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Sunshine to Petrol: Reimagining Transportation Fuels

For more information:

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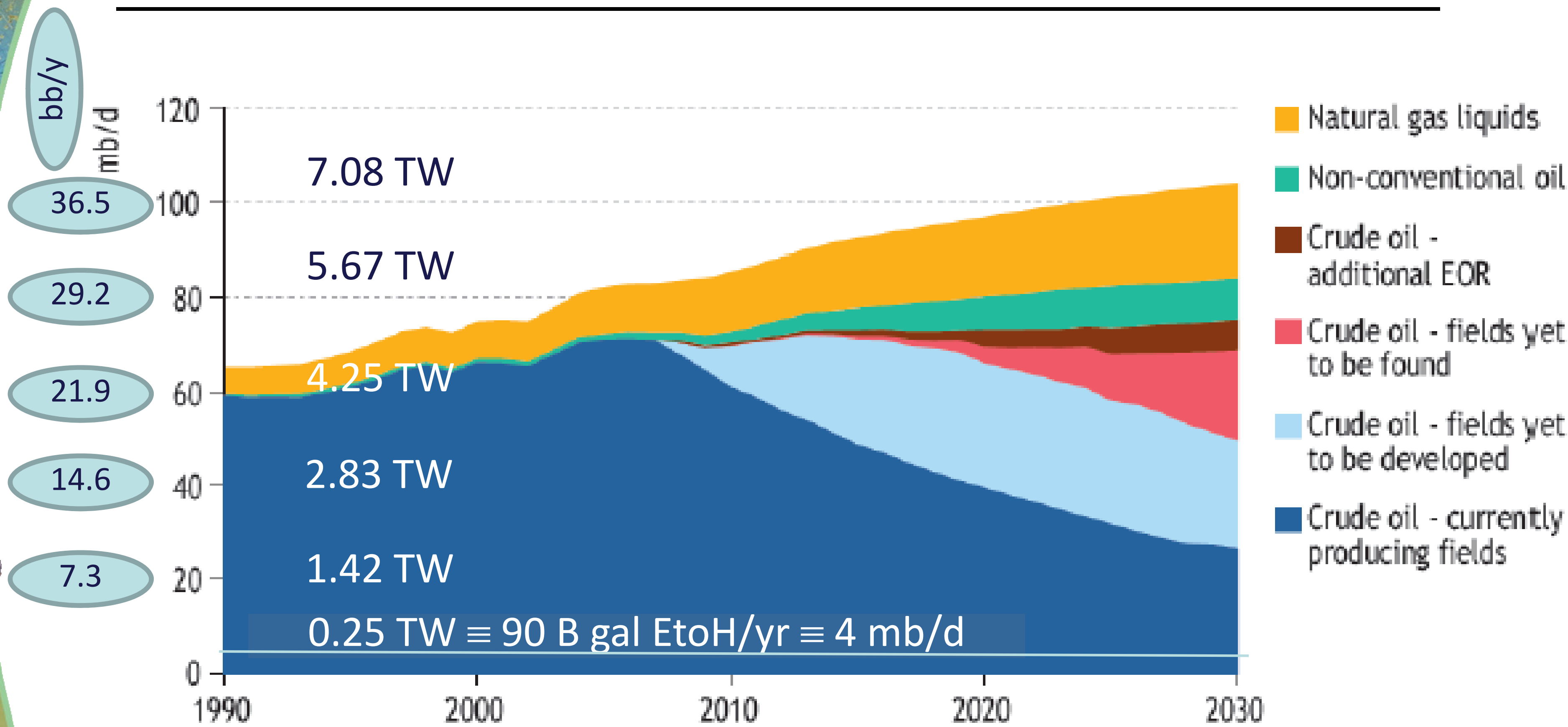
An Opportunity Worthy of National and Global Attention

- **Global Context**
  - Energy consumption is growing with development gains and population growth
  - Fossil fuels dominate energy sources and GHG emissions for all industrial sectors
  - Transportation & industrial sectors deeply dependent on vulnerable **petroleum** supplies
  - Price volatility of **petroleum** threatens economic recovery
  - Significant resources will be expended whether we transition away from fossil or not
- **Simultaneous Needs**
  - Assure energy security
  - Mitigate climate change risks
  - Enhance prosperity and competiveness
  - Create viable alternatives to petroleum-based fuels
  - Achieve scale with no dislocations
- **Transportation Fuels**
  - Liquid hydrocarbons are the “Gold Standard”
  - Energy Density, Infrastructure, Fueling Rate, Air and Heavy Ground Transport

Our Solution: **Fungible** fuels from concentrated sunlight, CO_2, and water

No other solution proposed can simultaneously meet the needs

Oil and Liquids Global Supply: Projected



To meet the demand growth and offset decline -
64 mb/d (4.53 TW) of gross capacity needed between 2007 & 2030
— This is 6× the current capacity of Saudi Arabia —
No consensus among the big industry players that the world can sustain >100 mb/d

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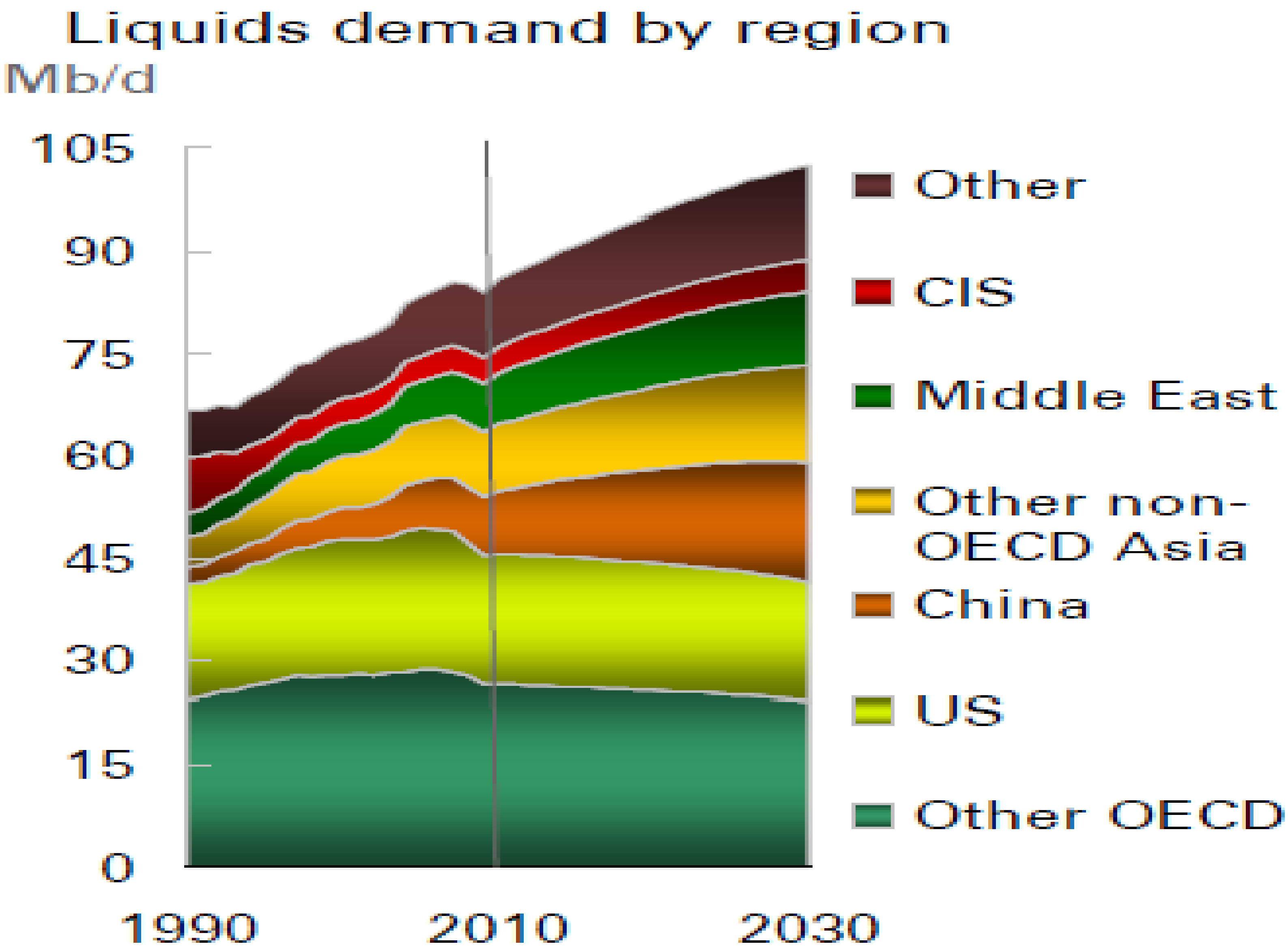
Oil and Liquids



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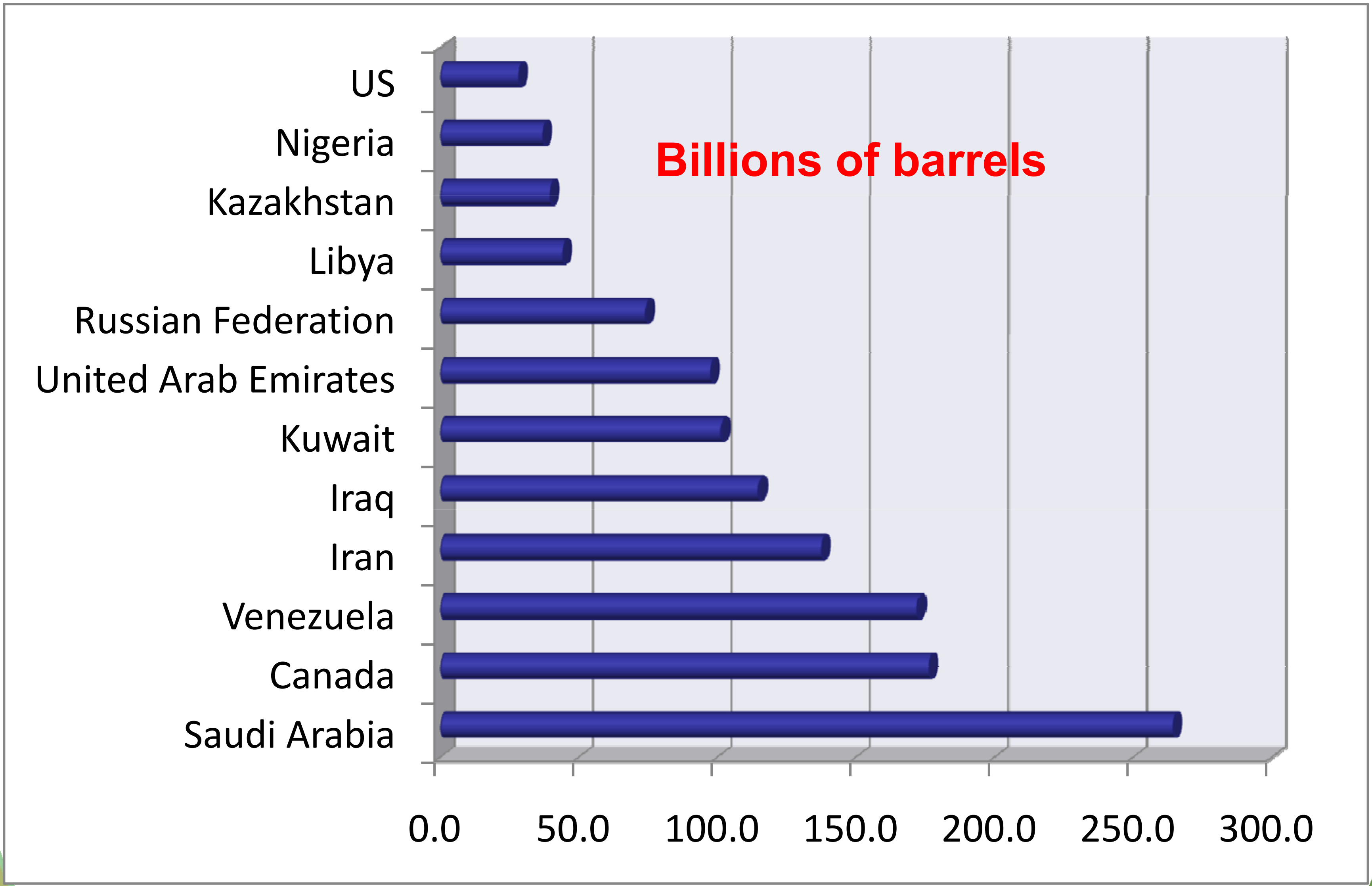
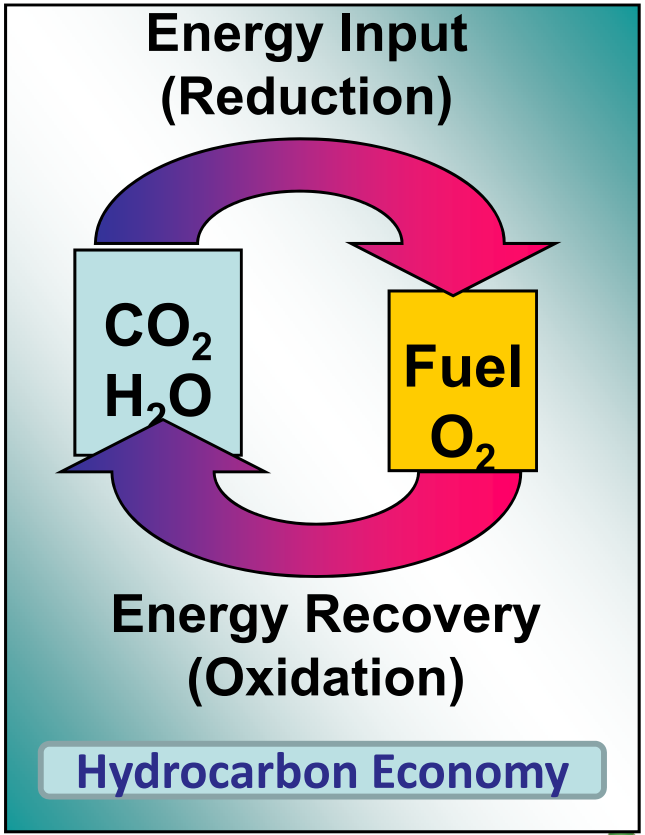
Oil Reserves



No Silver Bullet

- **Some things are universal**
  - Sunlight is not free: collectors and absorbers
  - Hence **efficiency matters**
  - This derives from considerations of **scale**
    - Diffuse (low areal density) nature of the energy source
- **Key challenge**:
  - Achieve high efficiencies with good durability using low cost materials
- **Timeframe**: intermediate term <20 years
  - High risk of a liquid fuels crisis during this timeframe

Closing the Cycle with a **Solar** Thermal Energy Source
Nature's Example but with an **Efficiency Boost**



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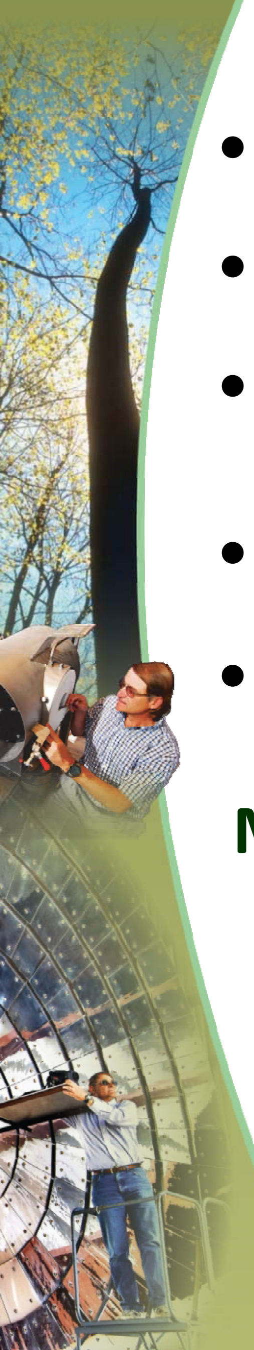
Vehicle Transport Fuel at a Fork in the Road



- Fossil fuels
  - Climate Change Risk
- Hydrogen
  - Infrastructure, Energy Density
- Electric vehicles
  - Heavy Duty, Air, Infrastructure, Energy Density
- Biofuels
  - Scalability
- Sunshine to Petrol
  - None

Multiple Options

- We need to be pursuing all viable options
- Derives from scale and urgency
- **Not the time to be down-selecting without a valid framework**

"When you come to a fork in the road, take it."

Yogi Berra

"Two roads diverged in a wood, and I took the one less traveled by, And that has made all the difference."

Robert Frost

"Rather than following a single path, particles take every path, and they take them all simultaneously"

Stephen Hawking

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Multi-Disciplinary Team: Three Thrusts

Principal Investigator – **James E. Miller**
Project Manager - **Ellen B. Stechel**

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Systems

- Terry Johnson, Chad Staiger, Daniel Dedrick (promoted), Christos Maravelias (Univ of Wisconsin), Carlos Henao (student,) Jiyong Kim (Postdoc)

Reactor

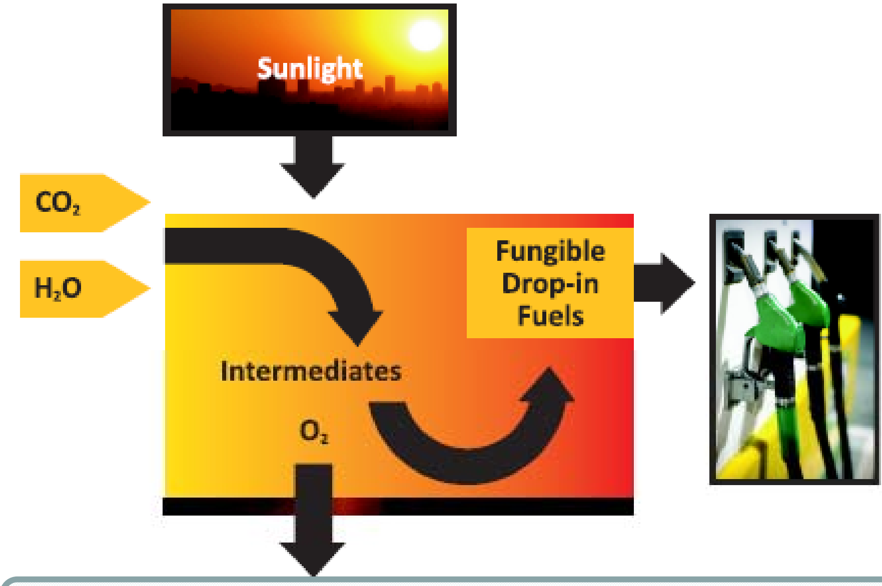
- **Solar Reactor** - Rich Diver (retired), Tim Moss, Scott Korey, Nathan Siegel, Robocasting, LLC
- **Reactive Structures** - Nathan Siegel, Terry Garino, Nelson Bell, Rich Diver (ret), Brian Ehrhart, Robocasting, LLC
- **Detailed Reactor Models** - Roy Hogan, Ken Chen, Spencer Grange, Siri Khalsa, Darryl James (Texas Tech), Luke Mayer (student)

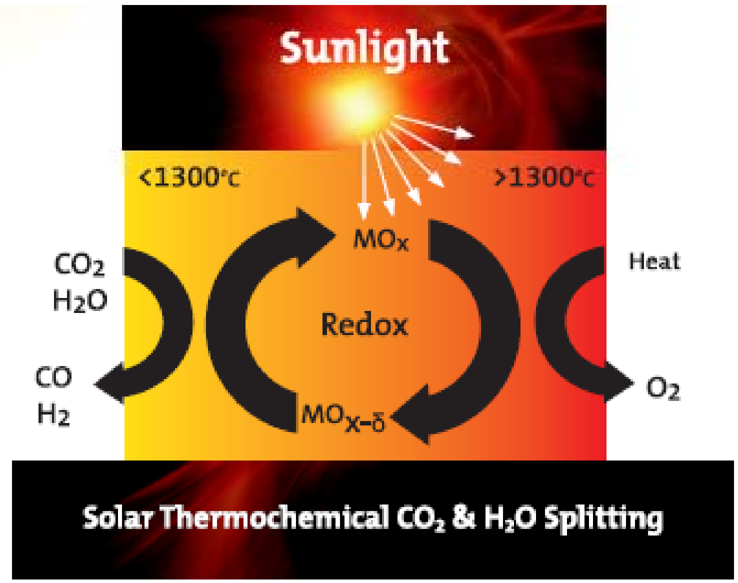
Materials

- **Reactive Materials Characterization & Development** - Andrea Ambrosini, Eric Coker, Mark Rodriguez, Lindsey Evans, Stephanie Carroll, Tony Ohlhausen, William Chueh
- **Bulk Transport & Surface Reactions** - Gary Kellogg, Ivan Ermanoski, Taisuke Ohta, Randy Creighton
- **Thermodynamics & Reaction Kinetics** - Mark Allendorf, Tony McDaniel, Chris Wolverton (Northwestern Univ), Bryce Meredig (student), Heine Hansen (Postdoc) , Al Weimer (Univ Colorado), Jon Scheffe (student, thesis)

Direct Chemical Routes Via Thermochemical Syngas

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





CO_2 (3.14 kg) + H_2O (2.57 kg) + sunlight → **Activation**

O_2 (3.42 kg) ↑ + CO (2 kg, 21.8 MJ) + H_2 (0.29 kg, 40.8 MJ) →

Fuel Synthesis

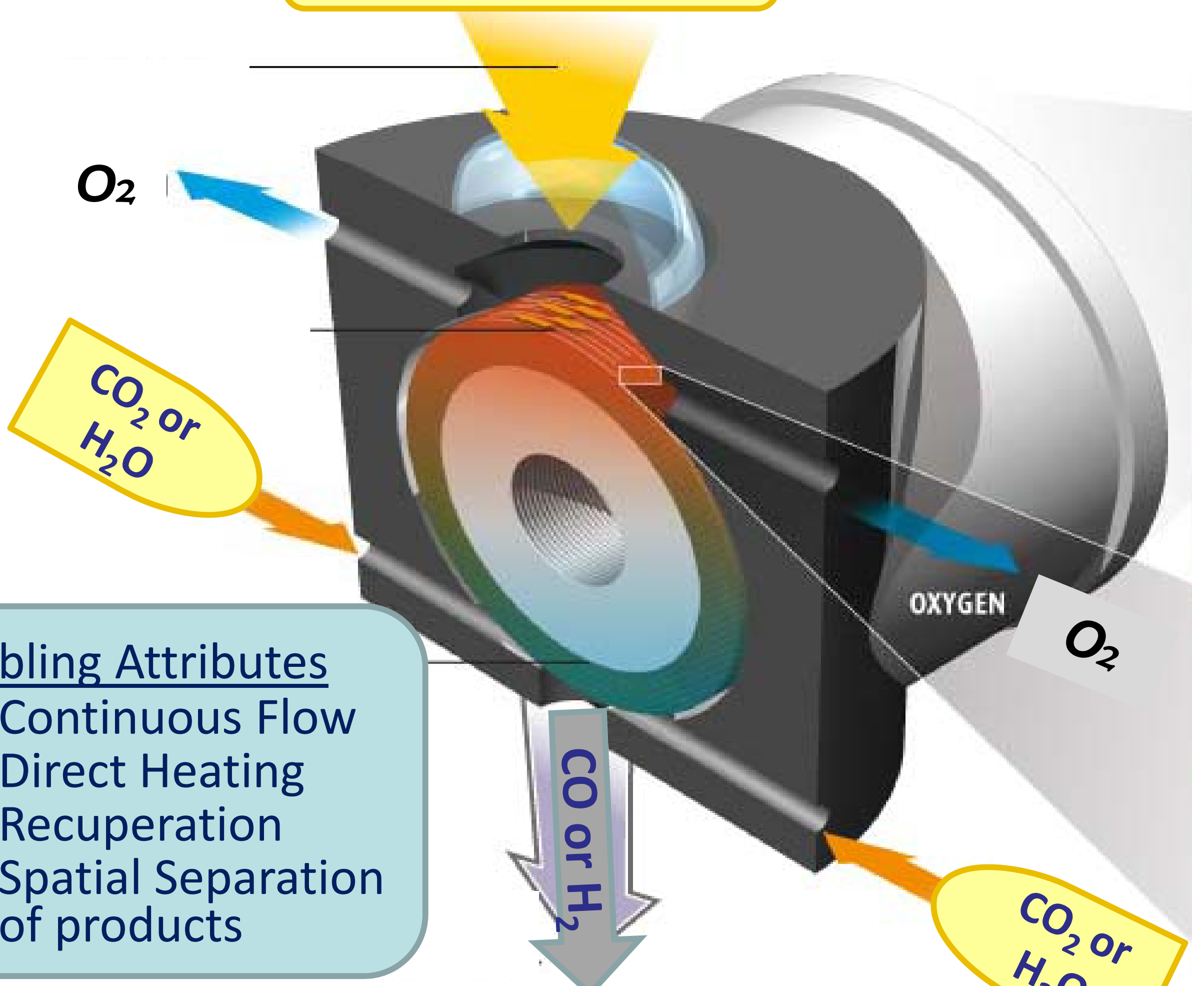
H_2O (1.28 kg) + CH_2 (1 kg, 46.7 MJ) + heat (15.85 MJ)

Final Product

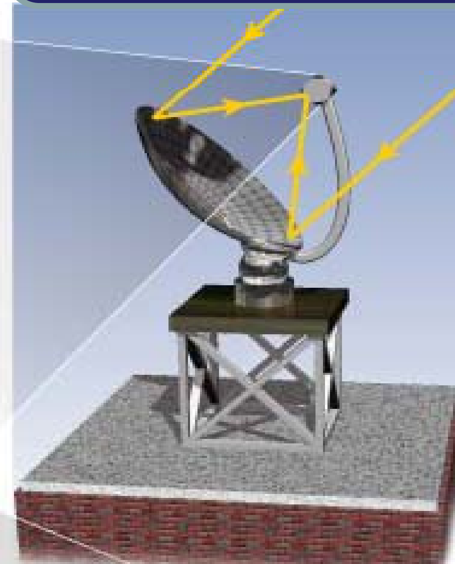
Enabling High Efficiency with Novel Reactor Design

"Reactorizing a Countercurrent Recuperator"

Solar Heat



Mirrored Dish Tracks the Sun and Focuses Heat into the Reduction Chamber



Alternate discs rotate in opposite directions

Enabling Attributes
1. Continuous Flow
2. Direct Heating
3. Recuperation
4. Spatial Separation of products

Figure Credit: Popular Science

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

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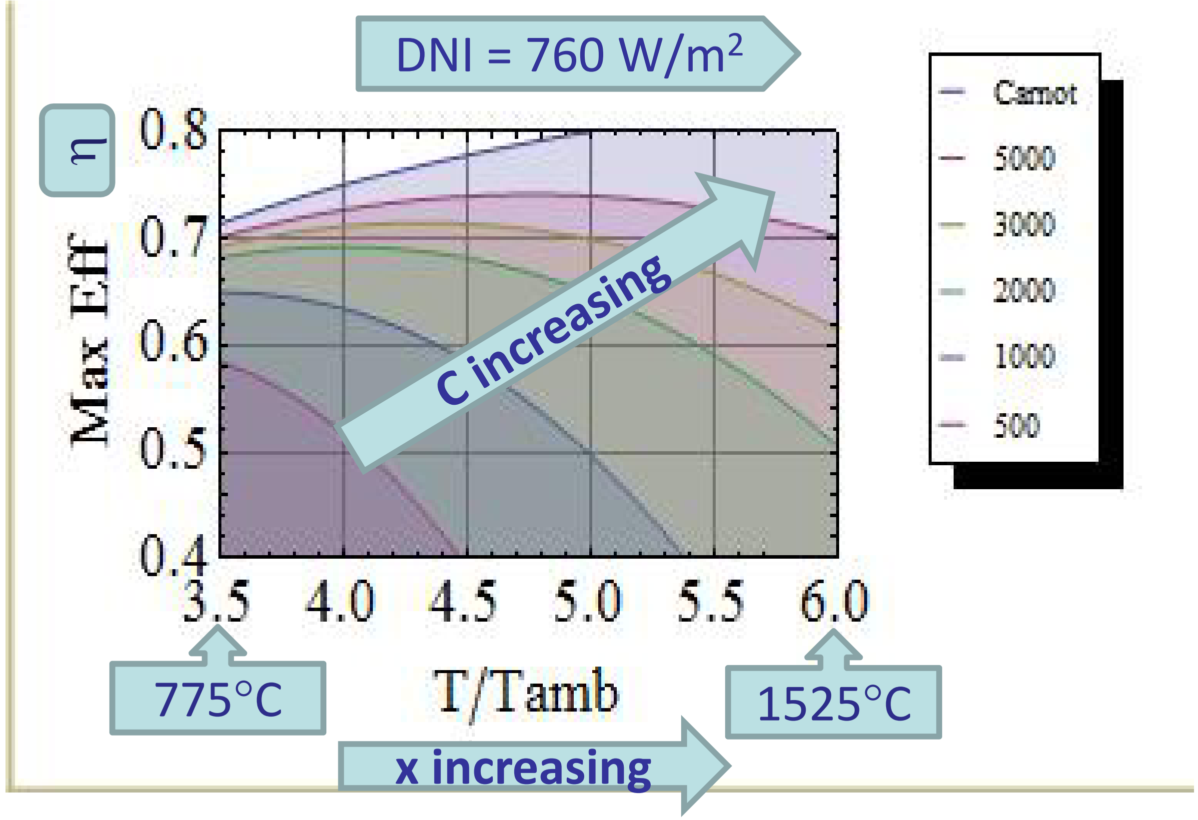
Thermal Reduction Theoretical Efficiency is High But Must Have Recuperation

Max Efficiency is a combination of Carnot limitations and thermal re-radiation

$$(1-1/x) \times (1-\alpha\, x^4/C)$$

Without **recuperation** drops substantially 36% maximum



Radiation losses < 1500 °C (x~5.9)

η≅60% at C=3000; 1300°C

Our target is 25% for market ready – 1st chemical heat engine (~40% of theoretical)

Realistic Engineering Limit on heat engines – 75% of theoretical (or ~45%)

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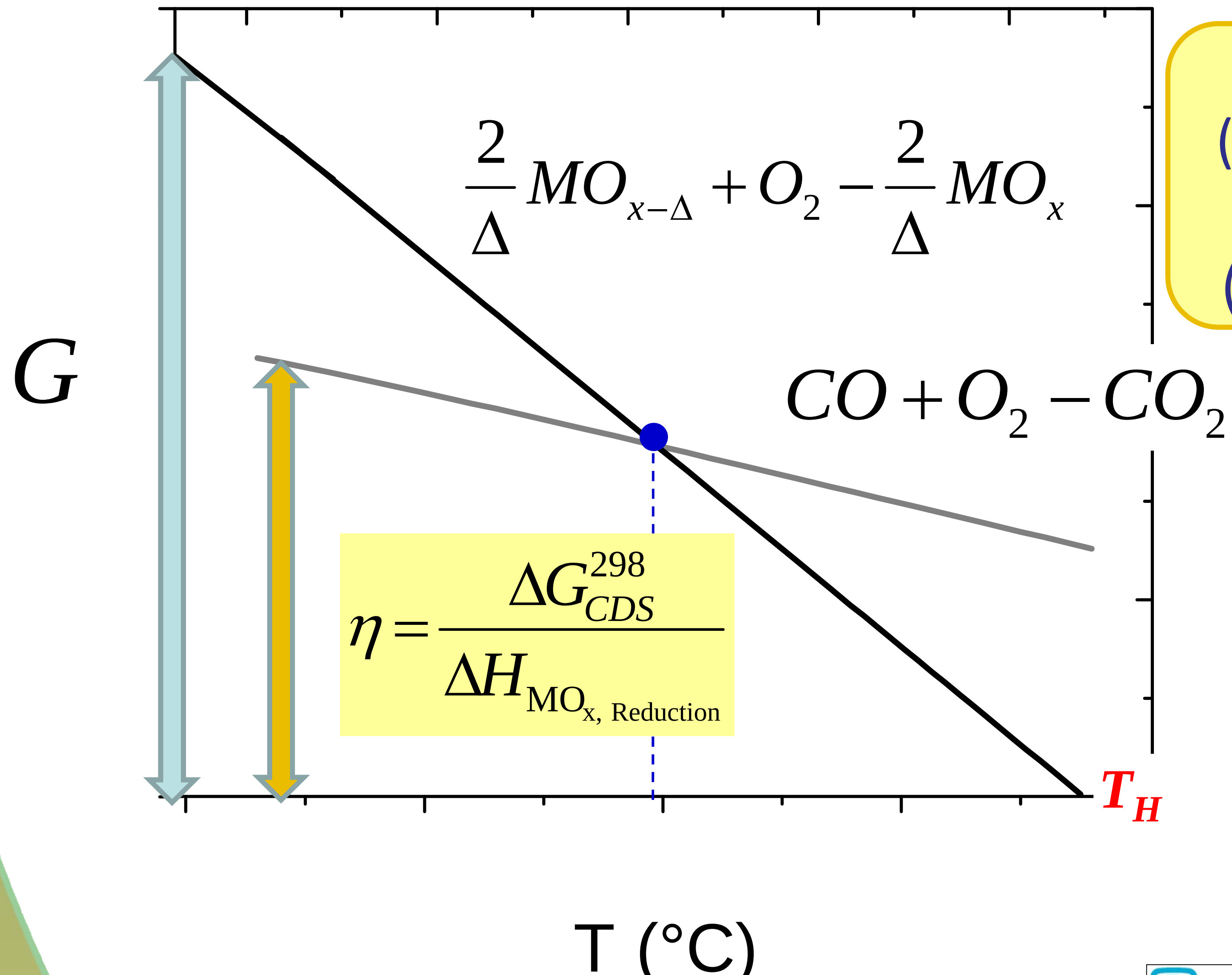
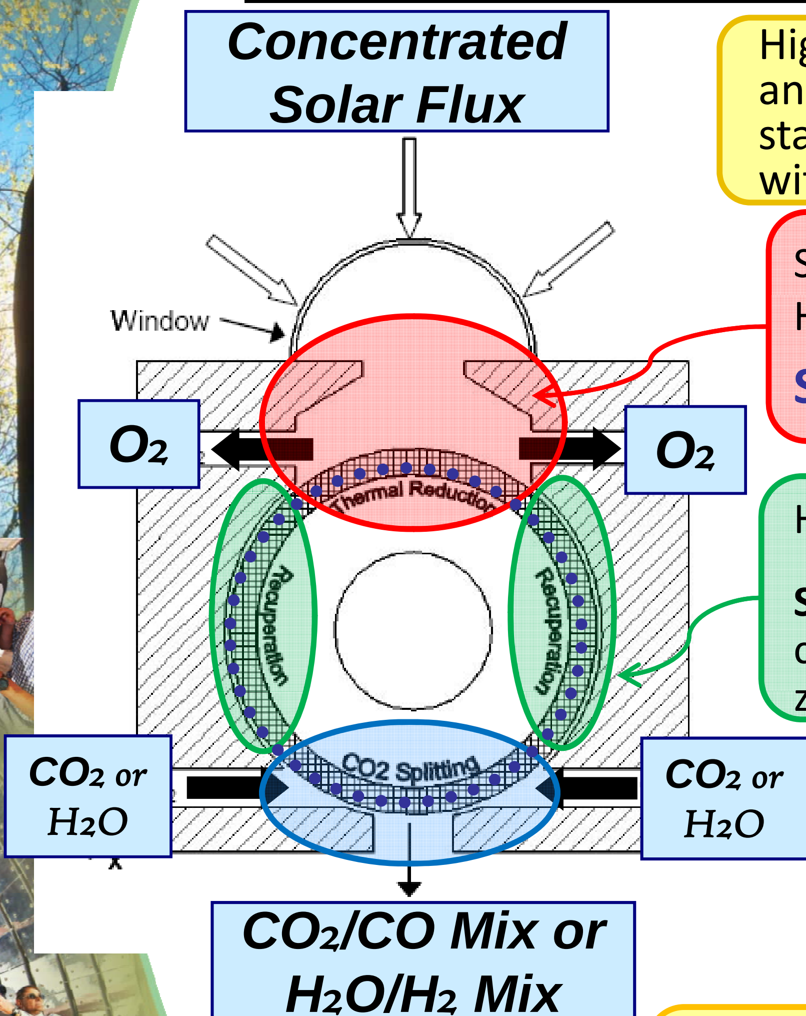
Thermodynamics



e.g. CeO_2
($Ce^{+4} \rightarrow Ce^{+3}$)
or Fe:YSZ
($Fe^{+3} \rightarrow Fe^{+2}$)

Lots Going On



Highly coupled problem: thermal radiation, heat conduction and convection, gas-phase flow and species transport, solid-state diffusion of charged species, and redox chemical reactions within moving reactant rings

Solar Flux in $\dot{E} \approx CA_a I$ less Re-radiation losses $\dot{Q}_a \approx A_a \sigma T_H^4$

Heat & mass exchange across the solid/gas interface

Solid Reduction: $O_{(s)}^{-2} \leftrightarrow 2e^-_{r,(s)} + \frac{1}{2} O_{2,(g)}$

Heat exchange between counter-rotating rings in the recuperator

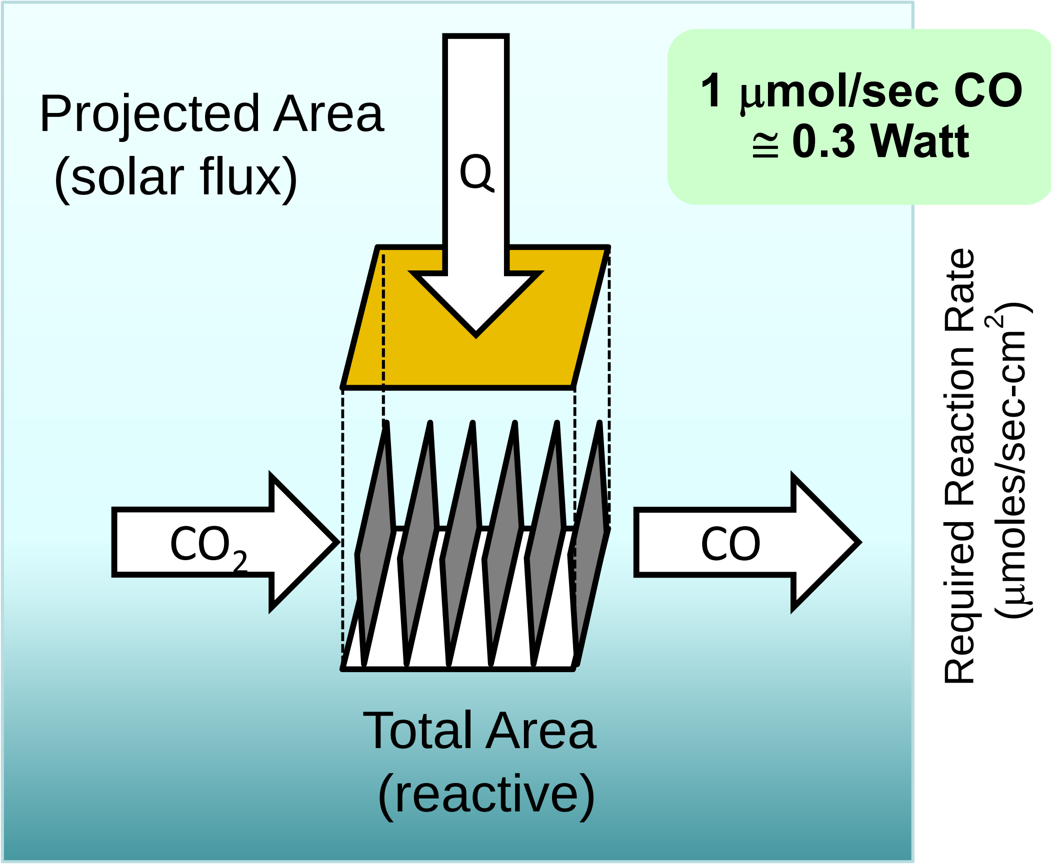
Spatial Separation: Flow strategies must limit crossover of product chemical species (O_2,CO) between the reduction and oxidation zones

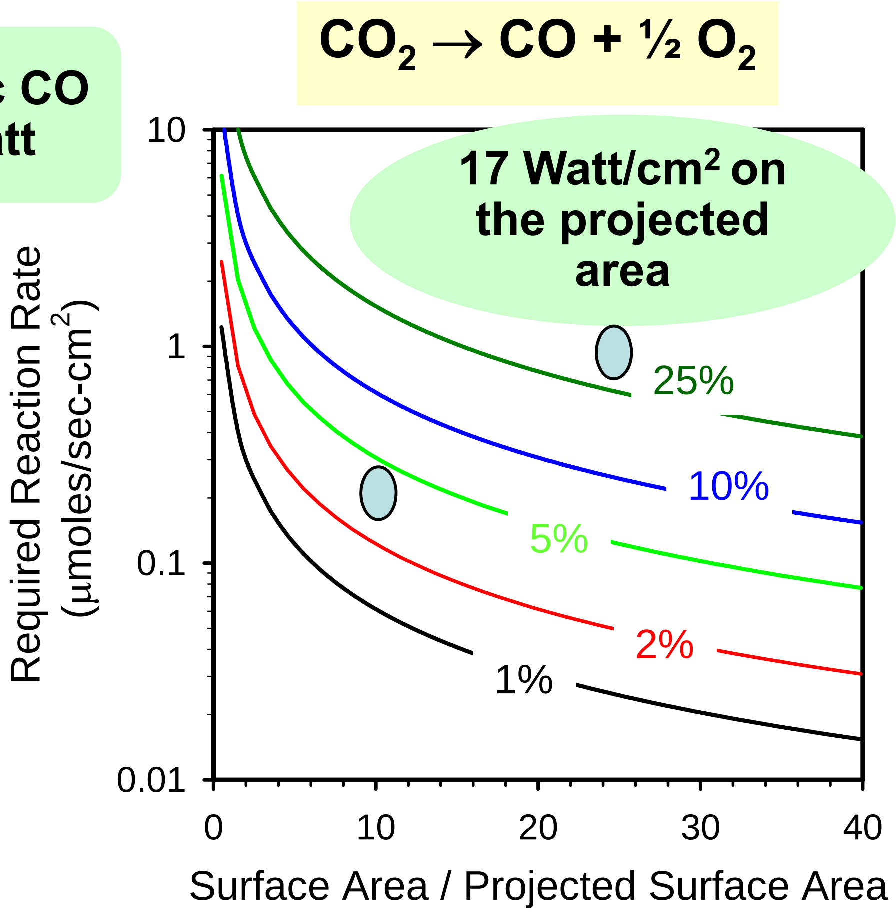
Re-Oxidation: CO_2 (or H_2O) injection, and heat & mass exchange across the solid/gas interface in the oxidation zone

Gas Reduction: $2e^-_{r,(s)} + CO_{2,(g)} \leftrightarrow O_{(s)}^{-2} + CO_{(g)}$

Challenge is to balance incident solar flux, redox chemical kinetics (limited by thermodynamics), reactant/product species transport, and heat recuperation to maximize efficiency and through-put.

For a Defined Flux: Efficiency ∝ Reaction Rate





<u>To Improve Efficiency</u>

- Improve Kinetics
- Increase Surface Area (Assuming Rates ∝ Surface Area
- Increase active (reducible metal) Loading (may have broader effects).

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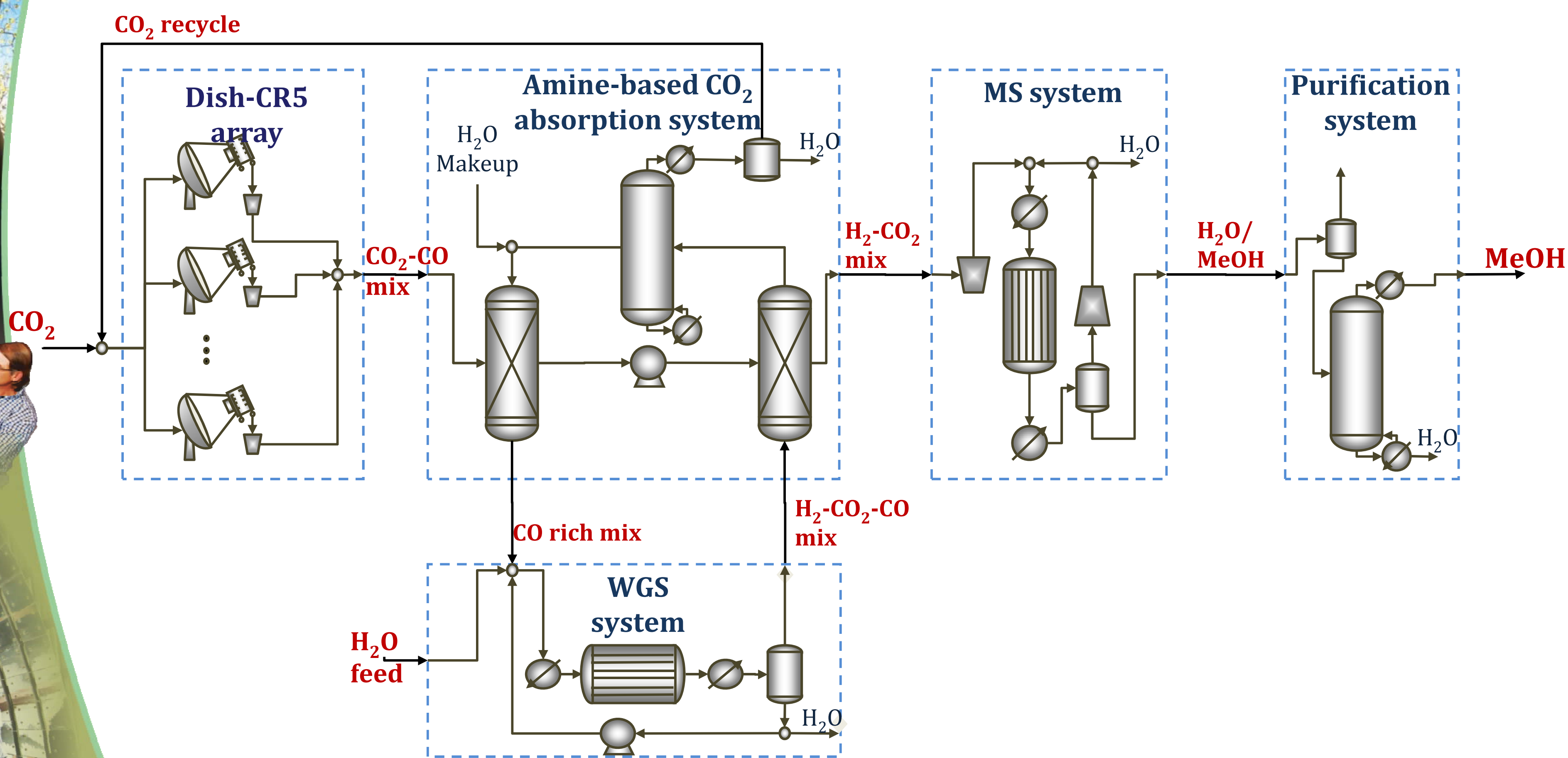
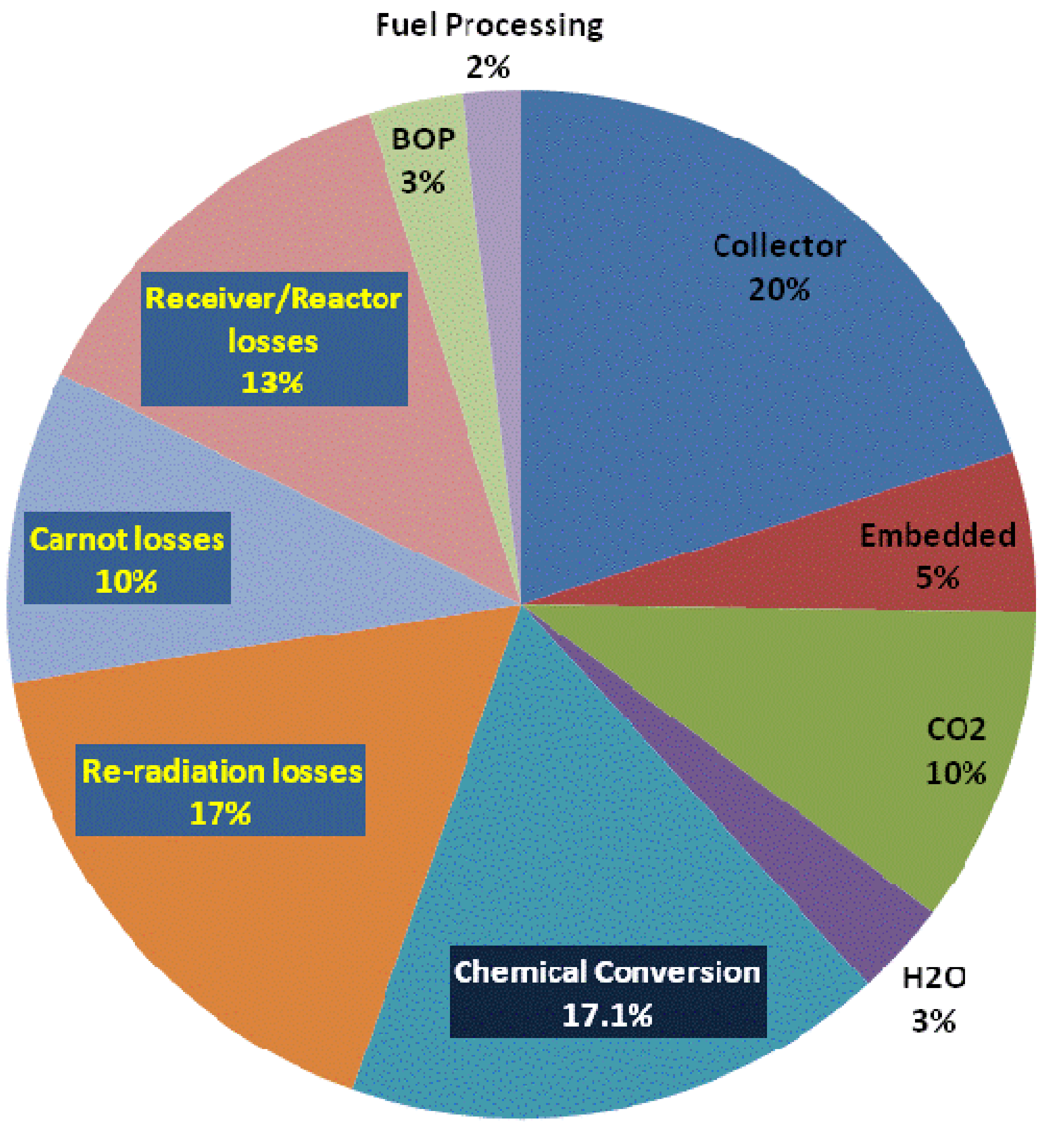
Detailed Process Simulation Confirms Viability

Process flow diagram (PFD) of CO_2 pathway for MeOH production

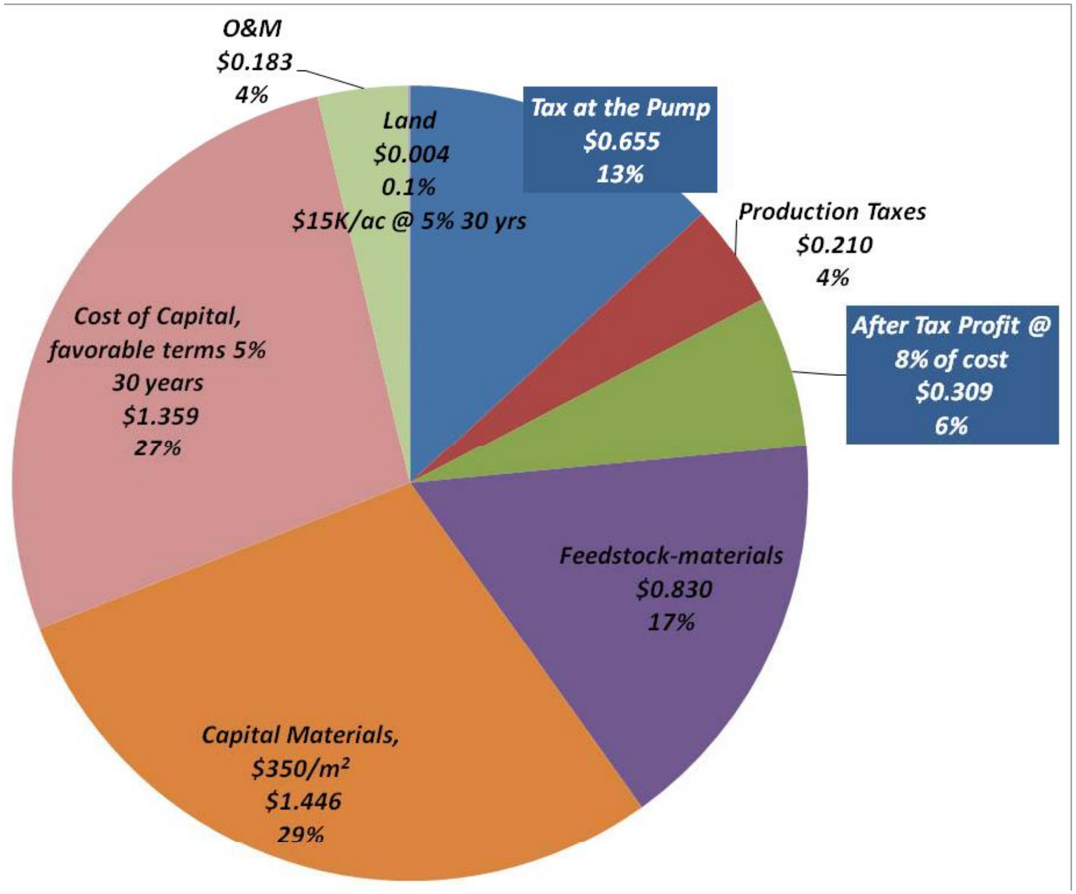


Graphical View of Where the Energy Goes: 12.5% LCE



- Reactor assumed at 57% of theoretical and 30% first law efficient
- Re-radiation losses assumed 1450°C reduction and 3000-sun concentration
- Lower temperature reduction will reduce losses
- Lower temperature reduction will reduced durability issues

Cost Breakdown For $5/GGE; S2P 12.5% LCE



- **Costs for S2P are in the ballpark of viability**
- **Learning curve will reduce the most expensive contributions**
- **Very sensitive to the cost of capital recovery**

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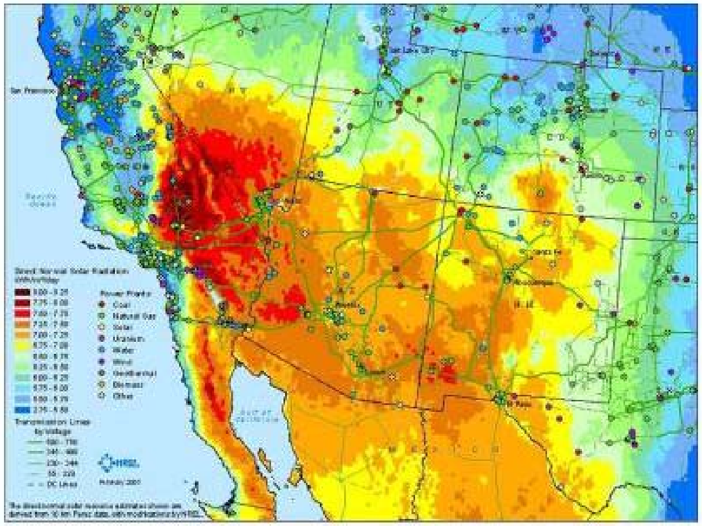
Solar Resource Potential Shows the Promise of Scale Assuming High Efficiency



Filters applied (Resource analysis by NREL): Over-filtered

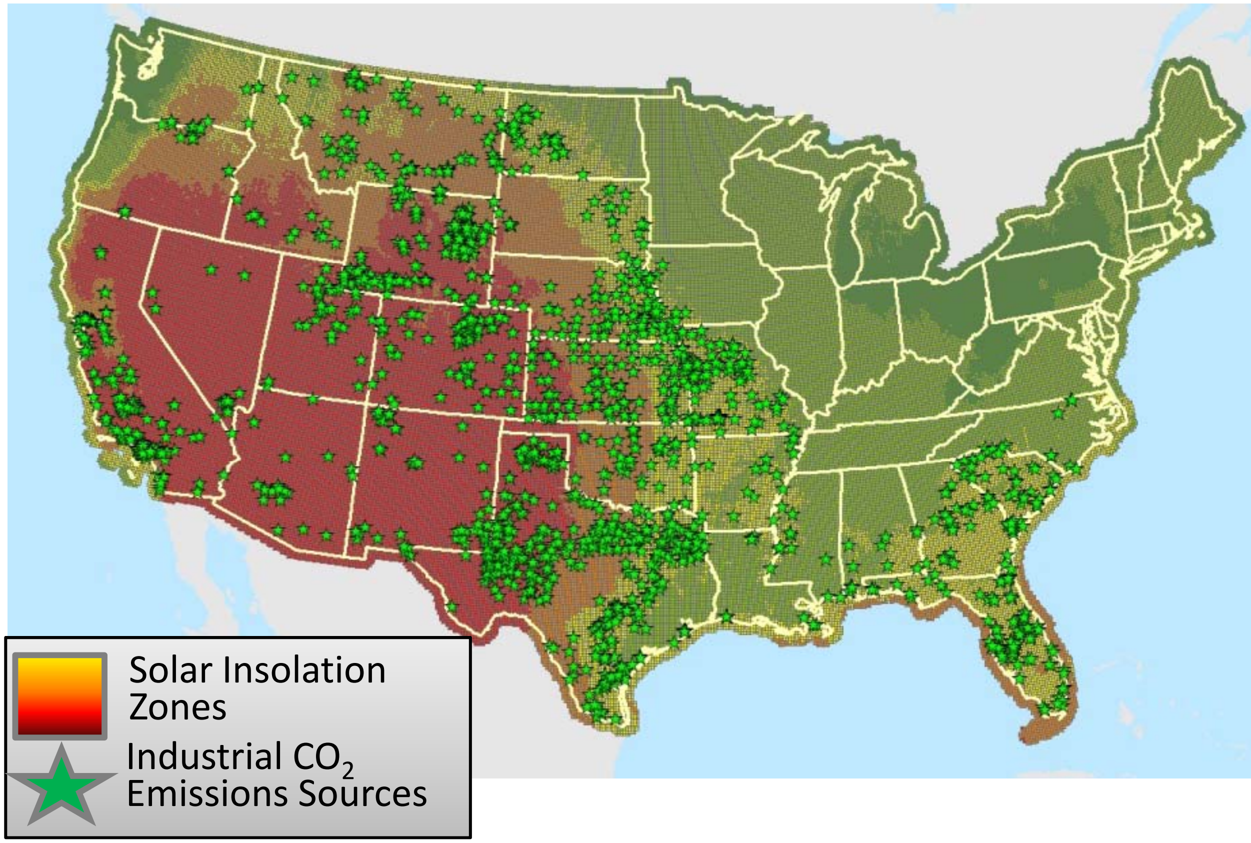
- Direct-normal solar resource
- Sites > 6.75 kwh/m^2/day and 27% Capacity (6.48kwh/m^2/day)
- Exclude environmentally sensitive lands, major urban areas, etc.
- Remove land with slope > 1%.
- Assume 25% packing density
- Only contiguous areas > 10 km^2 (675 $MW_{primary}$)

State	Land Area (10^9 m^2)	Solar Capacity (TW)	Fuel Capacity (GW)	(mb/d)
AZ	49.9	3.37	421	5.9
CA	17.7	1.20	150	2.1
CO	5.5	0.37	46	0.7
NV	14.5	0.98	122	1.7
NM	39.3	2.65	331	4.7
TX	3.0	0.20	25	0.4
UT	9.2	0.62	78	1.1
Total	139.2	9.39	1,174	16.6

- U.S. Petroleum Demand is **~1.46 TW** (20.7 M barrels/day (2007))
- **12.5%** lifecycle efficiency, requires enough land to collect **11.7 TW** of primary solar flux to produce 1.46 TW (20.7 mb/d) fuel
  - Same land CSP Potential ~2TW_e (Demand 400 GW_e in 2008)
  - **Substantial fuel and electric potential**

Land and Solar Capacity for 80% of Petroleum Demand
NM could supply ~23% of Petroleum demand

CO_2 Sources in Insolation Zones

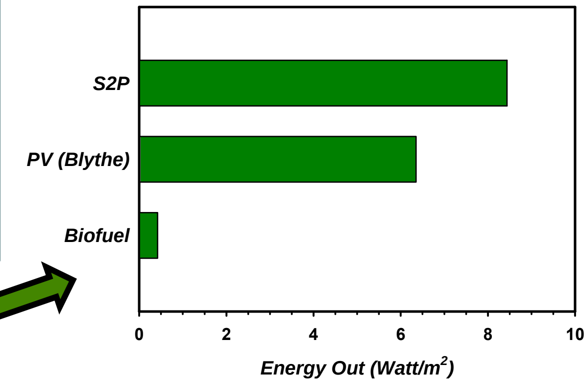


- Hundreds of large industrial CO_2 emissions sources exist in the United States in areas of high solar insolation.
  - 4-Corners Power Plant: 15.6 Mt/y and San Juan 13.4 Mt/y
  - At 81% utilization these two plants can supply fuel plants up to 9.8 GW (139 kb/d)
  - ~25 plants of comparable size to 4-Corners could supply US CO_2 for 10% of petroleum demand.

Substantial resources can be tapped. Note that an infinite source of CO_2 (direct air capture) should be available well before point sources are exhausted.

Resource Utilization: Comparing S2P, PV, Biofuels

- NRG Solar: commercial operation in Blythe, South Eastern CA
- Construction began in Sept 2009
- One of the first utility-scale PV projects
- **200 acre** ≡ 0.81 $(km)^2$, 21 MW_e

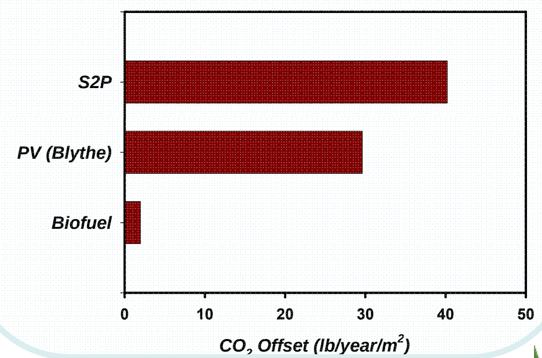


Energy Generation

- PV: 45000 Mega Watt Hour/Year ≡ 5137 KW (6.35 $Watt/m^2$)
- Biofuels: 6.25 Ton/Acre; 95 Gallons EtOH/Ton; 84600 BTU/Gallon ≡ 336 KW (4.75 b/d) - 0.42$Watt/m^2$
- Sunshine to Petrol; 25% packing and 12.5% **LCE**; ≡6829 KW (96 b/d) - 8.44 $Watt/m^2$)

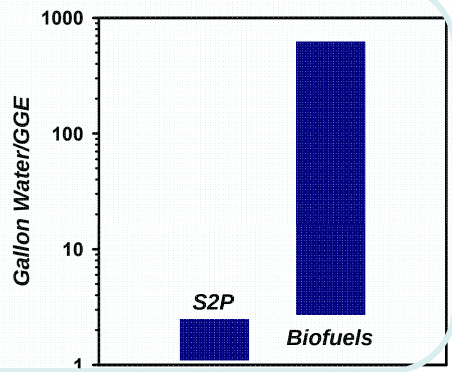
CO_2 Utilization

- PV: Displace >12000 ton/yr CO_2
- Biofuels: 802 ton/yr
- **S2P: 16293 ton/yr**



Water Utilization

- Biofuels: minimum 2.7-623 Gallons/GGE EtOH
- S2P: Sunshine to Petrol; **1.1-2.5 Gallons/GGE**



Macro Scale Issues: No Show Stoppers

- Systems analysis shows viability and scalable to today's demand
  - In three-five decades
  - With modest land utilization ~160×10^9 m^2 1.75% US
  - Assumes lifecycle efficiency ~12.5% and 25% packing
- Fungibility is key to a smooth transition and mitigating vulnerabilities from petroleum
- Supply chain adjacency in the market place, solar, automotive
- Most of the materials are readily available domestically
  - Concrete, steel, and glass
- CO_2 source (1.46 TW $\equiv$ 3.16 Gt/year CO_2)
  - Initially from stationary sources such as coal plants (~2 Gt/year emitted)
  - Ultimately from the atmosphere (outside scope for now)
    - 7.54 million cubic kilometers of air processed per year (if 60% extraction)
    - ~110×10^6 m^2 cross-sectional area – small fraction of solar collection (< 10% of the capital cost)
- Water – brackish or saline
  - Modest increase or no increase relative to petroleum

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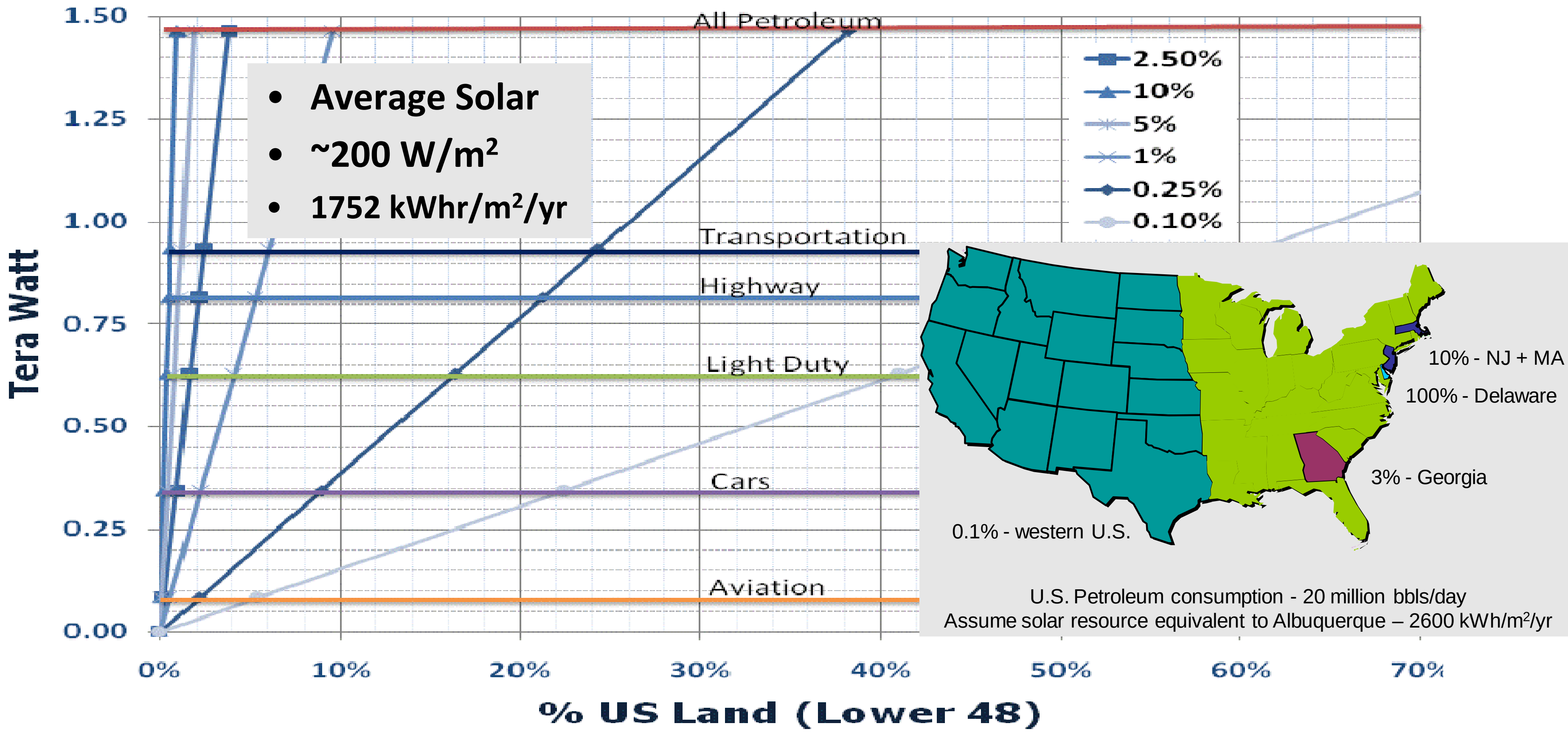
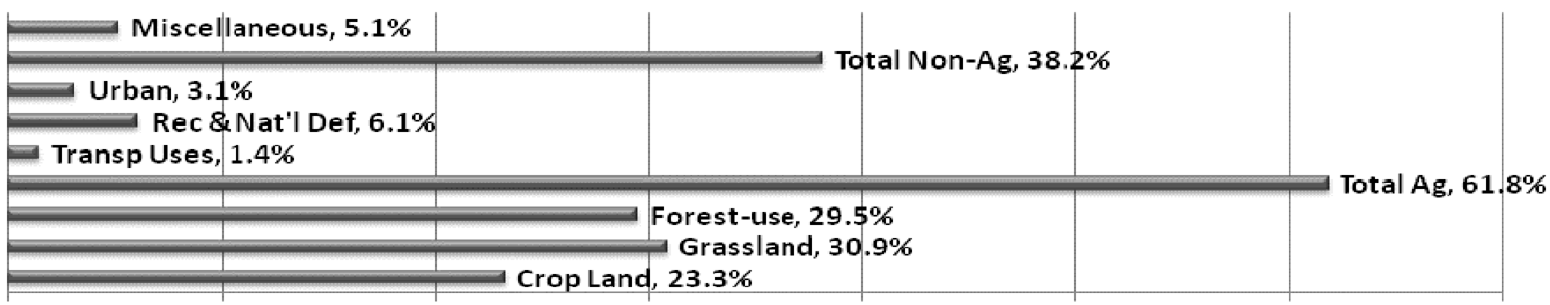
Efficiency → Scalability: Collector Area





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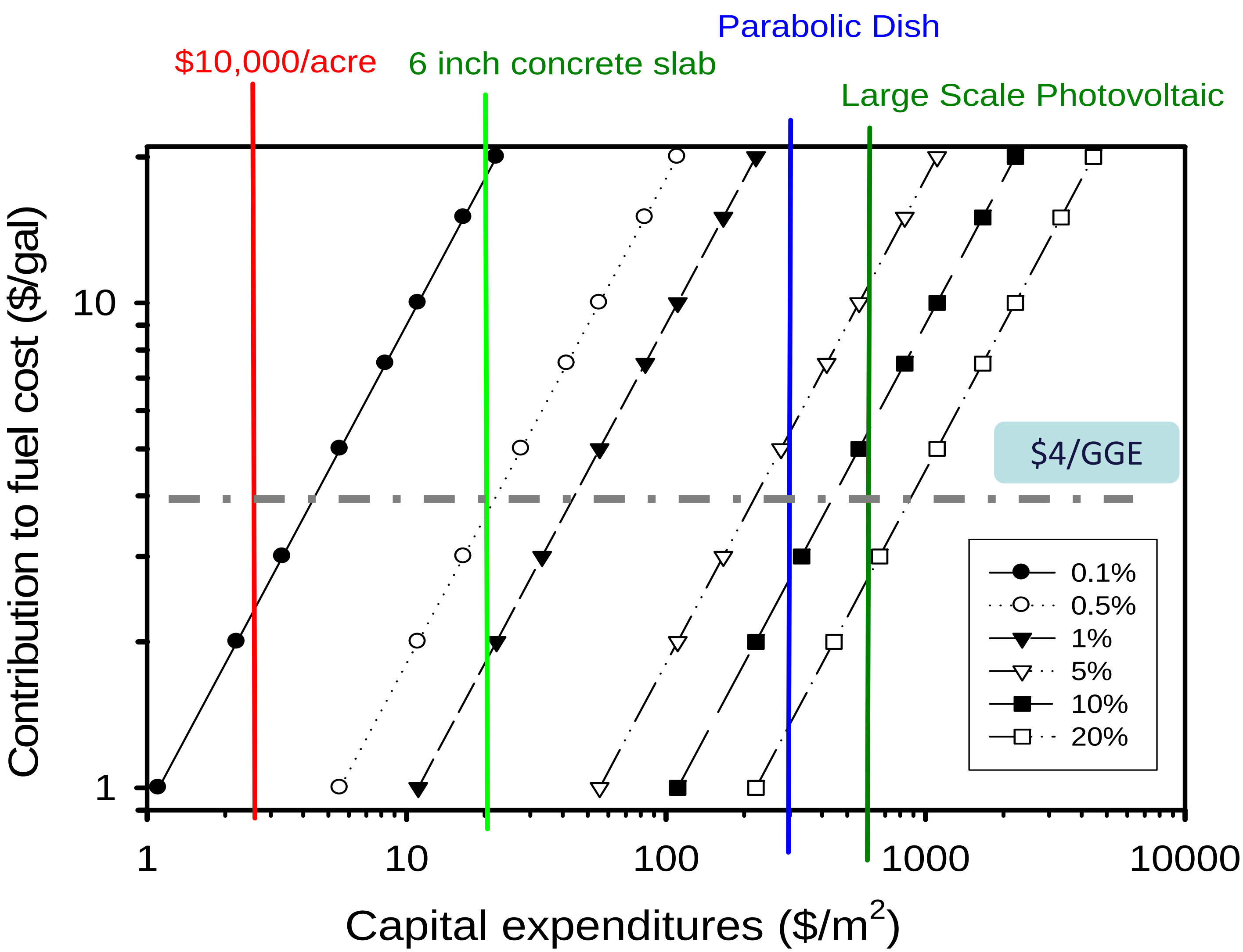
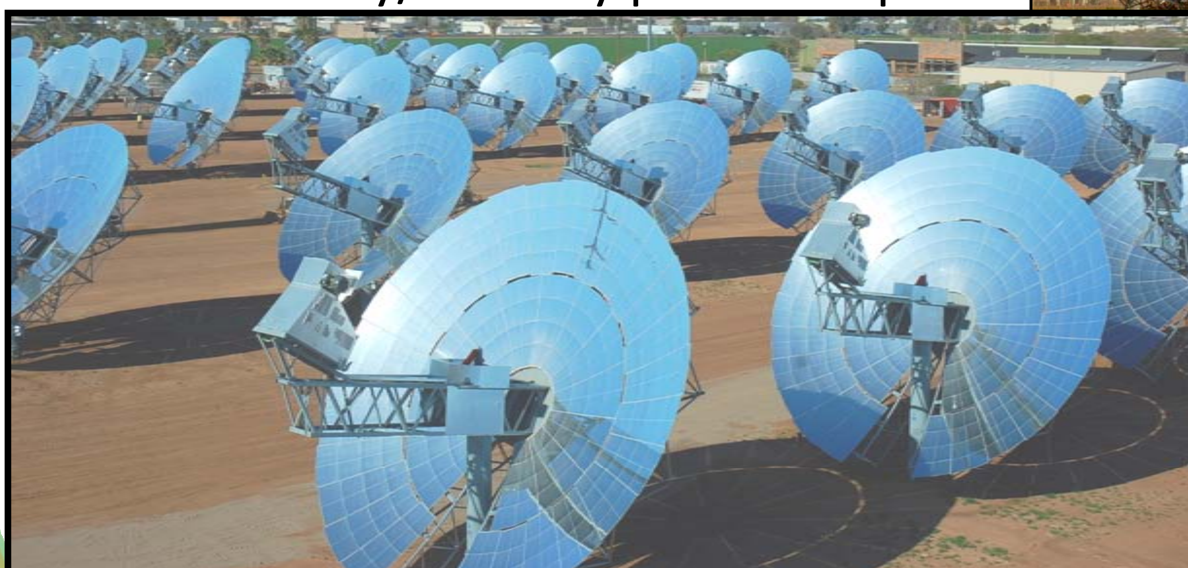
Efficiency → Costs Collector Area



Assumptions: GGE = 36 kWh, Solar Resource = 2600 kWh/m²/yr, Favorable Financing (5% interest, 30 years)

Path to the Market: Capitalizing on Adjacent Technology and Partnership

- CSP Dish Stirling – adjacency, analogous
- Modular utility-scale system
- 25 kW_e system each
- Autonomous operation
- Amenable to high volume manufacturing
- No exotic materials: steel, concrete, glass
- Record (net solar-to-grid electric) Peak efficiency 31.25% set at NSTTF
- Model laboratory/industry partnership



Goals and Challenges

- **Goal**: Demonstrate the technical feasibility of the solar conversion of CO_2 into CO in a thermochemical reactor with the four key attributes: direct heating, continuous flow, spatial separation, and recuperation
- **Metrics**: 2% sunlight into the reactor to CO out, pathway to 20% sunlight hitting the collector to CO in an advanced system
- **Challenges (Science, Engineering, Economics, Policy)**:
  - Materials discovery for improved material performance: thermodynamics and kinetics
  - Advanced reactor concepts: key attributes but minimize sweep gas or low pressure operation, disconnect reduction from oxidation kinetics
  - High recuperation and good spatial separation of products
  - Chemical and mechanical durability of the materials with high heat fluxes, high reduction temperatures, and fast thermal cycling
  - Reactor manufacturability and cost

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The Substitution Of All Petroleum Consumed In The US Would Require Millions Of Acres And Hundreds Of Millions Of Solar Dishes.

Thank You For Your Attention