The Future of Sustainable Transportation Fuels Forum

Webinar 3: Recycling CO_2 to Liquid Hydrocarbon Fuel

LightSpeed Solutions

Secure Energy · Sustainable Fuels

Future of Sustainable Transportation Fuels Forum

Ellen B Stechel
Deputy Director,
ASU LightWorks
Managing Director,
Light*Speed* Solutions

Light*Speed* Solutions, an initiative of Arizona State University LightWorks in partnership with the Security and Sustainability Forum is hosting **The Future of Sustainable Transportation Fuels Forum**, a free four webinar series to engage the range of future fuels stakeholders in online conversations about the future of sustainable transportation fuel production and use.

Edward Saltzberg
Managing Director,
Security & Sustainability Forum

LightSpeed Solutions
Secure Energy • Sustainable Fuels

ASU LightWorks
ARIZONA STATE UNIVERSITY

SECURITY & SUSTAINABILITY FORUM
Convening Global Experts to Guide Decision Making

Forum details

The Future of Sustainable Transportation Fuels Webinars

- Anchoring Themes
- Coupling the Electric Power & Transportation Sectors
- Recycling CO_2 to Liquid Hydrocarbon Fuels – **July 28**
- Challenges and Opportunities in Designing Good Metrics to Assess Promise – **August 26**

Watch recordings at Light*Speed*Solutions.org

Light*Speed*Solutions.org

LinkedIn

The Future of Sustainable Transportation Fuels Group

Promotional Partners

Environmental Law Institute

CAAFI – Commercial Aviation Alternative Fuels Initiative

NASEO – National Association of State Energy Officials

ASERTTI

frontiers

ACORE – American Council On Renewable Energy

SOFI – Solar Fuels Institute

SERC – Solar Energy Research Center

the center for negative carbon emissions

Moderator

Thomas Seager conducts research related to environmental decision making and life-cycle environmental impacts of alternative energy technologies. He currently leads a project funded by the National Science Foundation that applies game theory to develop new strategies for teaching ethical reasoning skills relevant to sustainability, science, and engineering graduate students.

Dr. Seager joined the School of Sustainable Engineering and the Built Environment at Arizona State University in 2010, and has previously taught at Rochester Institute of Technology and Purdue University.

Agenda

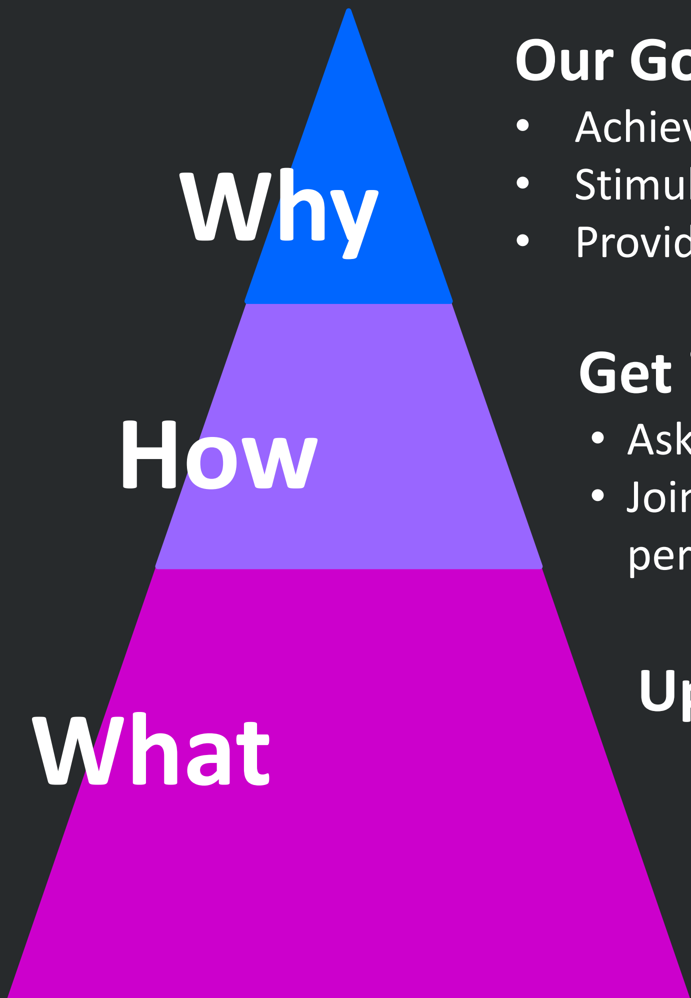
1. Overview and Introductions: **Thomas Seager**
2. Presentations
   a) **Klaus Lackner,** Center for Negative Carbon Emissions, ASU
   b) **Timothy Zenk,** Algenol
   c) **James E. Miller,** Sandia National Laboratories
3. Panel Discussion
4. Audience Questions *(submit through the side panel)*

(Please Take the Brief Exit Survey)

Forum introduction

Our ability to solve a problem is limited [only] by our conception of what is feasible

— Russell L. Ackoff, The Art of Problem Solving: Accompanied by Ackoff's Fables



Our Goal

- Achieve a sustainable low net carbon transportation future
- Stimulate conversation about a broad innovation space
- Provide useful input for policy and regulation

Get involved

- Ask questions for the panelists
- Join the associated LinkedIn discussion group and offer your perspective

Upcoming monthly webinar

- **Challenges and Opportunities in Designing Good Metrics to Assess Promise (August 26)**

Webinar series goals

To further the conversation on achieving a sustainable low net carbon transportation future

- To accelerate the transition and promote economic efficiency
- To convey where technical advances and better understanding are opening up opportunities to consider a broader range of options

To stimulate additional conversation and prove to be a starting point on exploring alternatives

- To offer a range of viewpoints, but won't be comprehensive and won't be providing "the answer(s)" nor debate perspectives
- To highlight new innovation spaces and ultimately assess promise of early stage technologies
- To further innovation and to further the conversation from a wide range of viewpoints and expertise
- To provide useful guidance for decision-makers, including policy makers and regulators

Webinar panelists

Klaus Lackner is the director of the Center for Negative Carbon Emissions and a professor at the Ira A. Fulton School of Engineering at Arizona State University. Dr. Lackner's recent research interests include closing the carbon cycle by capturing carbon dioxide from the air, carbon sequestration, carbon foot-printing, and innovations in energy and infrastructure systems.

Timothy Zenk is the Executive Vice President of Business Development for Algenol and formerly served as senior vice president of corporate development for Sapphire Energy, Inc. Zenk has years of leadership and notable success with public and privately held companies, including Sapphire Energy, Edelman Global, and Telecommunications Systems. In addition, he has held key roles in government, working for presidential administrations, U.S. congressional members and state governors.

James E. Miller is a chemical engineer who has been involved in energy, materials, and chemical processing research at Sandia National Laboratories for over 23 years. His work has touched on diverse topics ranging from hydroprocessing, to oxidation, lignin depolymerization, treatment of radioactive waste and automobile exhaust, and desalination. Over recent years his efforts have been largely focused on solar thermochemistry for the production of synthetic fuels from carbon dioxide and water, and for the past year on metal oxide-based thermochemical energy storage.

the center for negative carbon emissions

Closing the Carbon Cycle For Liquid Fuels

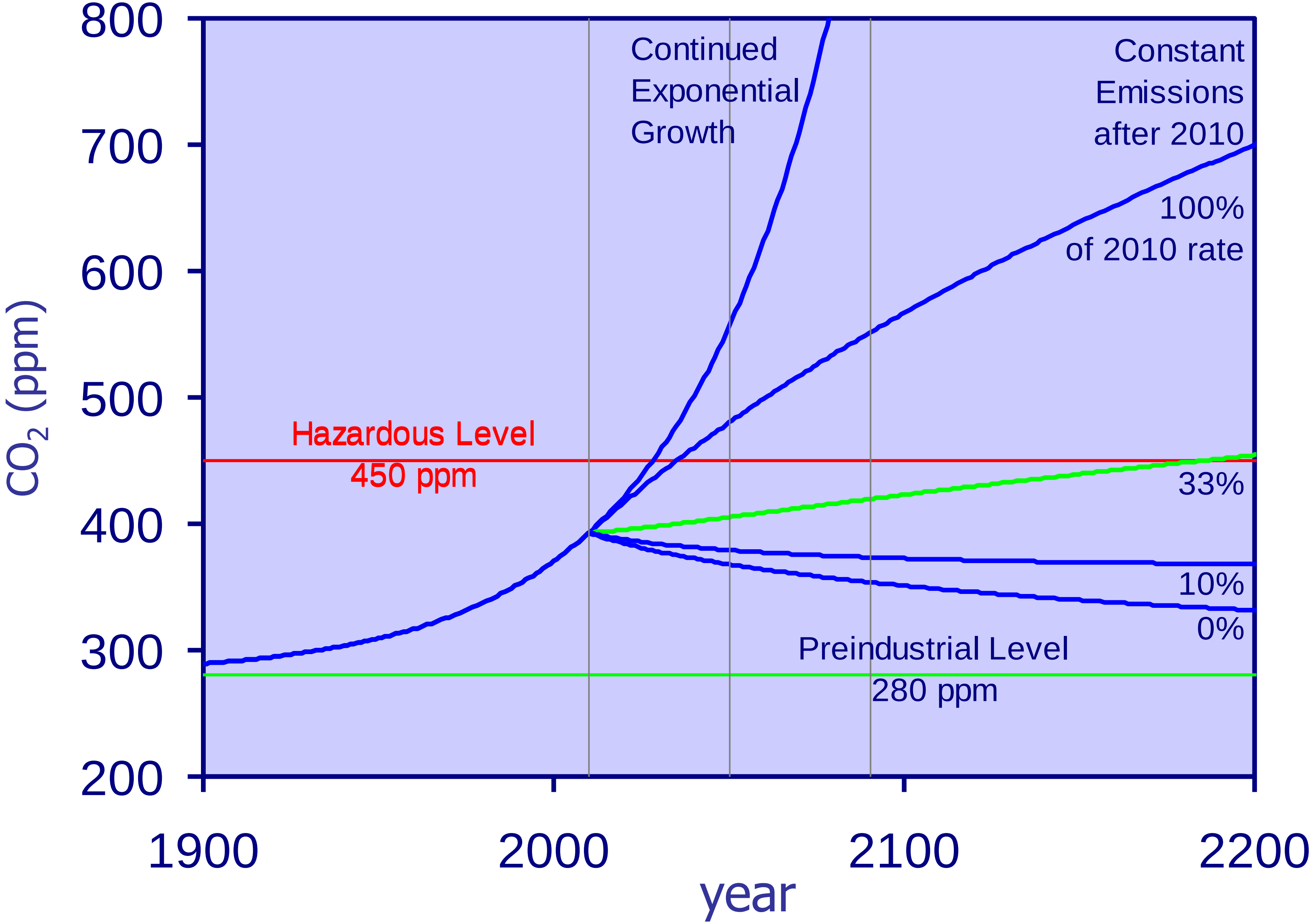
Klaus S. Lackner

Arizona State University

July 2015

ASU IRA A. FULTON SCHOOLS OF engineering

Stabilizing atmospheric CO_2 implies net zero emissions



Balancing the Carbon Budget

For every ton of carbon taken from the ground another ton must be returned

For every ton of carbon dioxide added to the atmosphere another ton must be removed

In the meantime temperatures will rise

Time is short

~ 30 tons C for every person on the planet will lead to 450 ppm

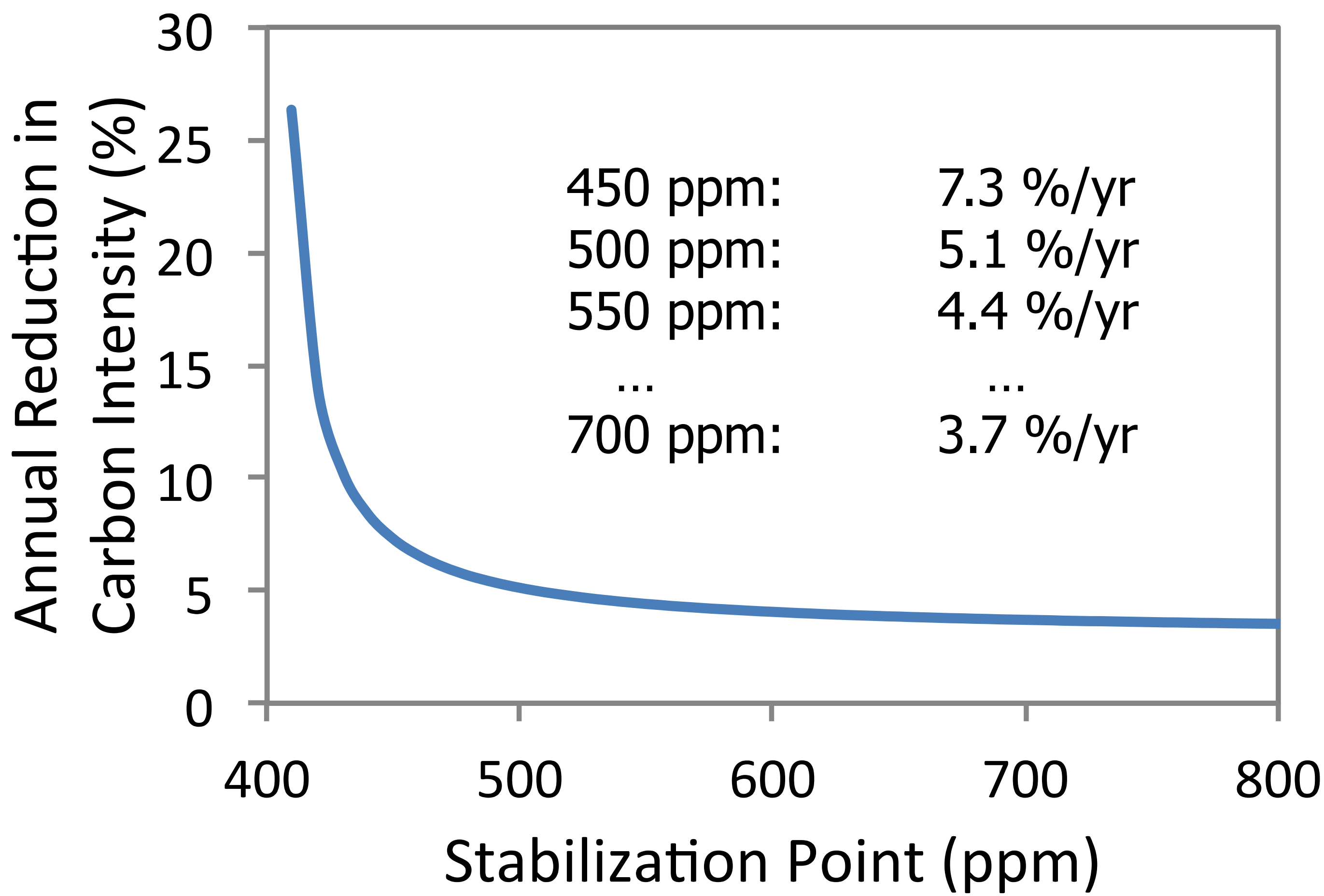
Total permanent allotment

Picture from emercedes online blog: http://www.emercedesbenz.com/Aug08/08_001327_Mercedes_Benz_Econic_Semi_Trailer_Tanker_Trucks_Enter_Service_At_London_Farnborough_Airport.html

Economy must decarbonize fast

Required annual reduction in the world's carbon intensity (CO_2/GDP)

Implied time scale 15 to 22 years



Overcoming 3% growth (economic + population)

Closing all carbon cycles

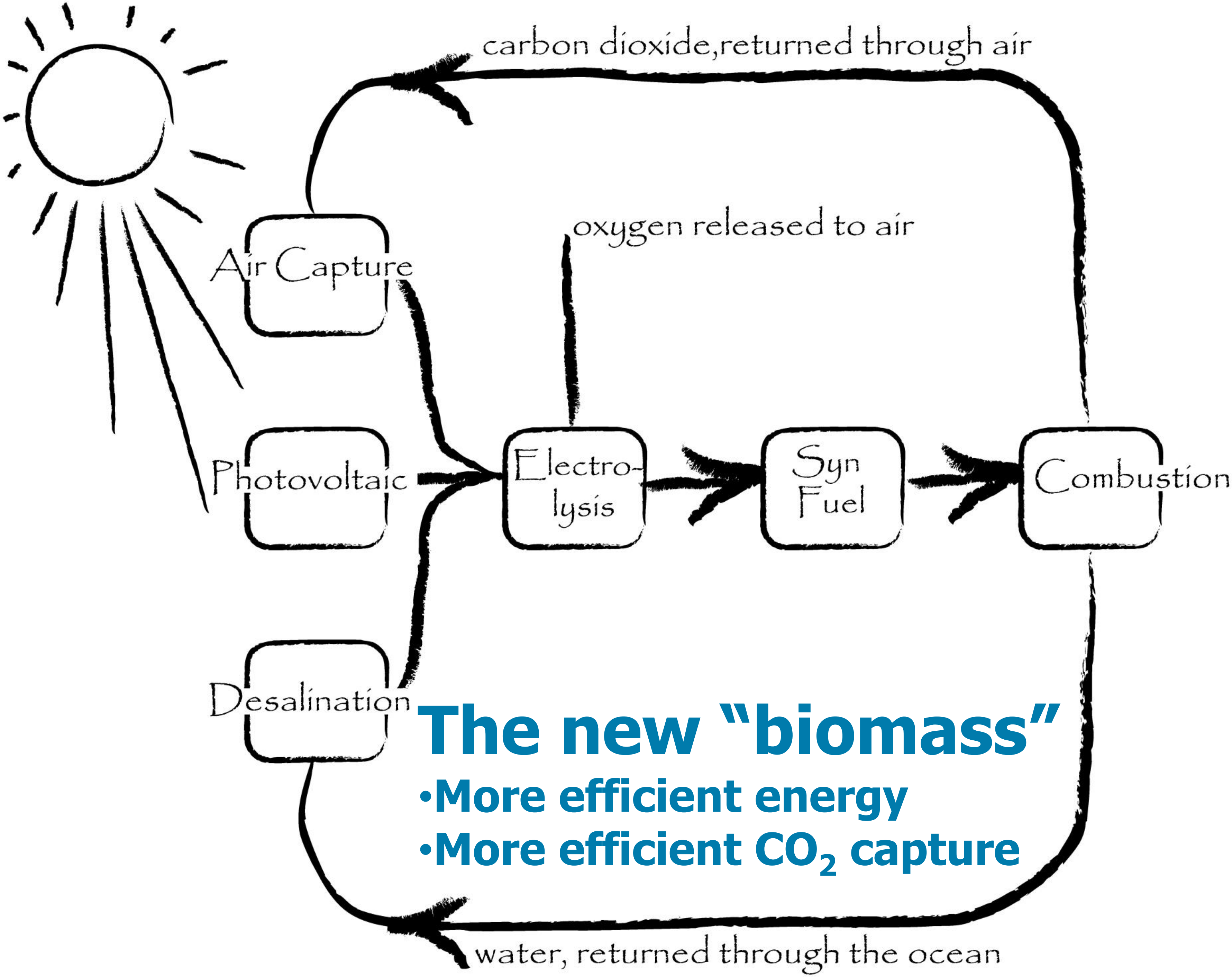
while providing ample electricity and liquid fuels

- **Eliminate emissions from point sources**
  - Mainly electricity generation
  - Capture & storage cannot reach zero emissions
    - 90% capture at coal plant reduces emissions by 75%
- **Reach net-zero emission from distributed sources**
  - Mainly applies to liquid fuels in the transport sector
    - Aviation, ships, and road vehicles
    - High energy density and stability make liquid fuels valuable
- **Cancel out overshoot emissions**
  - Potentially insatiable demand for CO_2 storage
  - High demand would prevent cost of storage from coming down
    - Future additional cost burden for fossil fuels

Produce valuable liquid fuels without fossil carbon from CO_2, H_2O and non-fossil energy

Ultimately, the CO_2 must come from the air

- **Biomass cycle – bio-crop or algae based fuels**
  - Open field agriculture incorporates natural air capture
  - Bioreactors rely on technical air capture
- **Direct thermochemical or electrochemical fuel cycles**
  - Conversion of CO_2 and H_2O into liquid fuels with non-fossil energy
  - Must rely on technical (direct) air capture
- **Utilizing fossil CO_2 from point sources**
  - Can only be a stepping stone toward zero emissions
  - Carbon flow in the environment has not been stopped
    - Dirty electricity or dirty fuel?



The new “biomass”

- More efficient energy
- More efficient CO_2 capture

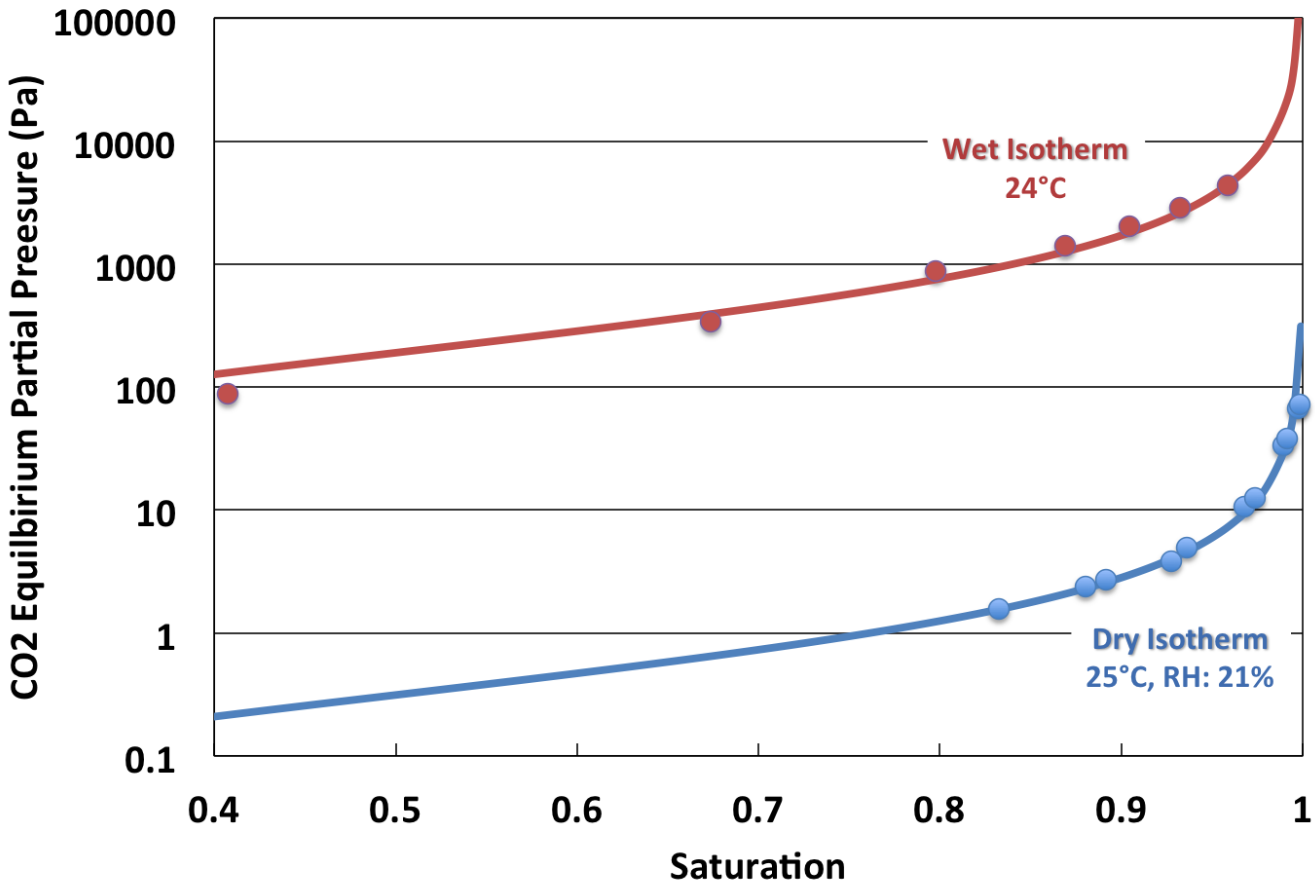
Air Capture: Feasibility & Affordability?

CO_2 in air is dilute and air is full of water

- **Sherwood's Rule suggests that costs scale linearly in dilution**
- **The air carries 10 to 100 times as much H_2O as CO_2**
- **First-of-a-kind apparatus is expensive (APS study: $600/t)**

The Moisture Swing

Novel sorbent whose affinity to CO_2 is controlled by moisture



Tao Wang et al

Strategies for cost reductions

- **Use passive collectors to avoid Sherwood's Rule**
  - Cost need not scale linearly with dilution (uranium from seawater)
  - Passive collectors
- **Match sorbent material to the problem**
  - Moisture swing, low energy consumption
  - Desorbing water during CO_2 sorption avoids water collection
- **Harness cost reductions from mass production**
  - Learning curves can give orders of magnitude cost reductions
  - This makes a priori cost estimates virtually impossible

Taking advantage of the resources in the air

Integration with the power grid

- **Intermittent, renewable energy**
  - needs time-flexible consumers
  - Needs storage to shift energy for days, weeks, and months
- **Liquid fuels need cheap power**
  - 2¢/kWh adds $1.60 to the gallon of gasoline
  - $100/ton of CO_2 from air capture adds $0.85 per gallon
  - Fuel production can take advantage of price fluctuation
- **Time flexible demand can balance load**
  - Fuel production can be intermittent and be limited to times of low electricity cost
  - Low utilization demands low capital cost of electrolysis equipment
- **Ease of storage allows liquid fuels to provide backup power**
  - For long-term storage, low cost fuel storage wins out over efficient battery storage

Sustainably produced liquid fuels made from carbon extracted from the air and hydrogen extracted from water can overcome the intermittency of a renewable based power grid

ALGENOL BIOFUELS

Harnessing the sun to fuel the world®

Utilization of CO_2 to produce low carbon fuels

Presentation July 2015

Tim Zenk

Photosynthesis is the best carbon recycler

Nearly 260 billion tonnes of CO_2 are consumed by photosynthesis annually

Algae are the best at photosynthesis

More than 40% of CO_2 is consumed through algae

Algenol's platform algae is best in class

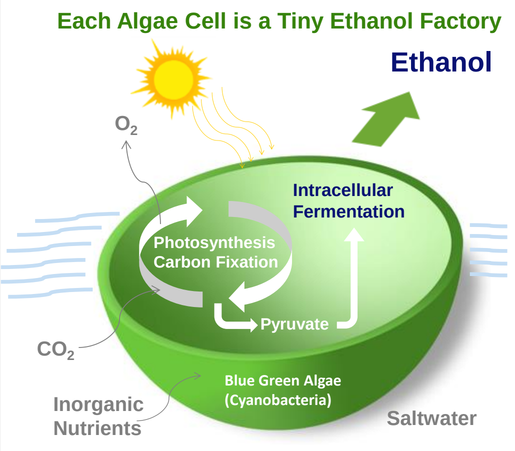
Algenol’s industrial strains are among the most productive photosynthetically active algae on the planet, consuming 75 tonnes of CO_2 per acre per year

Algenol’s algae is the best carbon recycler

Disruptive Core Technology

Algenol's Direct to Ethanol® process has three core components:

World's Most Productive Algae Platform



Proprietary enhanced algae make ethanol and biomass **directly** from CO_2, water, and sunlight

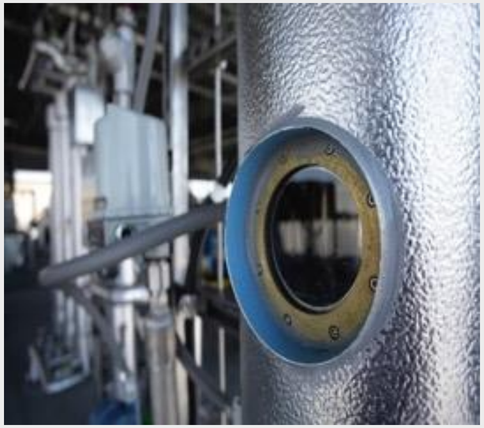
- **8,000 gallons per acre per year**
- 85% of the CO_2 is converted into products

Specialized VIPER™ Photobioreactors

Algae are grown in saltwater contained in proprietary PBRs that are exposed to the sun and are fed CO_2 and nutrients

- A production cycle runs 4 weeks
- Afterwards, the spent algae are separated from the water-ethanol mixture

Energy Efficient Downstream Processing



Water-ethanol mixture is sent to proprietary downstream processing equipment which separates and concentrates it into fuel grade ethanol

Spent algae are processed into a high grade green crude that can be refined into diesel, gasoline, and jet fuel

EPA OTAQ Already Uses Lifecycle Analysis

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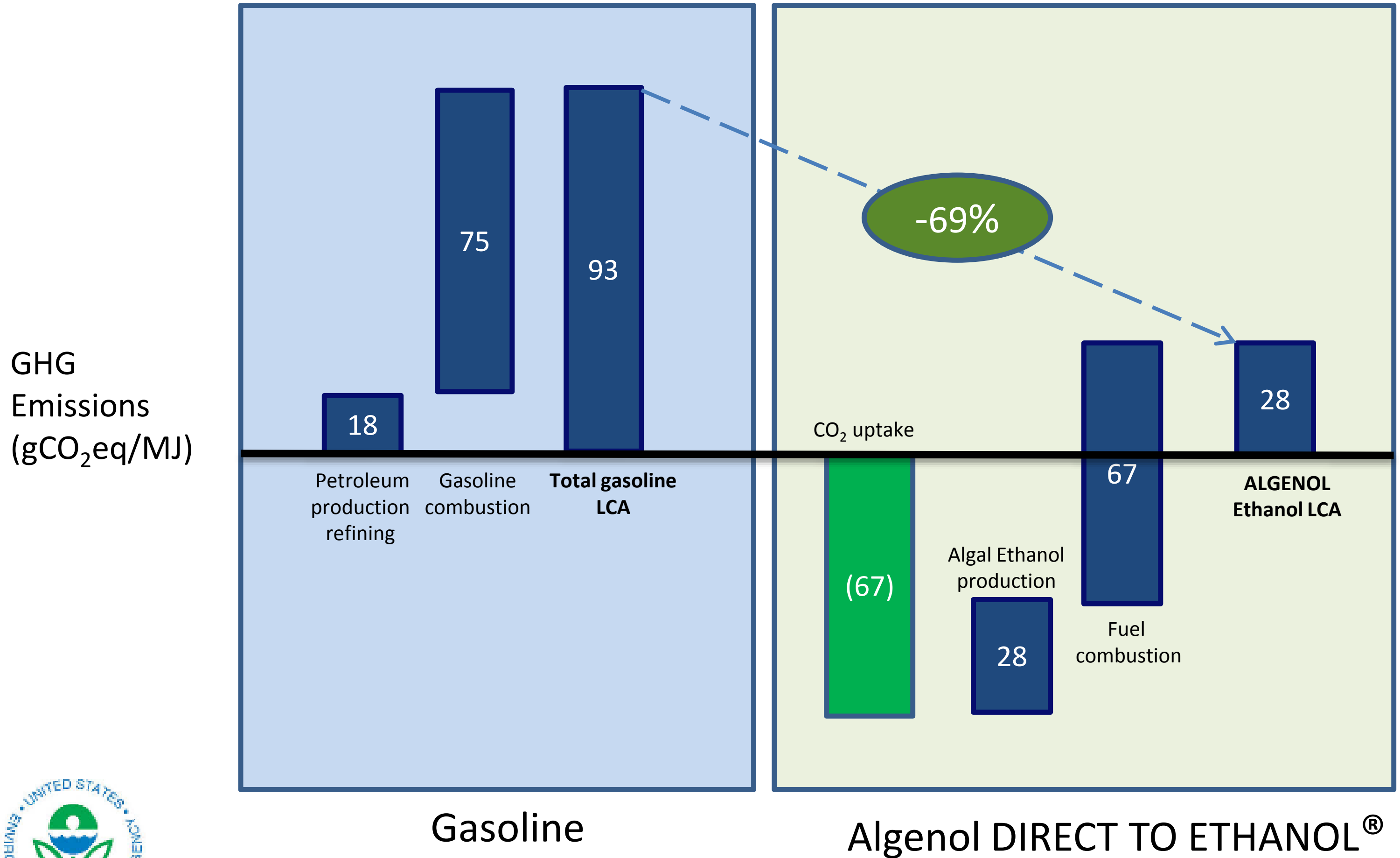
Algenol's pathway reduces Green House Gas (GHG) emissions by 69% compared to gasoline, as validated by the official EPA pathway approval process



This method accounts for carbon offsets, as would be needed with CCU

Official EPA approved pathway results

A Broad Set of Carbon Utilization Options

Companies	Energy & Fuels	Chemicals	Food & Feed
Accelergy		Biofertilizers	
Algenol	Ethanol, green crude		
Algix		Bioplastics	
Bioprocess Algae	Fuels		Fish/animal feed
Cellana	Biodiesel		Omega- 3 EPA, DHA Nutritional oils
Ferus	Enhanced Oil Recovery (EOR)		
Global Algal Innovations	Algal Oil	Polymers	Animal feed/protein
Joule Unlimited	Ethanol, renewable diesel		
Lanzatech	Fuels	Chemicals	
Sapphire	Green crude		Omega-3s
Skyonic		Bleach, Baking soda, hydrochloric acid	
Solazyme	Renewable diesel, renewable jet fuel	Oleochemicals, functional fluids	Algal protein, Algal flour
Synthetic Genomics			Omega-3s

Issues with EPA New Power Plant Rule

- Algenol, and many other industry players submitted formal comments on 111 b rule
- We are concerned that the rule does not include CO_2 utilization (CCU) as an option, which represent a missed opportunity
- The RIA did not account for the impact on this industry, or the potential reduced cost to ratepayers from CCU
- CCU is a proven technology that should be included in the final rule as a portfolio of options

Senate adds CCU to DOE List

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Sen. Manchin, WV, introduced a bill to add and 8th objective the department

Title 42 – Fossil Energy

The Secretary shall carry out research, development, demonstration, and commercial application programs in fossil energy, including activities under this part, with the goal of improving the efficiency, effectiveness, and environmental performance of fossil energy production, upgrading, conversion, and consumption. Such programs take into consideration the following objectives:

(1) Increasing the energy conversion efficiency of all forms of fossil energy through improved technologies.
(2) Decreasing the cost of all fossil energy production, generation, and delivery.
(3) Promoting diversity of energy supply.
(4) Decreasing the dependence of the United States on foreign energy supplies.
(5) Improving United States energy security.
(6) Decreasing the environmental impact of energy-related activities.
(7) Increasing the export of fossil energy-related equipment, technology, and services from the United States.

Subtitle E—Coal SEC. 3401. FOSSIL ENERGY.

Section 961(a) of the Energy Policy Act of 2005 (42 U.S.C. 16291(a)) is amended by adding at the end the following:

JAC15A18 S.L.C. 259

''(8) Improving the conversion, use, and storage of carbon dioxide produced from fossil fuels.''.




➢ Technology Maturation / Demonstration

- DOE-funded integrated algae biorefinery commercial demonstration projects in:
  - Florida (Algenol Biofuels)
  - New Mexico (Sapphire Energy)
- Pilot demonstrations with flue gas from variety of industrial sources:
  - Coal, other power plants
  - Cement, steel
  - Ethanol

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State of Algae Carbon Utilization Technology

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33-Acre Kauai Algae Facility

GLOBAL ALGAE INNOVATIONS

Distribution Statement "A" (Approved for Public Release, Distribution Unlimited)

ALGAE BIOMASS ORGANIZATION

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➢ BioProcess Algae

- 5-acre commercial demonstration in Shenandoah, IA, co-located with Green Plains corn ethanol plant
- Continuous operation since 2009 utilizing waste CO_2, waste heat, waste nutrients
- Markets: Fuel, fish/animal feed

bioprocessalgae
Valuing Carbon

AB
ALGAE BIOMASS ORGANIZATION


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State of Algae Carbon Utilization Technology

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➢ Supply contracts with major refiners

cellana

Sapphire Energy™

TESORO

ALGENOL BIOFUELS
Cleaner - Greener - Cheaper

Reliance Industries Limited

AB
ALGAE BIOMASS ORGANIZATION

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Global Strategic Partnerships

Sapphire / Sinopec
- Validate and deploy in China

Heliae / Sincere Corp
- Build first commercial facility in Japan

Solazyme / Bunge
- Manufacturing plant online in Brazil

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GHG Reduction Cost Curve

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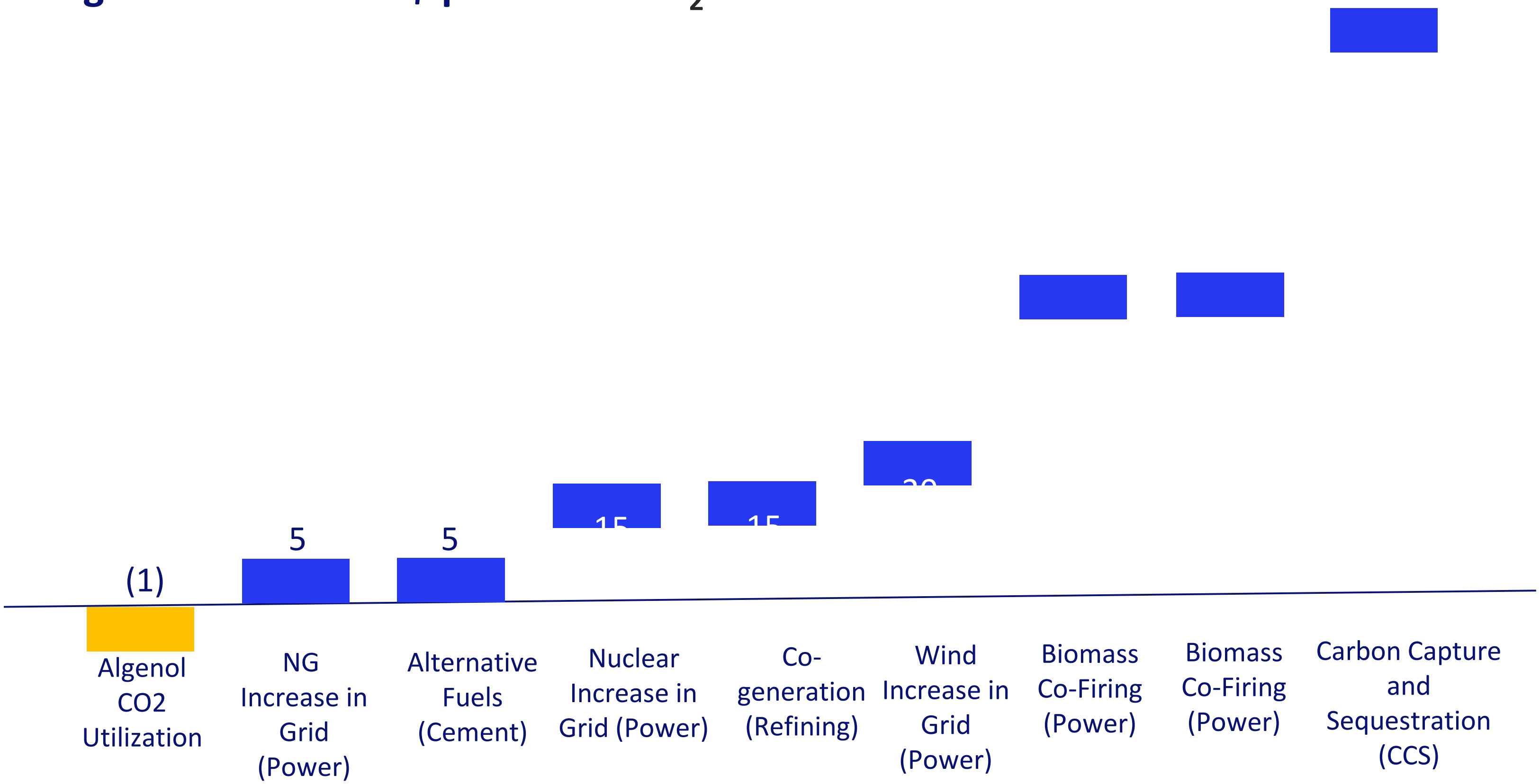
Current proposed "solutions" to GHG emissions involve additional investment or costs

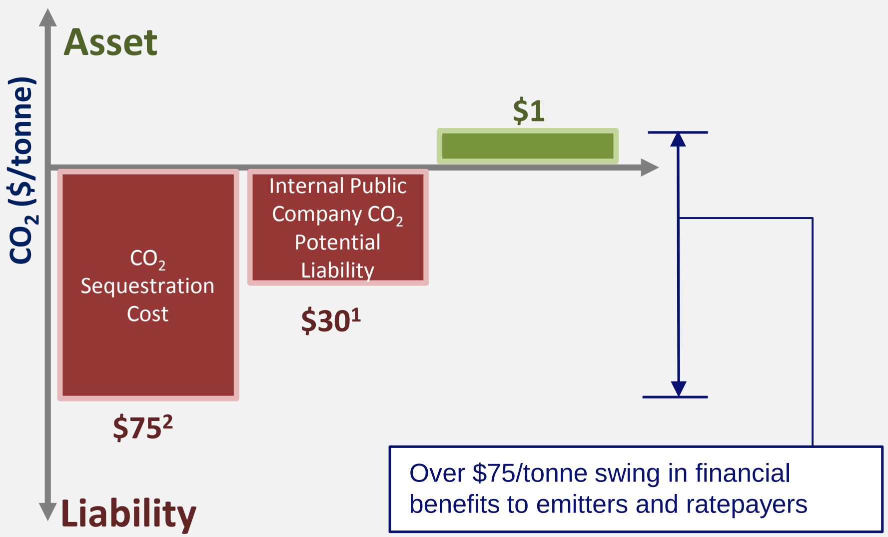
Mitigation costs in US$ per ton of CO_2 abatement



Sources: McKinsey's pathways to a low-carbon economy; IEA 2006; FAO, "Impact of the Global Forest Industry on atmospheric greenhouse gases", 2010; Climate Central, Aug. 2014

Algenol's $1 a Tonne Paradigm Shift – CO_2 Monetization

Algenol is the only solution that monetizes CO_2 through utilization, drastically altering the current paradigm by turning a liability into a revenue generating asset



Current CO_2 Paradigm vs. Algenol's Solution

- **Algenol pays emitters $1 a ton for industrial CO_2, utilizing it as a revenue generating feedstock**
- Current CCS plans could cost electric customers more $50 billion per year
- Displaces fossil fuels, providing real CO_2 reduction
- Policymakers achieve climate goals, consumers avoid $0.04 per kW increase on their bill

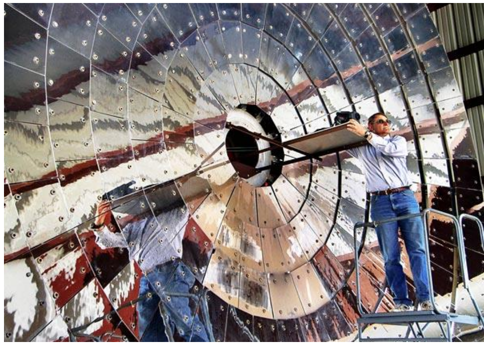
(1) Carbon Disclosure Project: Use of internal carbon price by companies as incentive or strategic planning tool
(2) McKenzie & Company: Pathways to a Low-Carbon Economy

--Timothy Zenk, EVP Business Development, tim.zenk@algenol.com

Exceptional service in the national interest

Sandia National Laboratories

solar.sandia.gov



Solar Thermochemistry for Producing Fuels from Carbon Dioxide and Water

Presented by James E. Miller

Sandia National Laboratories

Advanced Materials Laboratory

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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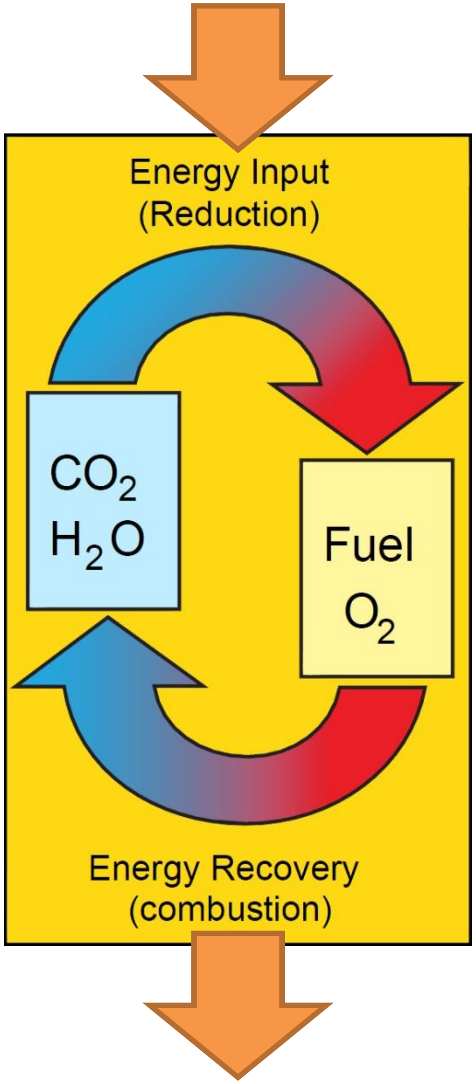
Closing the Cycle



For now and for transportation fuels, liquid hydrocarbons are the "Gold Standard"

Vision: ***Achieving many of the benefits of hydrogen while preserving the advantages of the Hydrocarbon Economy*** by effectively and efficiently reversing combustion, i.e. "energizing" CO_2 and H_2O back into hydrocarbon.

$$Sunlight + CO_2 + H_2O \rightarrow Fuel + O_2$$

Process should be analogous to, but more efficient than, those that produce bio and fossil fuels.

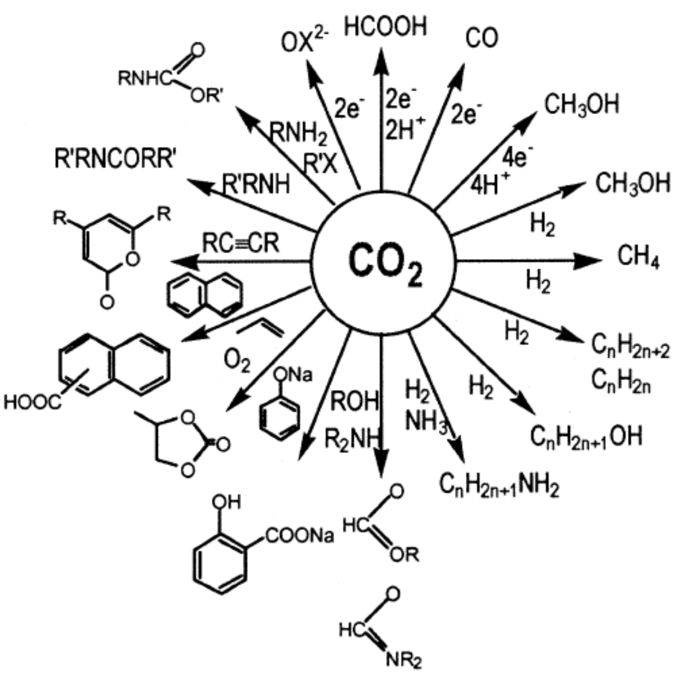
Capitalize on decades of Synfuel technology, e.g.

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$$

Why Fuels for CO_2 Utilization:

Fuels are the high impact Opportunity Space, Commensurate with CO_2 Production

CO_2 utilization chemistry (From Aresta, Studies in Surface Science and Catalysis 114,1998).



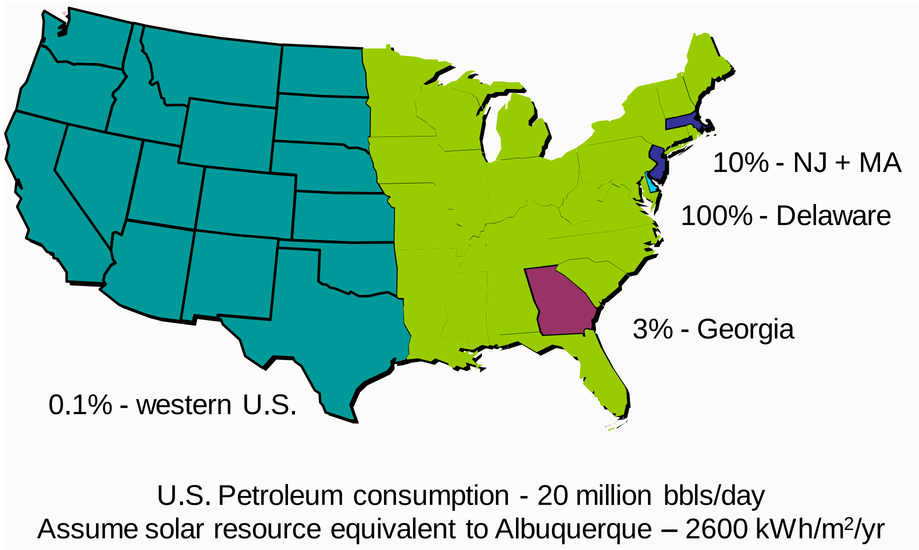
	2004 U.S. production (1,000 metric tons)	CO_2 equivalents* (1,000 metric tons)
Ethylene	25,682	80,641
Propylene	15,345	48,183
Ethylene dichloride	12,163	10,811
Top 3 U.S. Chemicals		139,635
U.S. Petroleum		2,458,000 (5.7%)
Petrol, Coal, NG		5,705,000 (2.4%)

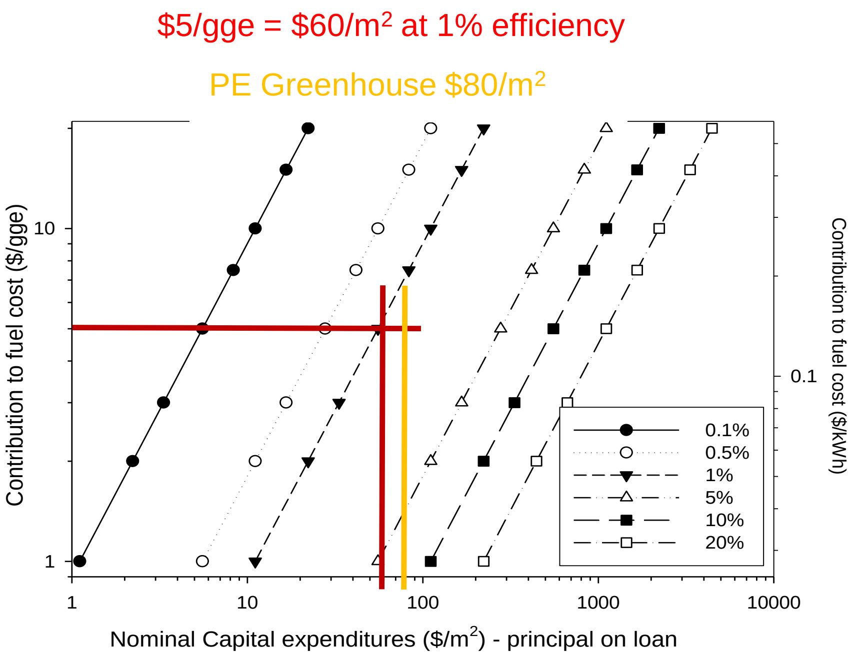
Sources: C&E News July 2, 2007; Report DOE/EIA-0573 (2004).
* Assuming 100% conversion of CO2 into the hydrocarbon, e.g. 2 moles of CO_2 would supply the carbon for 1 mole of C_2H_4.

Meeting a significant fraction of transportation fuel demand with solar fuels is certainly plausible!

Sandia National Laboratories

- ***High solar to fuel LC efficiency (>10%) is a requirement.***





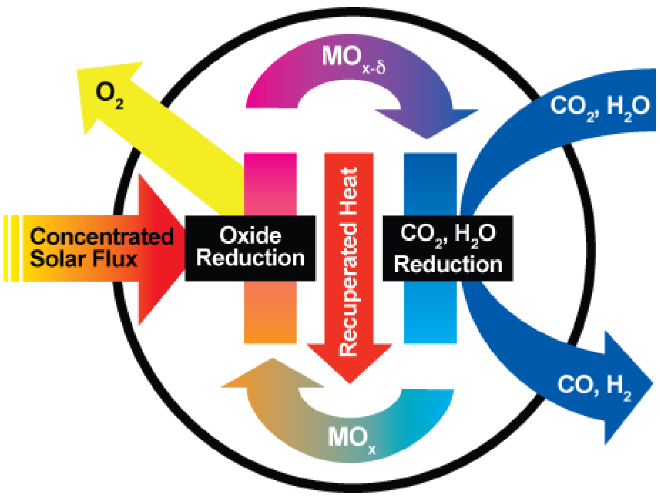
- ***Water, CO_2 are not limiting resources***
  - **Water consumption/cost relatively low – (may be spoken for)**
  - **High impact opportunity for CO_2 (short term stationary, long term air capture)**
- ***Consistent with other human activities occurring over multiple decades.***

E.B. Stechel and J.E. Miller "Re-energizing CO_2 to fuels with the sun: Issues of efficiency, scale, and economics" Journal of CO_2 Utilization, 1 (2013) 28–36.

Thermochemical Cycles: A Simple Concept …

Unfavorable reaction
e.g. $H_2O \rightarrow H_2 + ½ O_2$
divided into two more favorable reactions.

1) $1/\delta\ MO_x \rightarrow 1/\delta\ MO_{(x-\delta)} + ½ O_2$



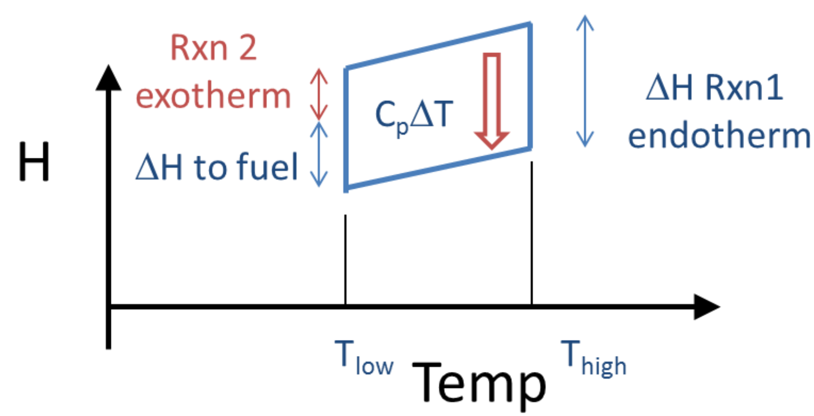
2) $1/\delta\ MO_{(x-\delta)} + CO_2 \rightarrow 1/\delta\ MO_x + CO$

3) $CO_2 \rightarrow CO + ½ O_2$

Fe_3O_4/FeO is the archetypical cycle

A thermochemical cycle is essentially an engine that converts heat into work in the form of stored chemical energy. ***Efficiency gains are possible as initial conversion to mechanical work and electricity are avoided.***

$$\Delta H_{endotherm} - \Delta H_{rxn\ exo} = \Delta H_{fuel}$$

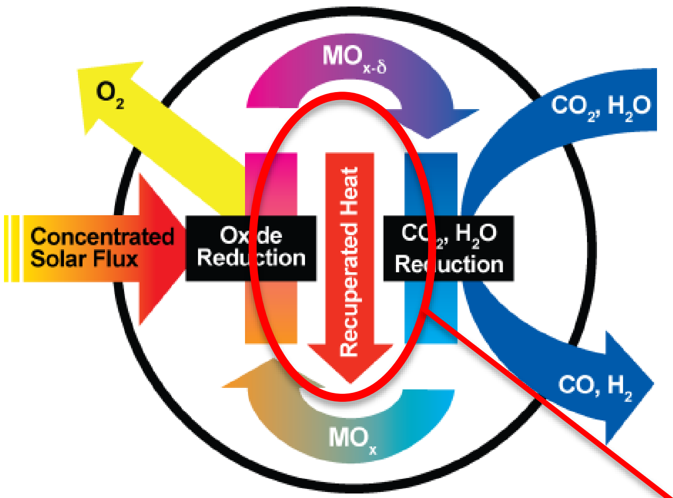


Thermodynamics require a temperature difference for the two reactions.

… With A Lot of Nuances to Doing it Well.

Unfavorable reaction
e.g. $H_2O \rightarrow H_2 + \frac{1}{2} O_2$
divided into two more favorable reactions.

1) $1/\delta\ MO_x \rightarrow 1/\delta\ MO_{(x-\delta)} + \frac{1}{2} O_2$

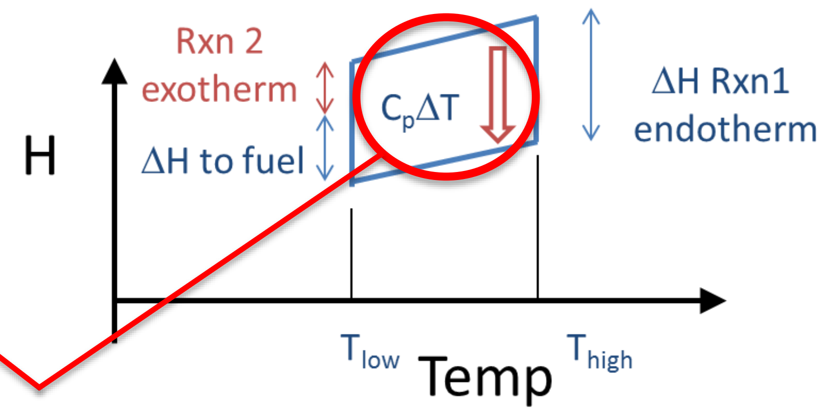


2) $1/\delta\ MO_{(x-\delta)} + CO_2 \rightarrow 1/\delta\ MO_x + CO$

3) $CO_2 \rightarrow CO + \frac{1}{2} O_2$

A thermochemical cycle is essentially an engine that converts heat into work in the form of stored chemical energy. ***Efficiency gains are possible as initial conversion to mechanical work and electricity are avoided.***

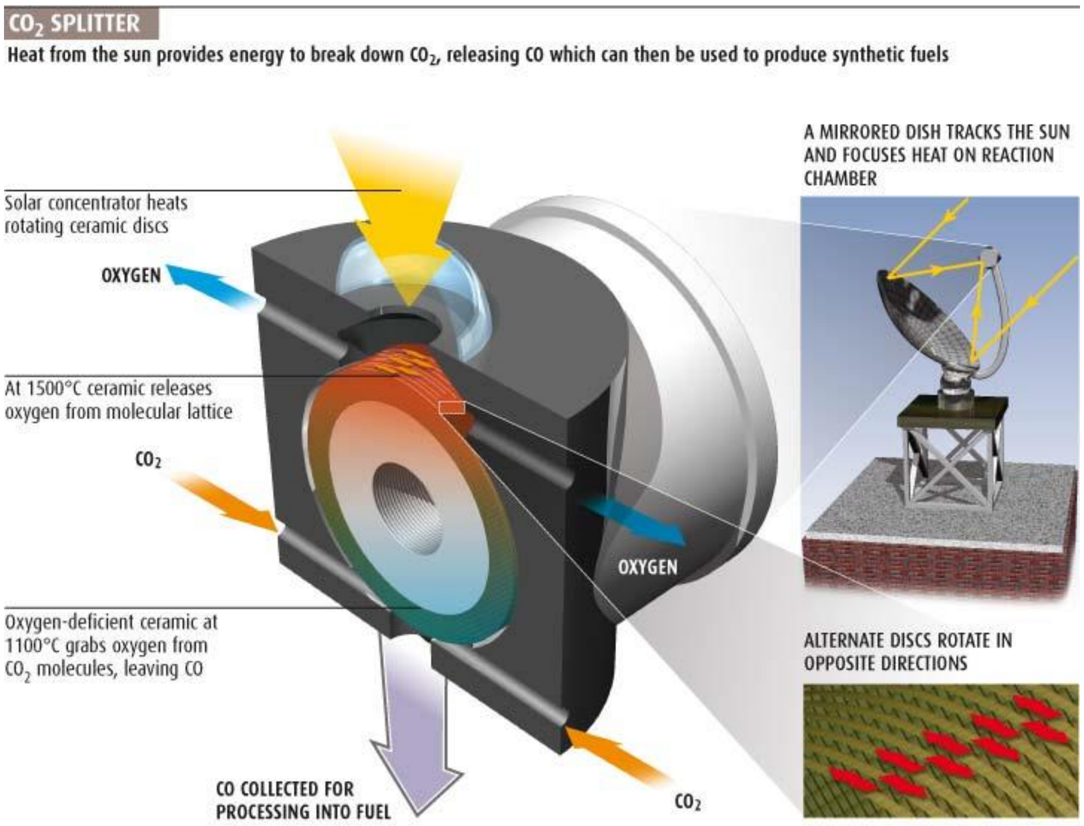
$$\Delta H_{endotherm} - \Delta H_{rxn\ exo} = \Delta H_{fuel}$$



Example: Managing Sensible Heat is Essential to Efficiency

CR5 : First-of-a-kind approach and our attempt to apply the lessons.

Counter-Rotating-Ring Receiver/Reactor/Recuperator (CR5)



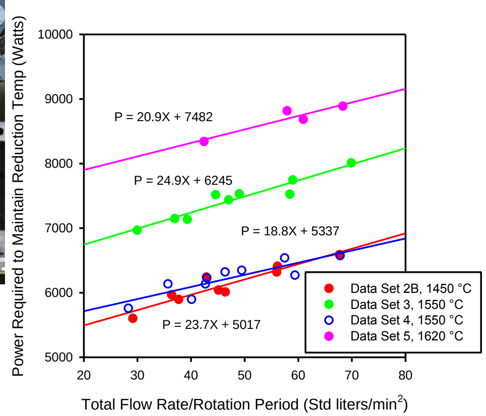
"Reactorizing a Countercurrent Recuperator"

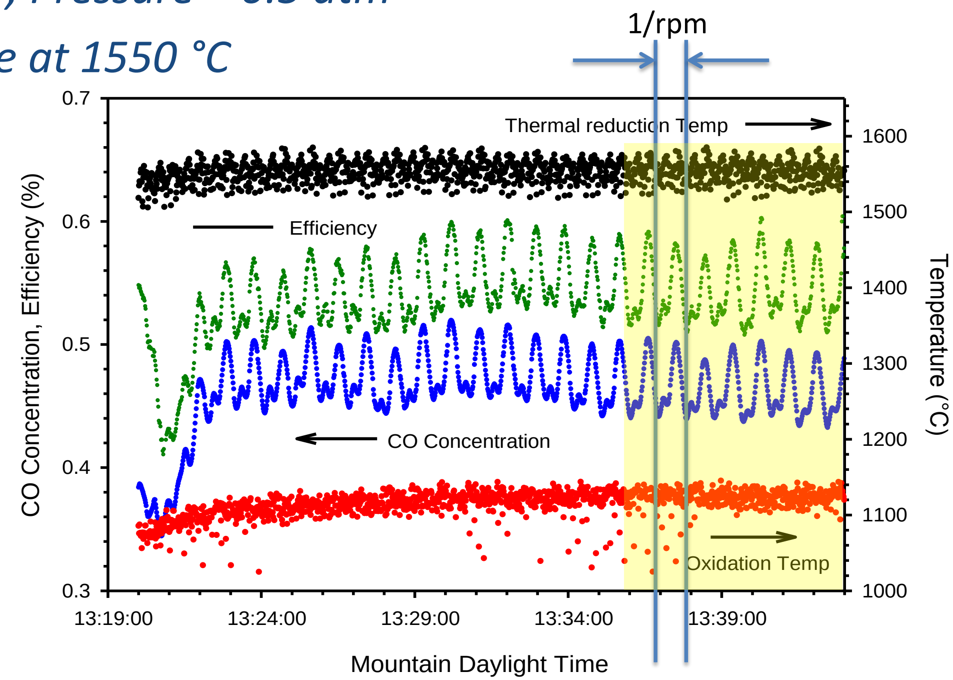
Continuous flow, Spatial separation of products, Thermal recuperation

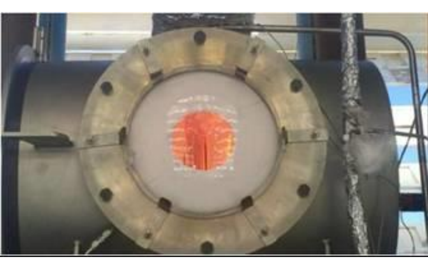
Performance Map of Gen-1 Prototype

Collect data to validate models, guide improvements

- *Ceria-based fins on rings*
- *6 Data Sets: Cold, 2@ 1450 °C, 2@ 1550 °C, 1620 °C*
- *3 ring rotation speeds, 3 CO_2 flow rates for each*
- *Constant Ar flow, Pressure = 0.5 atm*
- *Floating Pressure at 1550 °C*







J.E. Miller, M.A. Allendorf, A. Ambrosini, E.N. Coker, R.B. Diver, I. Ermanoski, L.R. Evans, R.E. Hogan, and A.H. McDaniel "Development and Assessment of Solar-Thermal-Activated Fuel Production: Phase 1 Summary" SAND2012-5658, July 2012

Take-home points

- For any approach to Solar Fuels- Efficiency is key for cost and scalability – 10% solar to fuel minimum (lifecycle)
  - Often it is unappreciated that sunlight is a “high cost” feedstock (capital cost)
  - Low efficiencies increase scale, further challenge efficiency and stretch resources.
  - CO_2 and water (and associated energy costs) are not limiting
- Thermochemical approaches have potential for high efficiency and thus high impact
  - Systems studies support idea of eventual economic viability – difficult but not implausible
  - Small global community has made significant advances in recent years
- Materials, Reactors, and Systems are all areas of opportunity and need
  - All impact efficiency, all relatively immature for this technology.
  - Adjacency to other technologies (e.g. solar electric, solar reforming) can help move technology forward, but focused cross-discipline efforts are also needed.

Solar fuels have the potential for transformational impact in our future energy mix.

Thank You.

Panel discussion

Sample discussion questions

1. **Some are convinced that recycling fossil CO_2 from stationary sources to fuels would impede a transition away from accumulating fossil carbon in the atmosphere and others that it would be an enabler.** *What is your viewpoint and what underlies your thinking?*
2. **Some are convinced that there would be no net *lifecycle* emissions benefit from recycling fossil CO_2 and others that the benefit would be significant.** *What is your viewpoint and what underlies your thinking*?
3. **Assuming recycling is an option worth pursuing then:**
   a) *What are the biggest technical and economic challenges in various CO_2-to-fuels technologies?*
   b) *What is the expected timeframe for development and deployment?*
4. **What are some important considerations for carbon policy (either to incentivize or to create barriers for CO_2 reuse and recycling) in general and/or specifically with regards to EPA's Clean Power Plan?**

The panelists

Moderator
Thomas Seager
Associate Professor, School of Sustainable Engineering and the Built Environment, Arizona State University

Klaus Lackner
Director, Center for Negative Carbon Emissions, ASU
Professor, School of Sustainable Engineering and the Built Environment, Ira A. Fulton School of Engineering

Timothy Zenk
Executive Vice President of Business Development, Algenol

James E. Miller
Principal Member of Technical Staff, Sandia National Laboratories

Upcoming webinars

Thank you for joining

Future of Sustainable Transportation Fuels webinars

Challenges and Opportunities in Designing Good Metrics to Assess Promise – **August 26**

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The Future of Sustainable Transportation Fuels Group