ARPA-E Electrofuels Program Meeting & Workshop

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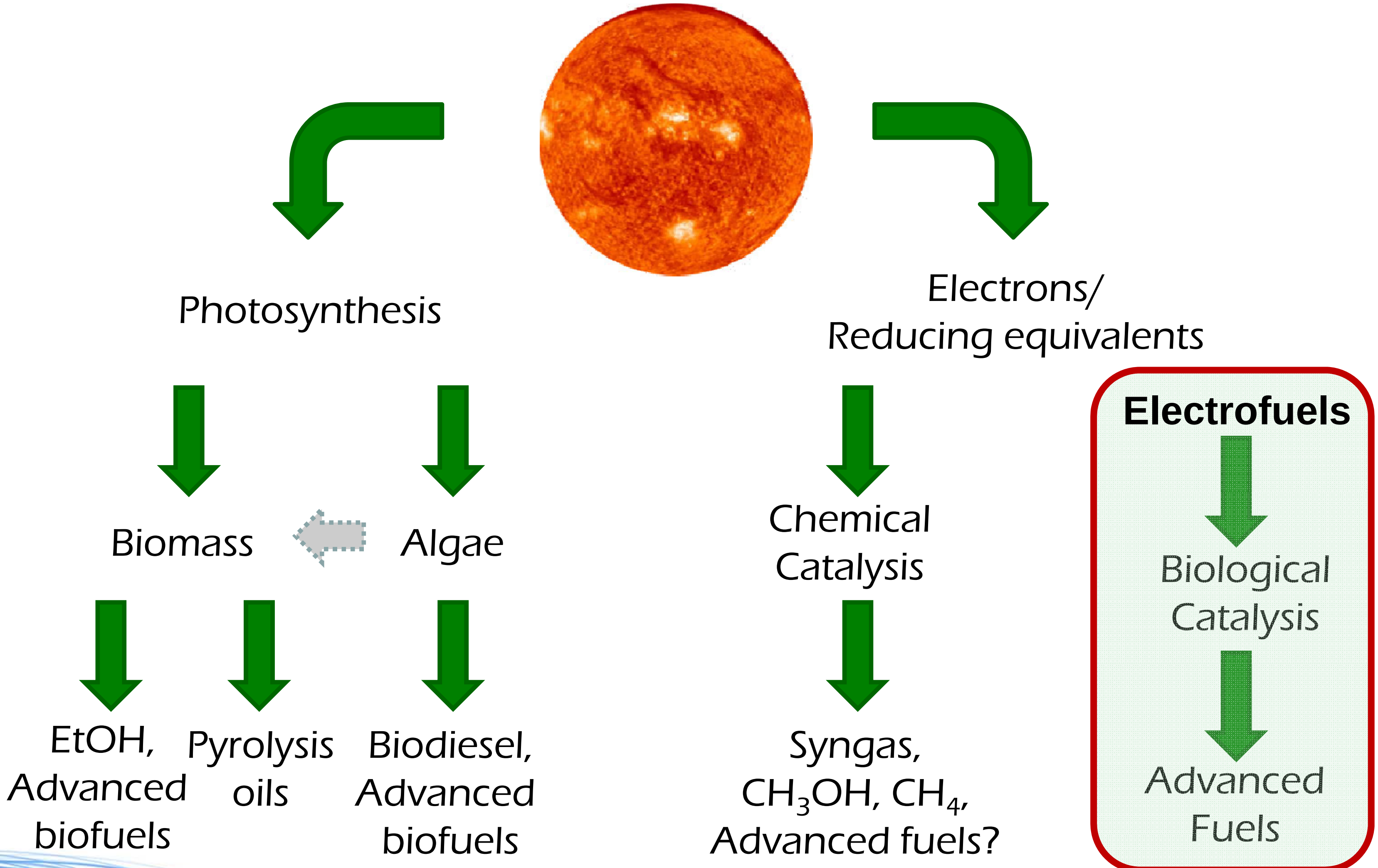
Original vision of the program focused on the opportunity to utilize renewable electrons to power Electrofuels production…



Strategic vision has evolved as the program has matured and new insights have come to light

Original Concept(s)
(e.g. standalone next to wind farm)

NEW INSIGHT →
Sourcing CO_2
Systems Level Analysis

"Near-term" Concept(s)
(e.g. "co-gen like")

Originally vision of CO_2 sourced from coal/NG electricity production
- Systems level analysis suggests this is an inefficient way to GTL/CTL
- Also not likely to qualify as a biofuel

Electricity & CO_2

1. Biofuels production releases up to 1/3 of total carbon feedstock as CO_2
   - e.g. Sugar-to-fuel fermentation releases 2/6 carbon from every sugar molecule
   - Extremely pure and concentrated CO_2 stream
2. CO_2 from geothermal could enable Iceland/Japan to become "oil" producers

H_2 & CO_2

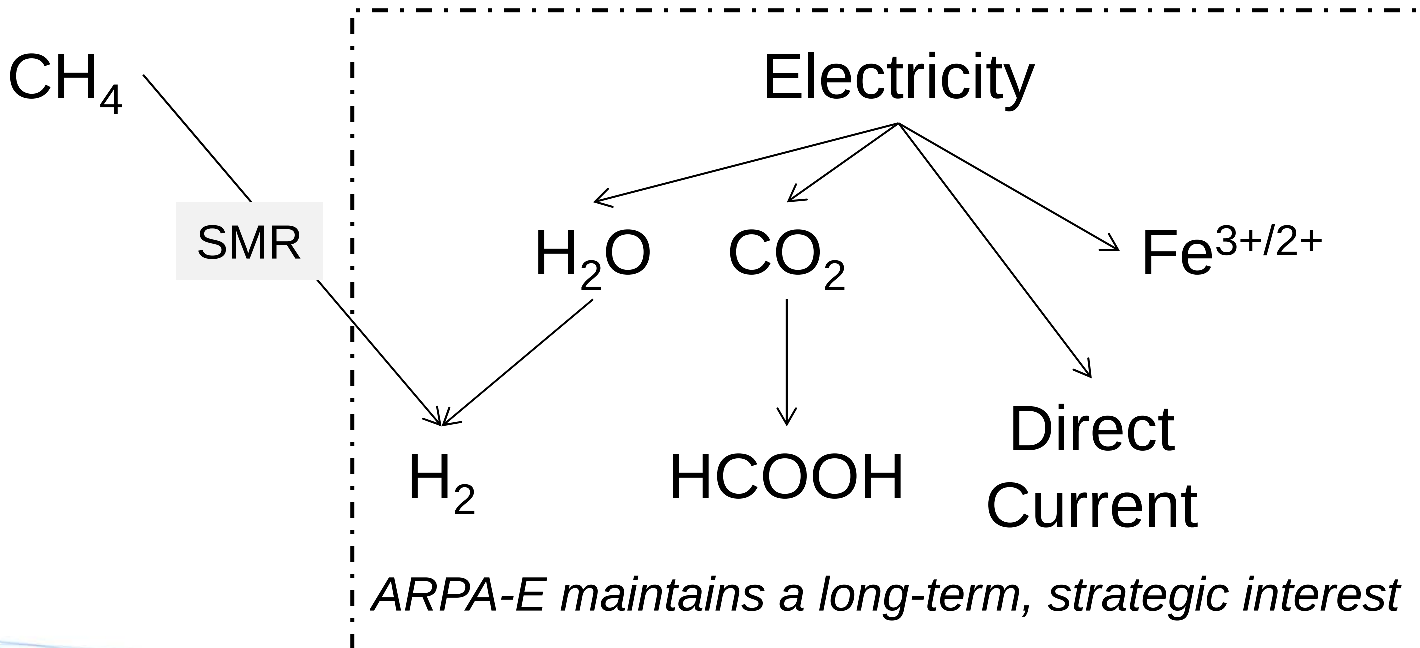
1. GTL/XTL using Electrofuels to convert CO_2/H_2 into fuel
2. Opportunity to couple fuel and ammonia production in same reactor

Certain feedstocks are advantaged and more near term due to particular market opportunities

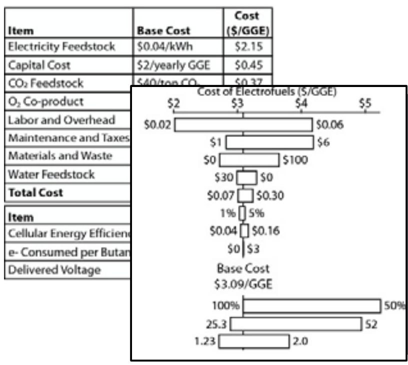
South African Company to Build U.S. Plant to Convert Gas to Liquid Fuels

By CLIFFORD KRAUSS
Published: December 3, 2012

sasol
reaching new frontiers



ARPA-E conducted techno-economic analysis (TEA) to compare Electrofuels to other biofuel/fuel approaches



ARPA-E built a preliminary model to explore operating costs

Selected representative examples where a process could be envisioned

Built general models to explore the diversity of the program

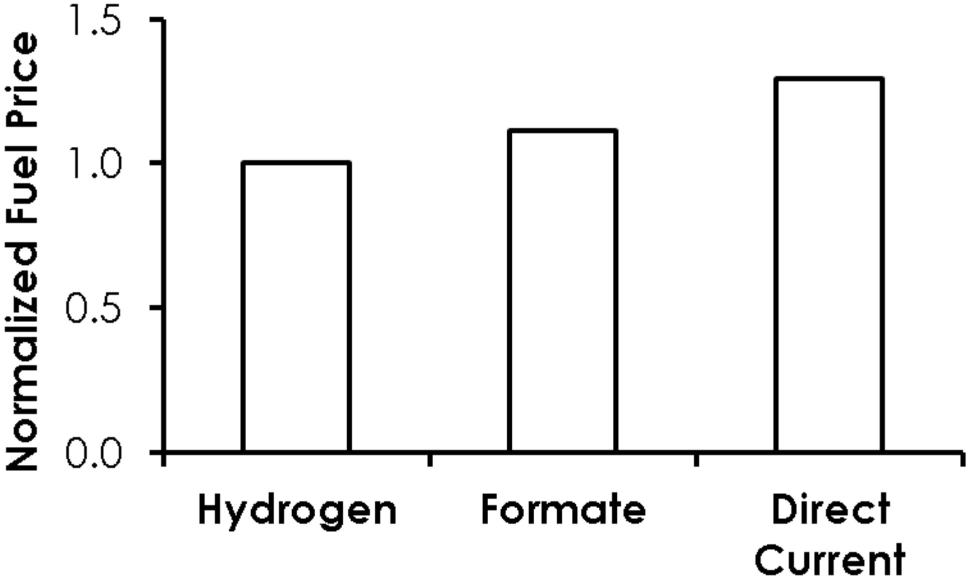
Expanded and improved the model to assess capital costs

Added precision around cost of reducing equivalents

ARPA-E and NREL specifically addressed hydrogen, formate, and direct electrosynthesis in first iteration of the models

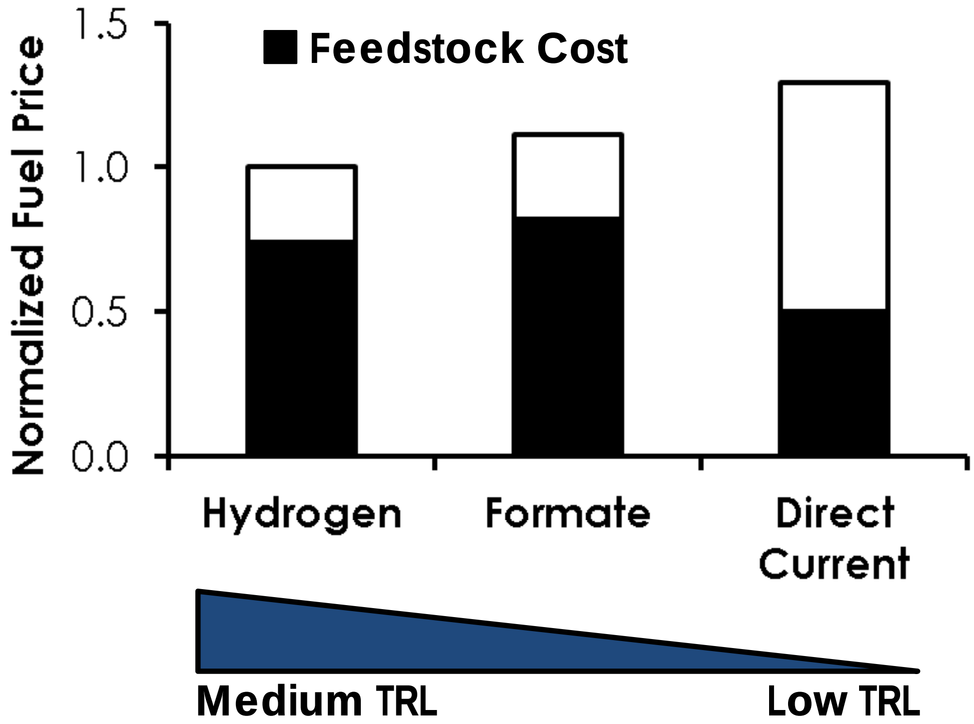
<u>Hydrogen:</u> H_2 → NADH, ATP + CO_2 → Calvin Benson Cycle	
H_2 can be generated from H_2O with high efficiency	High costs associated with improvements in gas mass transfer
<u>Formate:</u> CO_2 + $2H^+$ + 2e- → HCOOH → CO_2 + NADH + H^+ → Calvin Benson	
Formate is readily soluble and a source of energy and CO_2	CO_2 reduction to formate requires large overpotential and energetic cost
<u>Direct Current:</u> Direct current + CO_2 → Wood-Ljungdahl	
High columbic efficiency to acetate	Low current density and high CapEx cost

TEA comparison of representative approaches using electricity as feedstock



- Apples-to-apples comparison using the same feedstock and producing the same final fuel molecule
- Compares the cost of assimilating electrons and fixing carbon dioxide to a final fuel

Despite TRL disparity, the target cases show similar cost of production, however feedstock dominate



Technologies are needed to reduce the cost burden of feedstocks and improve performance

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What technologies are needed to take advantage of low cost feedstock?

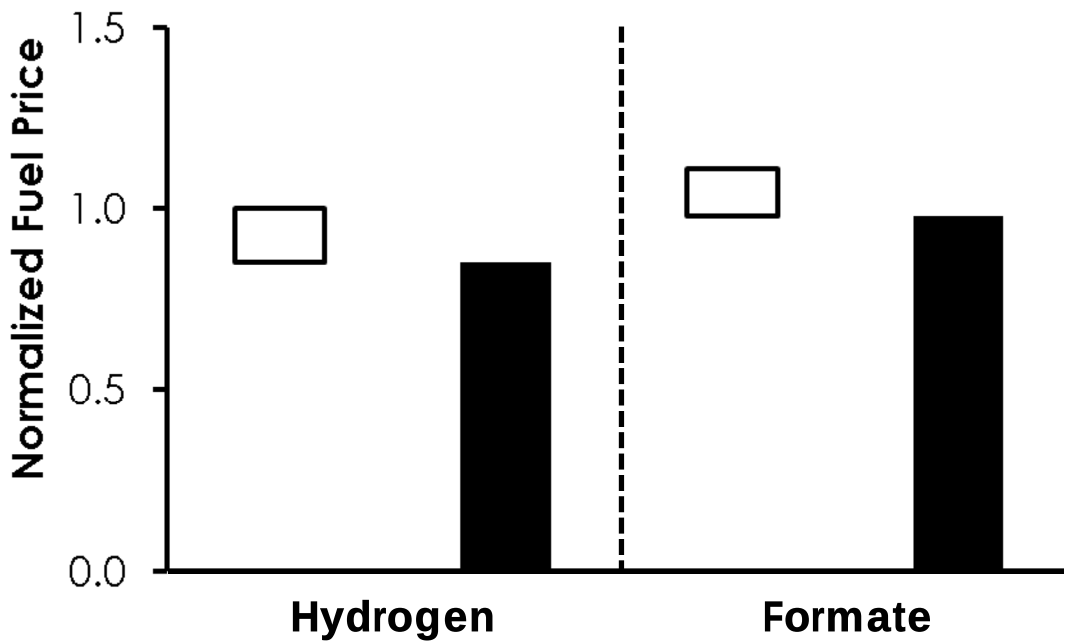
Efficient use of Feedstocks

- Efficient carbon fixation pathways
- Fuel assimilation pathways with minimal ATP requirements

Access to Cheap Feedstocks

- Cheap capital that can be deployed with low capacity factors
- “Energy storage” by accumulating acetate or formate with intermittent electricity supply for later conversion to fuel
- Small, modular deployment

Relative cost savings of switching to a more efficient carbon fixation pathway



By addressing these, we can go after niche opportunities in early deployment scenarios

- **H_2/CO/CO_2 energy source**
  - Ethanol refinery bolt-on
  - Geographic niches with resource availability
    - TX = cheap wind e- & EOR CO_2
    - ND = natural gas processing with wind
    - Iceland & Japan = geothermal for e- and CO_2
- **Electricity as energy source**
  - Intermittent renewable electricity and opportunity for energy storage as formate/acetate

Challenges and opportunities identified in the RFI

- New materials and scalable reactor technologies to improve gas to liquids mass transfer
- Development of microbial systems capable of assimilating energy from multiple sources (e.g. H_2, CO, and HCOOH)
- Power/feedstock costs
- Real-time protein expression control systems
- *In situ* hydrogen generation
- Deployment opportunities targeting cheap feedstocks, resources, and permitting
- Reactor capable of operating as a dispatchable load

Challenges to be explored in the afternoon breakout session

- **H_2/CO/CO_2**
  - Fuel production rates of 10 g/L/hr
  - Efficient carbon fixation pathway (e.g. not Calvin cycle)
  - High gas transfer without high pressure reactor
  - H_2 from CH_4, biomass, e^-
  - Scale to 10,000 BOE/d (150M gal/yr)

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Challenges to be explored in the afternoon breakout session

- **Formate**
  - Current density of 200 mA/cm^2
  - Overpotential of 0.2V
  - Selectivity of HCOOH::H_2 of 95%
  - Fuel production rates of 10 g/L/hr
  - Efficient carbon fixation pathway (e.g. not Calvin cycle)
  - Electrochemical reactor at 1 bar
  - Intermittent formate production, with continuous fuel production
  - Formate accumulation of 25 g/L (production, toxicity)
  - Scale to 1000 BOE/d (15M gal/yr; 70 MW)

Challenges to be explored in the afternoon breakout session

- **Direct Current**
  - Current density of 50 mA/cm^2
  - Overpotential of 0.2V
  - Selectivity of $e^-::H_2$ of 95%
  - Fuel production rates of 2 g/L/hr
  - Coulombic efficiency to fuel of 90%
  - Intermittent electricity delivery
  - Intermittent acetate production, with continuous fuel production
  - Acetate accumulation of 60g/L (production, toxicity)
  - Scale to 1000 BOE/d (15M gal/yr; 70 MW)