefits

• *Pre-CCS regime* (CO$_2$ captured from flue gases):
  – Roughly C-neutral.

• *Post-CCS regime* (CO$_2$ from CCS pipelines):
  – Similar to petroleum-based fuels.
  – Comparable to new reservoir of domestic crude oil.
GHG Emissions: Pre-CCS

Petroleum-based fuels

- Algae
- S2P
- CTL-RC-V
- CTL-RC-CCS
- CBTL-RC-V
- CBTL-RC-CCS
- BTL-RC-V
- BTL-RC-CCS

Greenhouse Gas Index (GHGI)
**Greenhouse Gas Index (GHGI)**

- **Very useful** GHG emissions metric for systems that co-produce fuels and electricity.

- GHGI is the ratio of plant to BAU GHG emissions:

  \[
  GHGI = \frac{\text{Total plant GHG emissions}}{\text{BAU GHG emissions for same products}}
  \]

- Here, BAU refers to:
  1) old coal-fired power plants (992 kg CO$_2$eq/MWh)
  2) petroleum-based fuels (91.7 kg CO$_2$eq/GJ LHV)
Calculated Climate Benefits

- Petroleum-based fuels: 91 kg CO$_{2eq}$/GJ LHV
• Algae and S2P yield significant reductions in GHG emissions
**GHG Emissions: Pre-CCS**

- CTL: CO$_2$ venting = 2x petroleum; CCS ~ petroleum

---

**Greenhouse Gas Index (GHGI)**

- Petroleum-based fuels
- Algae
- S2P
- CTL-RC-V
- CTL-RC-CCS

---

**Legend**

- Pre-CCS
GHG Emissions: *Pre-CCS*

- Adding biomass: \(\text{CO}_2\) venting ~ petroleum; CCS ~ C-neutral
GHG Emissions: *Pre-CCS*

• BTL provides dramatic reductions in GHG emissions
GHG Emissions: Post-CCS

- Post-CCS era: higher GHG emissions due to decarbonized power
GHG Emissions: Post-CCS

- CCTF emissions are worse: pipeline CO₂ has no negative emissions
Economics

- Examine how the *generic* cost of CCTF varies with CO₂ price.
- Focus on cost of CO₂ acquisition and emissions.
- Overnight capital costs *(sure to be incorrect!)*:
  - Microalgae: 4,500 M$ for 50 kha system *(too low)*
  - S2P: 37,700 M$ *(yields 10 $/gal – too high)*

<table>
<thead>
<tr>
<th>Cost Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity factor</td>
<td>90%</td>
</tr>
<tr>
<td>Capital charge rate (CCR)</td>
<td>15% per year</td>
</tr>
<tr>
<td>Interest during construction</td>
<td>16.0% of overnight capital</td>
</tr>
<tr>
<td>Operation &amp; maintenance</td>
<td>4% of overnight capital, per yr</td>
</tr>
<tr>
<td>CO₂ transport+storage costs</td>
<td>10 $/tonne CO₂</td>
</tr>
<tr>
<td>U.S. dollars valued in year</td>
<td>2007 *</td>
</tr>
</tbody>
</table>

* Cost escalation via Chemical Engineering Plant Cost Index (CECPI)
Cost of CO₂ Acquisition & Emissions

- Pre-CCS: CO₂ is cheap; it has no emission cost
Cost of CO\textsubscript{2} Acquisition & Emissions

- S2P pre-CCS: MEA CO\textsubscript{2} capture is relatively expensive
Levelized Cost of Fuel (LCOF)

- Cost of CO₂ is reflected in LCOF

![Graph showing Levelized Cost of Fuel (LCOF)]
LCOF – Algae vs. S2P

- High assumed capital cost of S2P leads to high LCOF.
• CTL LCOF has intermediate value; upward sloping
• CBTL: more costly than CTL; lower emissions.
• BTL: higher LCOF; negative emissions (negative slope).
• BEOP generally reflects LCOF; quantifies competitiveness.
Conclusions

• CCTF can alleviate energy security concerns to some degree by providing domestic transportation fuels.

• Capturing CO₂ from stack gases (or from air), CCTF can produce transportation fuels that are roughly carbon neutral.

• Nevertheless, it appears unlikely that CCTF will play a significant long term role in decarbonizing the US transportation sector (and thus reaching US GHG emission goals) because:
  – After the power sector is decarbonized, large point sources of concentrated CO₂ are likely to be relatively rare, and
  – When using pipeline CO₂ lifecycle GHG emissions are not dramatically reduced.
  – In a sense, CCTF best provides a climate benefit when coupled with a plant that is harming the atmosphere with its CO₂ emissions.
  – Such “rogue emitters” are expected to be “scarce resources” in the Post-CCS era.
Conclusions

• In the Pre-CCS regime, CCFT has significant energy security and climate advantages. In the Post-CCS era, it might be a good “clean-up” strategy for remaining CO₂ point sources.

• At sufficiently high oil prices, CCFT will always replace CCS; this could ultimately work against achieving climate goals.

• CCFT is not a replacement for CCS. “Using the carbon twice” fails to achieve deep reductions in GHG emissions; only one sector (either power or transportation) can claim the benefit of carbon-neutrality.

• For deep reductions, fossil carbon emissions must be held to a minimum.

• Alternate CCR schemes like CCBF can produce low carbon energy, but not convenient hydrocarbon transportation fuels.

• Distributed CO₂ emissions can only be mitigated by systems that reverse the process, i.e. re-capture CO₂ from air.