Sunshine to Petrol: Reimagining Transportation Fuels

BP Executive Visit

Albuquerque, NM

19 July 2011

Ellen B Stechel, presenting

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

WELCOME

Overview of the “Sunshine to Petrol” Project

Systems Perspective

Reactor and Reactive Structures Design and Test

“Working” or Redox-Active Materials Science and Engineering

Sunshine to Petrol

Multi-Disciplinary Team: Three Thrusts

Principal Investigator – **James E. Miller**
Project Manager - **Ellen B. Stechel**
GC Director **– Carol Adkins → Steve Rottler**
Program Director Champion **– Margie Tatro→ Rick Stulen**
Renewables Program **– Jose Zayas**

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, Diver Solar, LLC), Brian Ehrhart, Robocasting, LLC
- **Detailed Reactor Models** - Roy Hogan, Ken Chen (transferred), Spencer Grange, Siri Khalsa, Darryl James (Texas Tech), Luke Mayer (student, thesis)

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)

Our External Advisory Board has Provided Great Advice and Validation

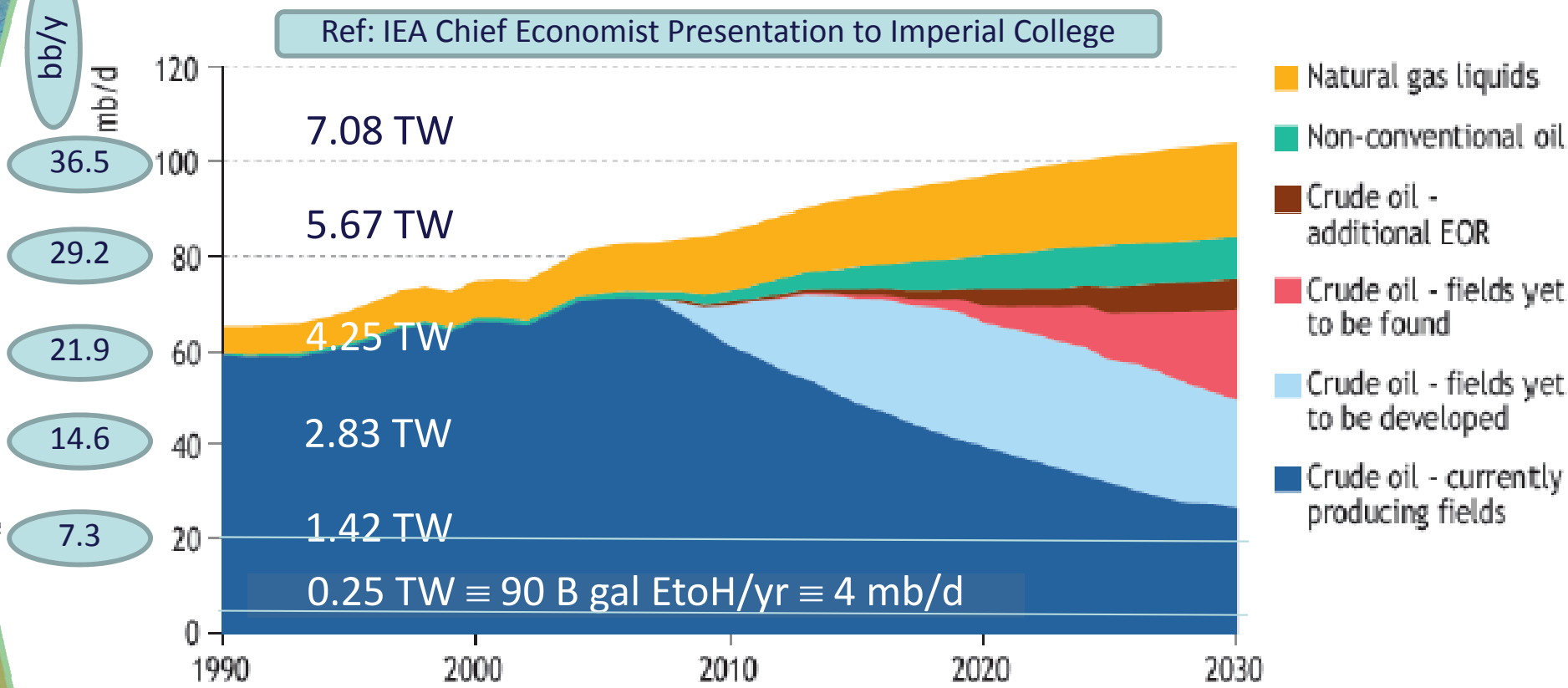
- Board
  - George Crabtree (Chair, ANL)
  - Martha Krebs (UC Davis, formerly CEC)
  - Mike Aimone (Batelle, retired Air Force)
  - Charlie Campbell (UW)
  - Gary Dirks (ASU, retired BP)
  - Tom Kreutz (Princeton)
  - Terry Manzanec (consultant, formerly Velocys, Inc)
  - Bill Schneider (Notre Dame)
  - Aldo Steinfeld (Solar Tech Lab, Paul Scherrer Institut, ETH-Z)
- Four reviews to date
  - Last one was February 23-24, 2011, Next one is August 23-24, 2011
- **Their assessment** of our current state and the prospects
  - The nation and world needs **this** solution; but if the Sandia team disbands, "**game over**"
  - Virtually nowhere else could so much rigor and technical diversity be assembled
  - The team is up to the challenge and will meet aggressive goals and milestones
  - The team demonstrates great progress between meetings and momentum continues to accelerate

This is a Strong and Cohesive Team

- Have demonstrated that they can set challenging technical goals and meet them
- Have put together a rigorous, comprehensive, and multi-perspective inventory of the challenge and determined:
  - There are no show-stoppers
  - This is a difficult challenge, and it demands depth and breadth of expertise that is hard to assemble – except at Sandia
- Have made smart use of thorough analytical modeling to complement experiment and have demonstrated:
  - A solid, plausible case that this technology can significantly impact the dual challenge of energy (petroleum) and climate (CO_2) security
  - This may be the only technology capable of this promise within a relevant timeframe.
- Have capitalized on unique and diverse capabilities at Sandia

Sunshine to Petrol

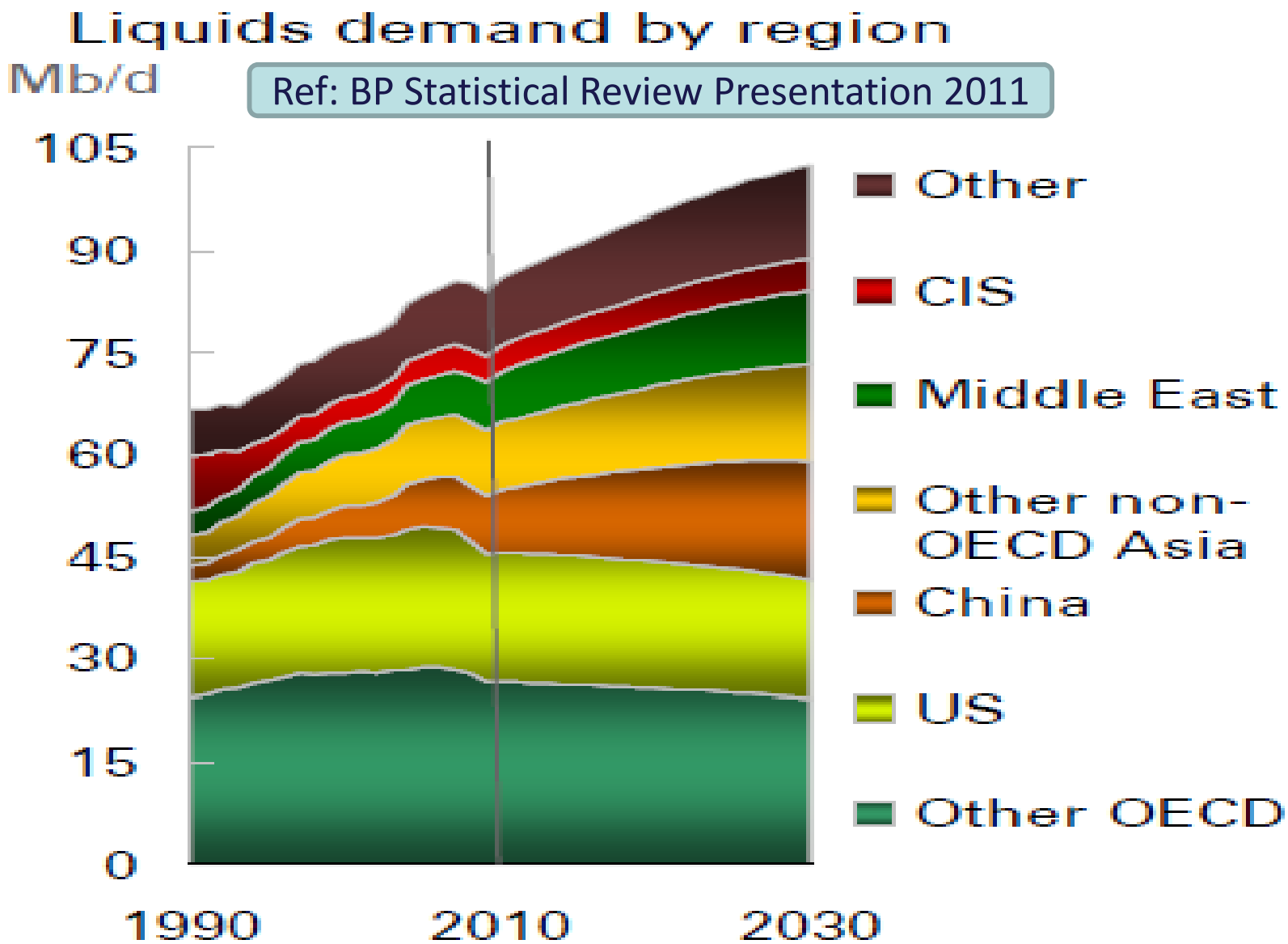
Oil and Liquids Supply: Projection



To meet the demand growth and offset decline -
64 mb/d (4.53 TW) gross capacity needed 2007 – 2030
— This is 6× the current capacity of Saudi Arabia —
We understand there is no consensus in the industry:
Can the world can sustain >100 mb/d of petroleum

Sunshine to Petrol

Oil and Liquids



An Opportunity Worthy of National Laboratory Attention

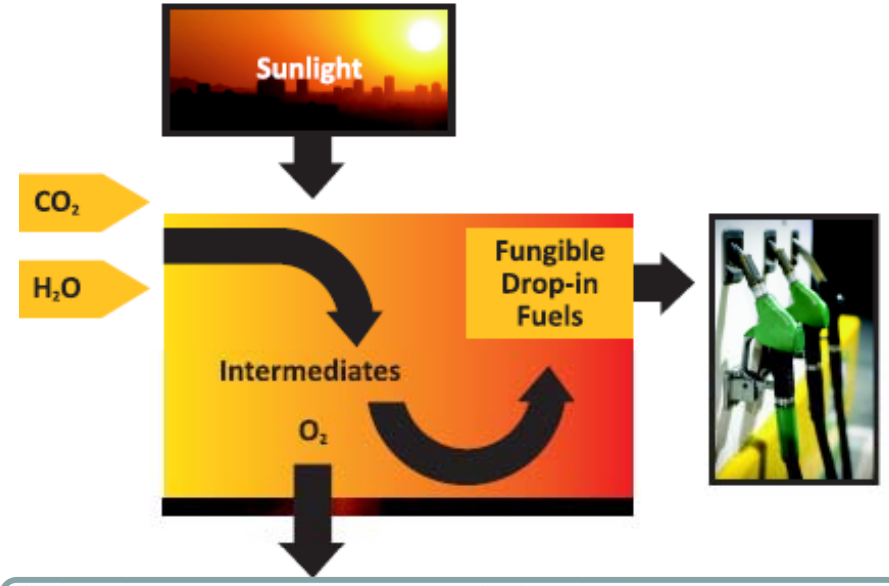
- **Global Context**
  - Energy consumption is growing with development gains and population growth
  - Fossil fuels dominate energy sources and GHG emissions for all industrial sectors
  - Transportation & industrial sectors deeply dependent on vulnerable **petroleum** supplies
  - Price volatility 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

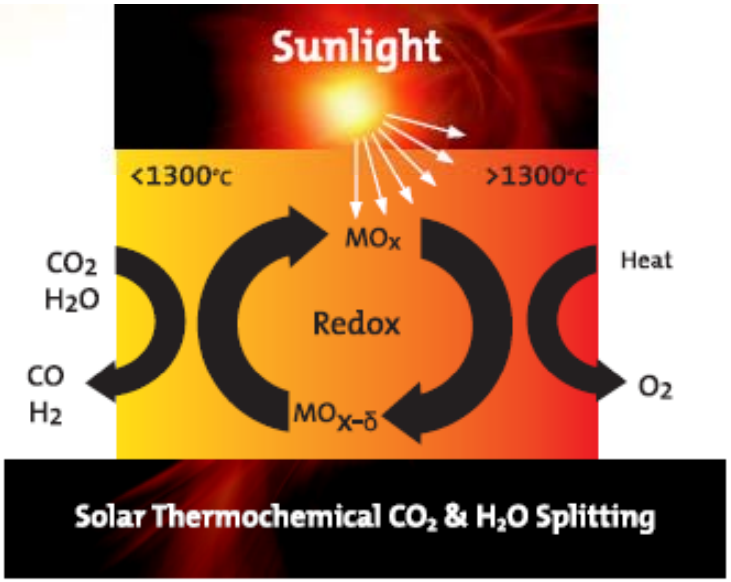
Our Solution: **Fungible** fuels from concentrated sunlight, CO_2, and water

No other solution proposed can simultaneously meet all five needs

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

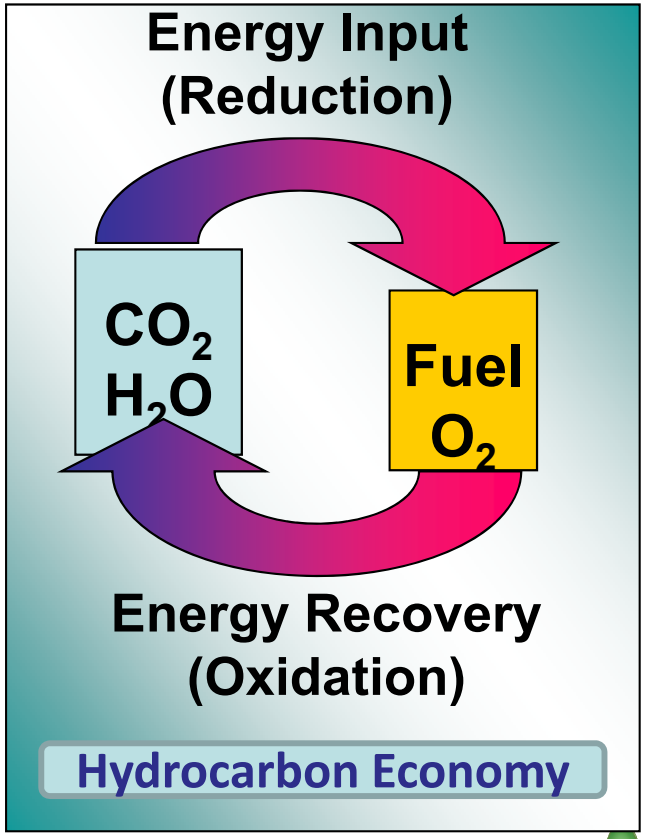
There are several good options to diversify and address energy security , economic competitiveness, and climate change risks for the electric grid, but precious few for transportation

THIS REALLY IS A GAME CHANGER

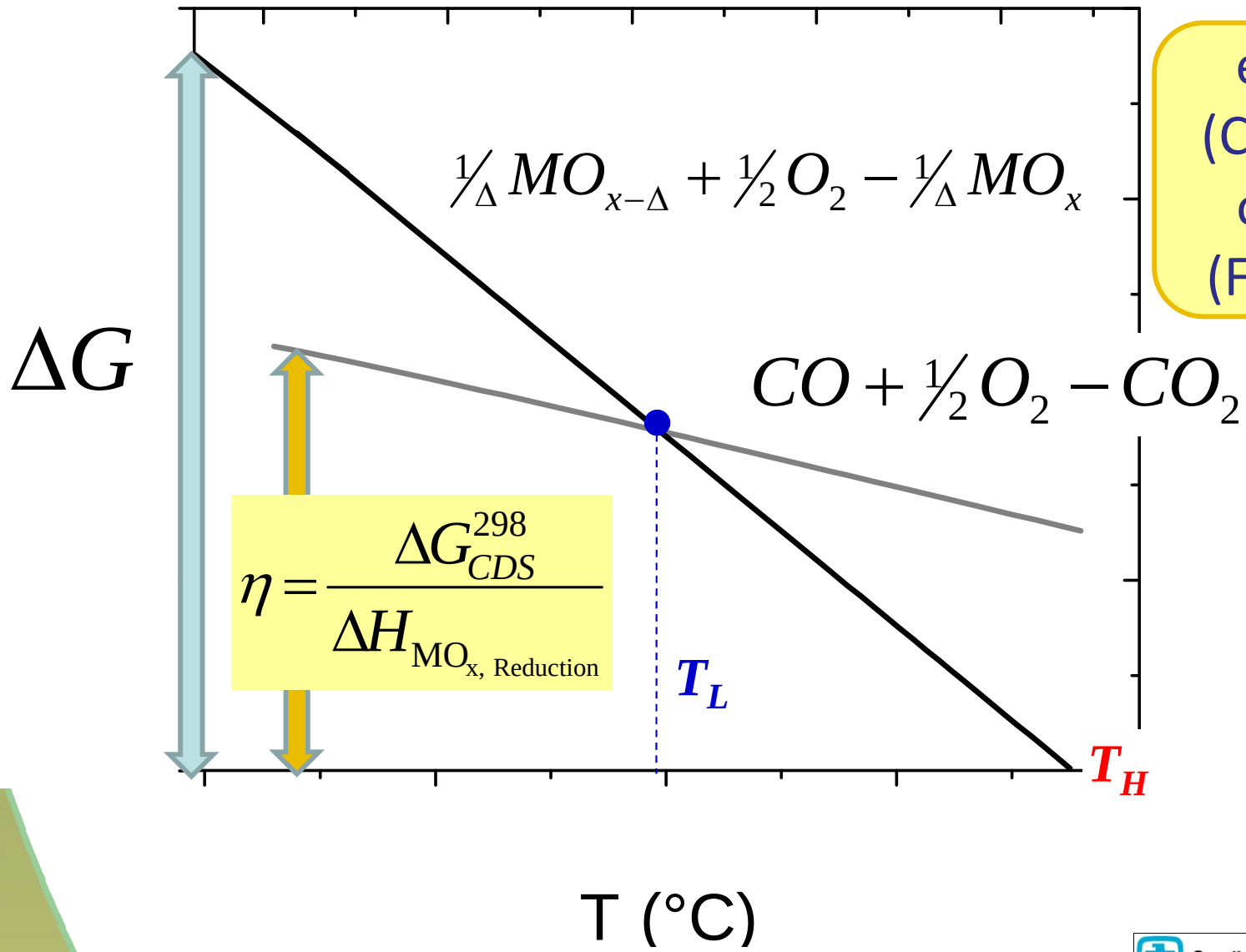
No Silver Bullet

- **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**



Thermodynamics



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

Enabling High Efficiency with Novel Reactor Design

"Reactorizing a Countercurrent Recuperator"

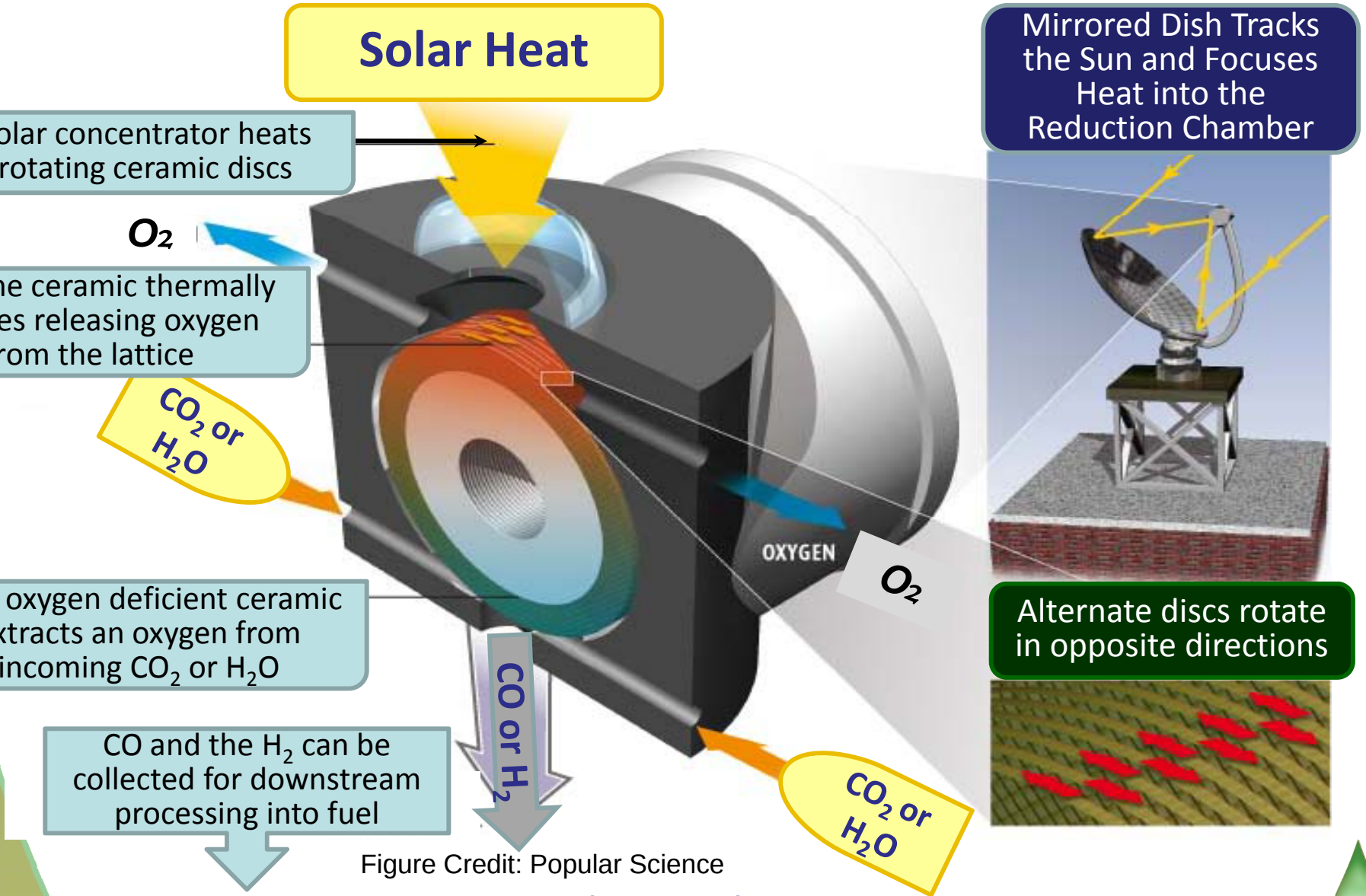
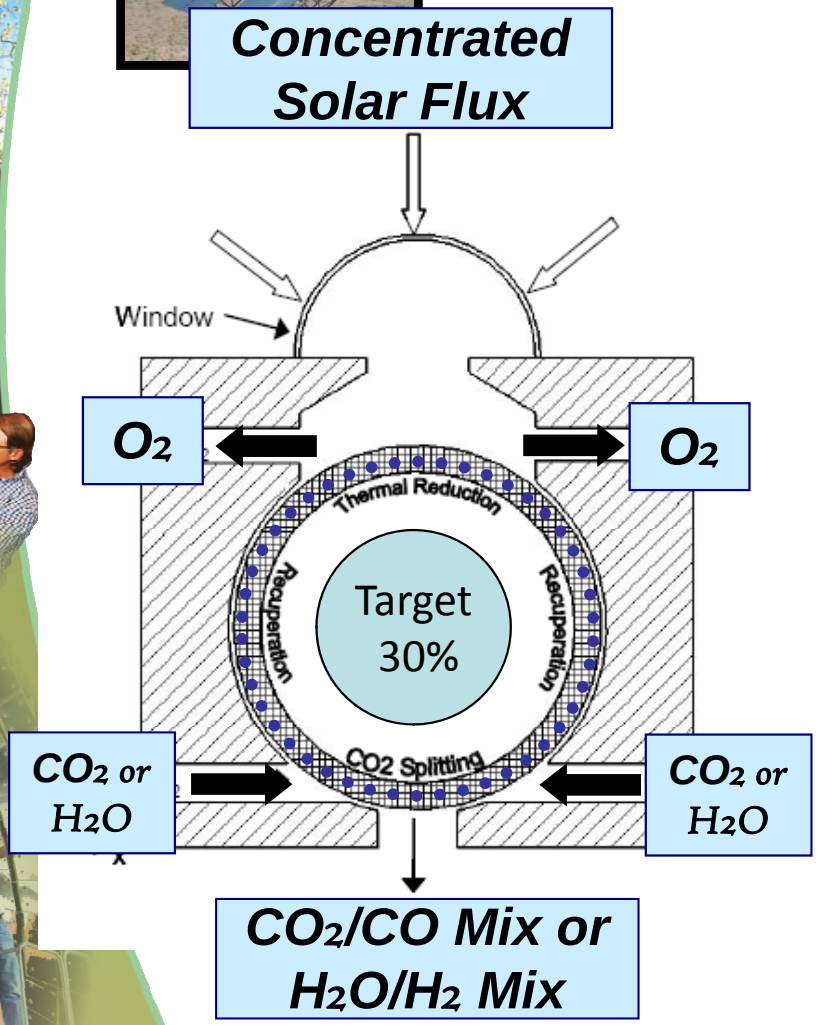


Figure Credit: Popular Science

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

The Enabling Innovation?
A "ThermoChemical Heat Engine"



To get High Efficiency- Enabling Attributes:

1. **Direct Radiative Heating,**
2. **Continuous flow,**
3. **Spatial product separation, and**
4. **Thermal recuperation**
5. **Durability**

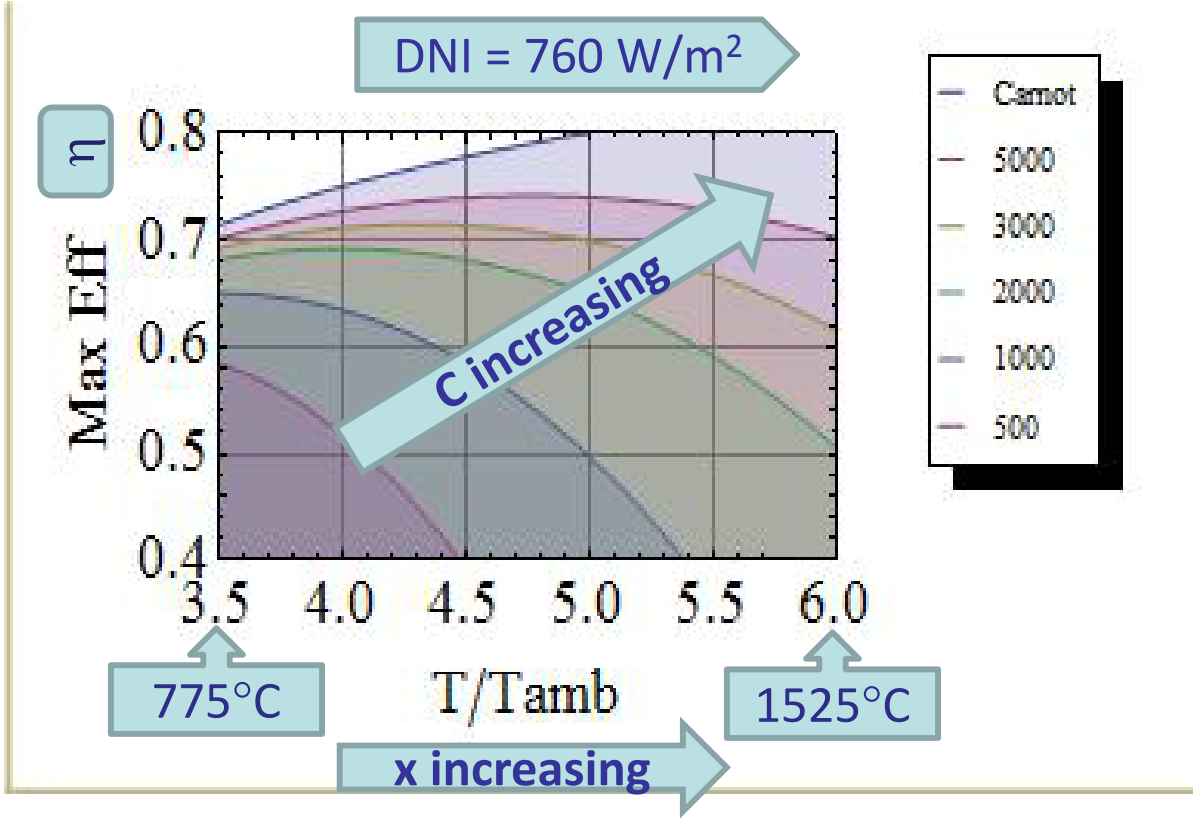
- Thermodynamics requires reactions be carried out at two temperatures.
- A thermochemical cycle is essentially a heat engine that converts heat into work in the form of stored chemical energy.
- Here, the "working fluid" is a metal oxide (e.g., Ce- or Fe-based.)
- High end temperatures of ~1300-1500°C couple well with CSP. (A bit lower would be better)
- Efficiency gains are possible as conversion to mechanical work and electricity are avoided.

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

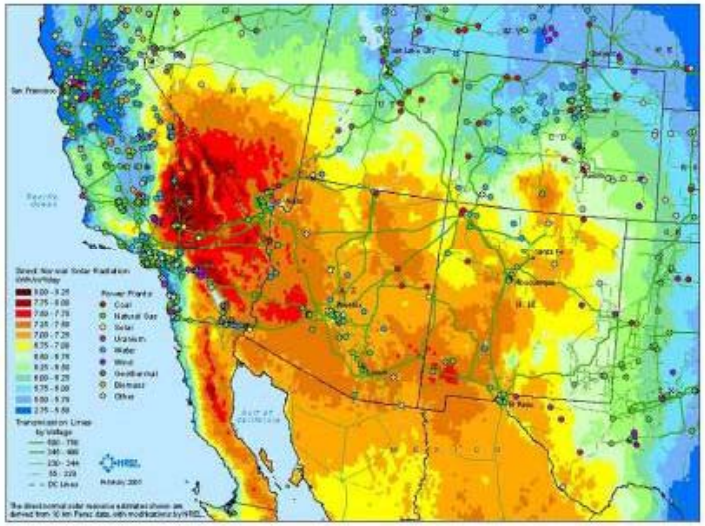
Target is 25-30% market ready – 1st chemical heat engine (~40-50% theoretical)

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

Goals & Milestones

- **Goal**: Demonstrate the technical feasibility of the solar conversion of CO_2 into CO in a thermochemical reactor with five key attributes: **direct heating, continuous flow, spatial separation, recuperation, and durability**
- **Metrics**: 2% sunlight into the reactor to CO chemical energy out, pathway to 20% sunlight (hitting the collector) to CO in an advanced system, and pathway to >10% Lifecycle efficiency
- **Timeline:** Demonstrate 2% steady state operation in the prototype (Generation 1) – 2011
  - 5 Year ECIS goal is to demonstrate 12.5% with materials and reactor advances (summer 2016) – Generation 2
    - **ARPA-E Target is 10% in 3 years**
  - 10 Year goal is to demonstrate 25-30% with additional materials and reactor advances and be market Ready (2021) – Generation 3
  - 15 Year goal is to demonstrate durable, economical system, manufacturable, developed supply chain, .. (2026) – Generation 4

Solar Resources Analysis Shows the Promise of Scale with High Efficiency Target



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

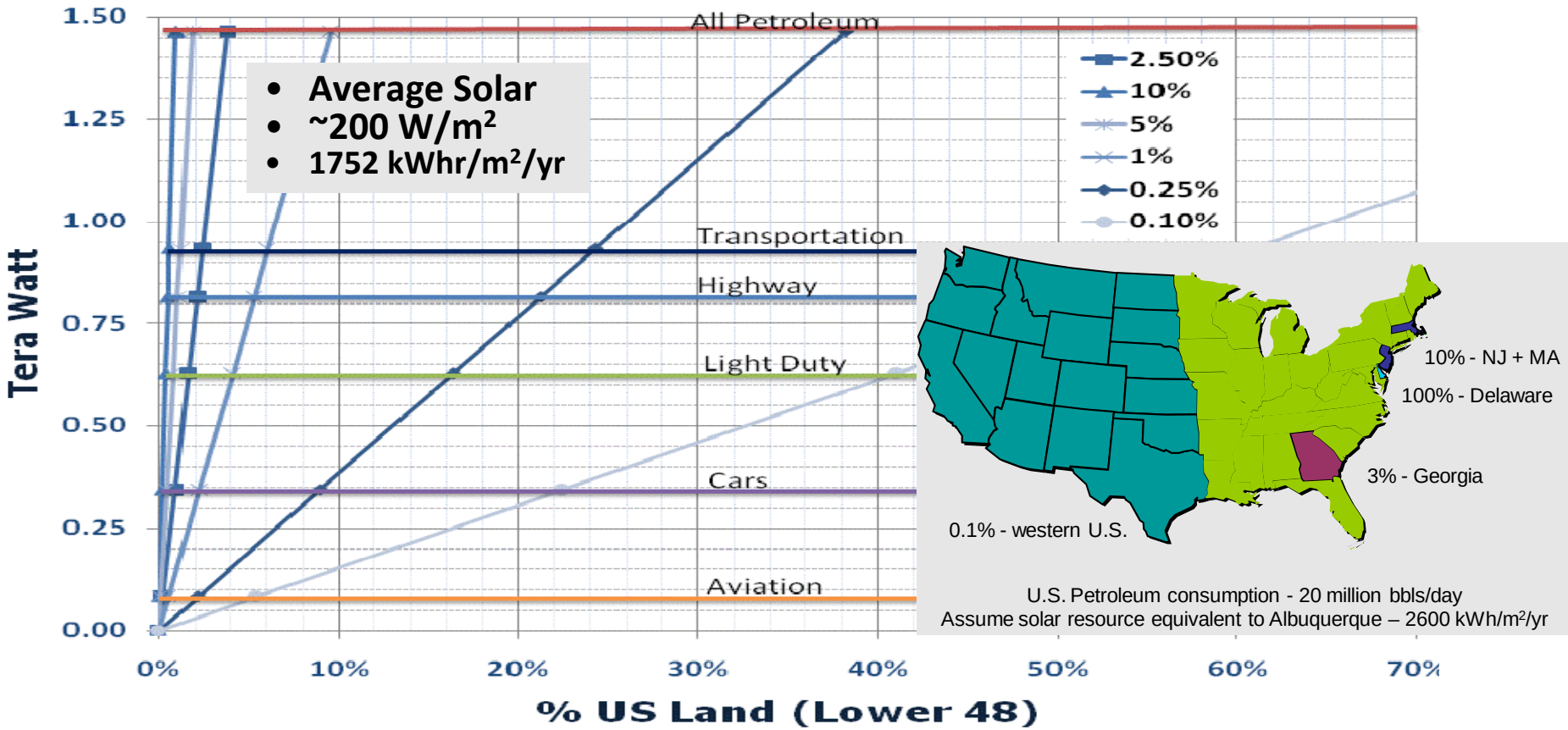
- Sites > 6.75 kwh/m^2/day
- Exclude environmentally sensitive lands, major urban areas, etc.
- Remove land with slope > 1%.
- Assume 25% packing density
- Only contiguous areas > 10 km^2 (675 $MW_{primary}$) 10 km^2 = 10^7 m^2 = 3.86 mi^2

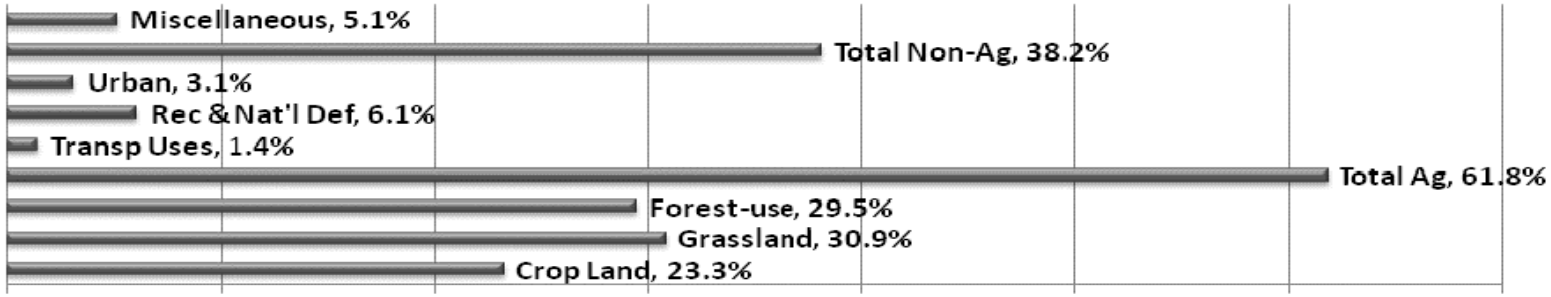
- U.S. Petroleum Demand is 20.7 mb/d (2007)
- **12.5%** lifecycle efficiency could produce 16.6 mb/d (**80%** of total U.S. demand)
- NM alone could produce **23%** of U.S. demand
- **12.5%** of available land (17.4 × 10^9 m^2) could provide **10%** of U.S. demand

State	Land Area (10^9 m^2)	Solar Capacity (TW)	Fuel Capacity (GW)	Fuel Capacity (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

139 billion m^2 is 1.5% of total U.S. land

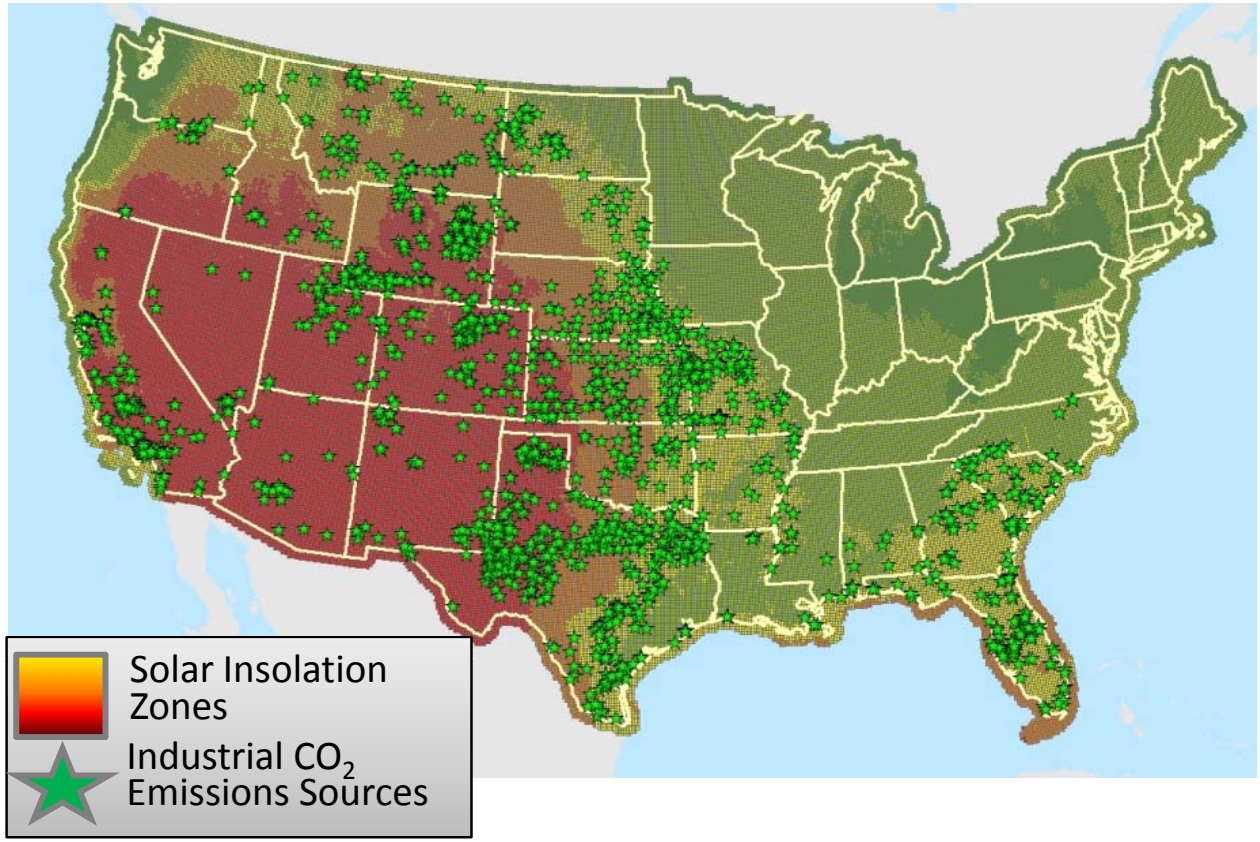
Efficiency → Scalability: Collector Area





Sunshine to Petrol

Numerous Large CO_2 Sources Exist



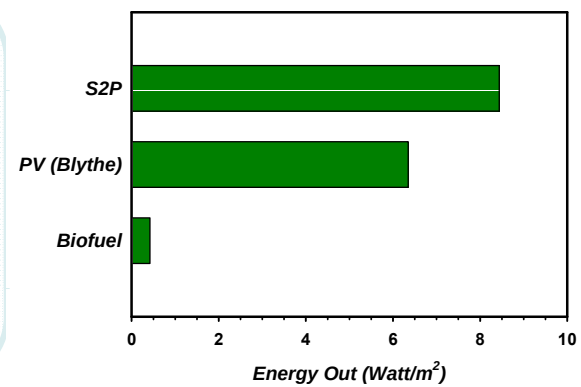
- Hundreds of large industrial CO_2 emissions sources exist in the United States in areas of high solar insolation.
  - 4-Corners Power Plant: 15.6 Mt/y and San Juan 13.4 Mt/y
  - At 81% utilization these two plants can supply fuel plants up to 9.8 GW (139 kb/d)
  - **~25 plants** of comparable size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

Substantial resources can be tapped.
Infrastructure exists for CO_2 transport.

Example of Resource: NRG Solar in Blythe, SD

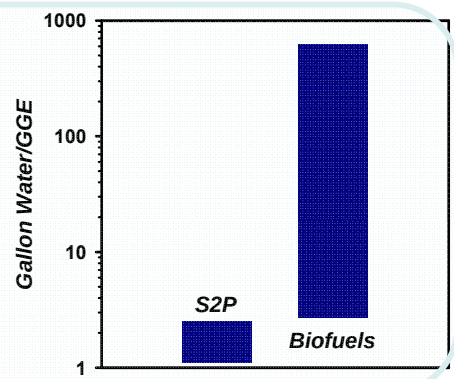
Energy Generation

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



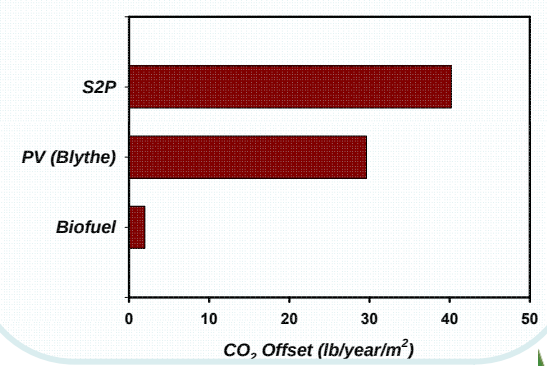
Water Utilization

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



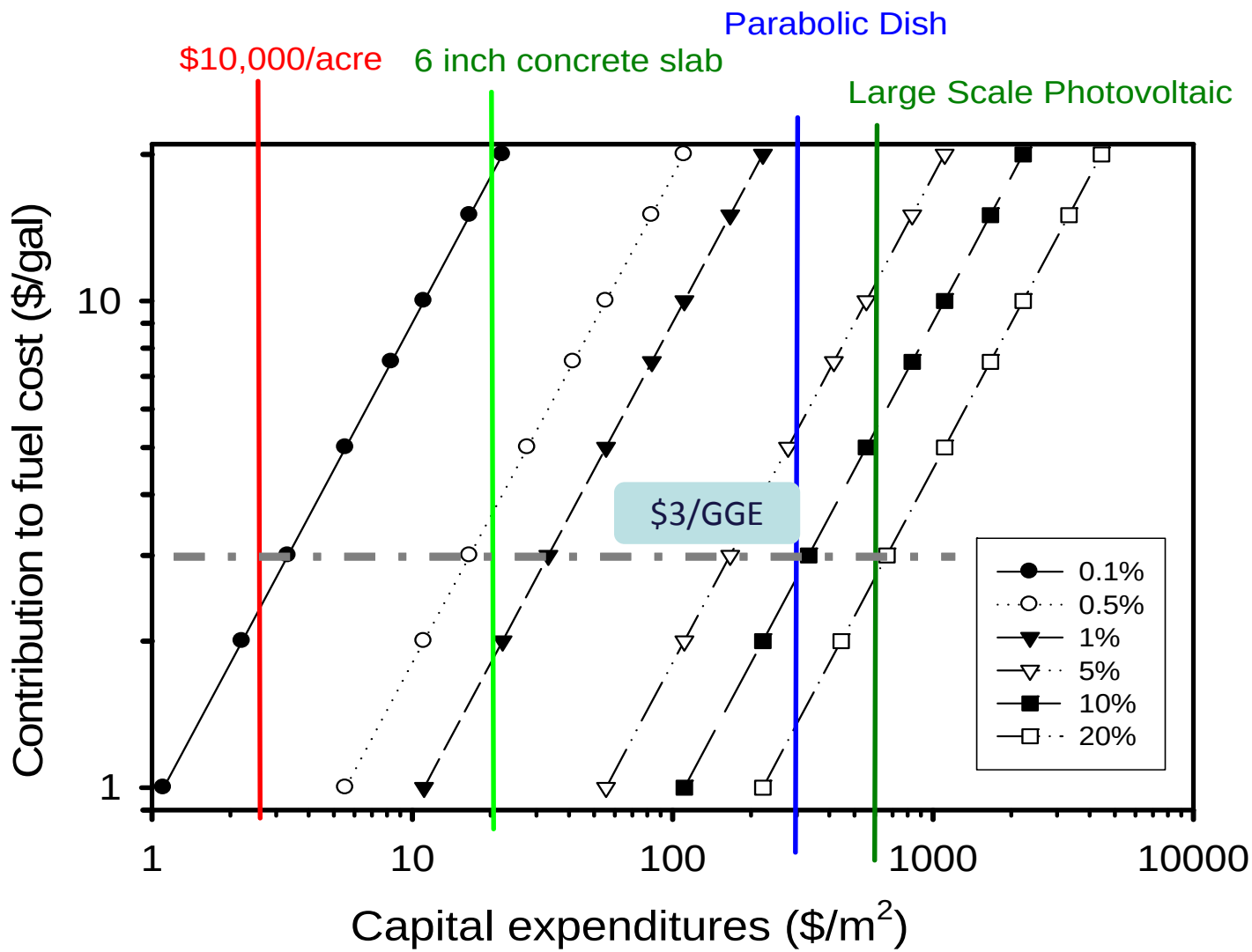
CO_2 Utilization

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



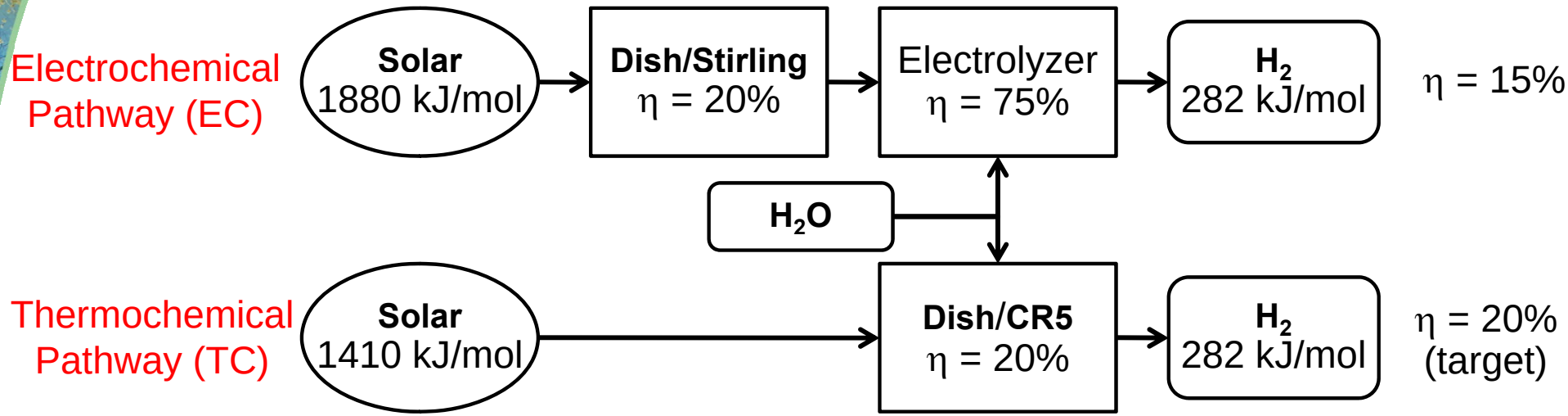
200 acre ≡ 0.81 $(km)^2$, 21 MW_e

Efficiency → Costs Collector Area



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

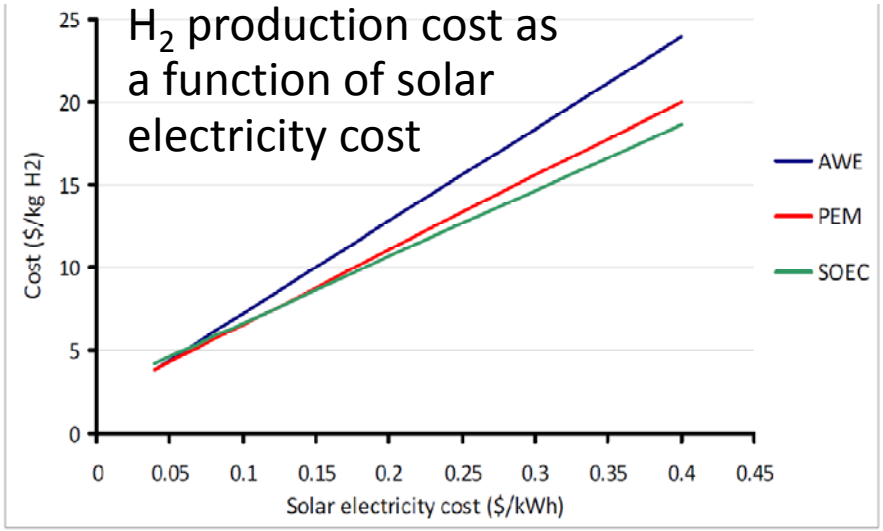
Comparison to Electrochemical Pathway Indicates Both Efficiency and Cost Benefits



Hydrogen Production Cost

- Assume 20 year plant lifetime
- Includes BOP* (separations, etc)

- Electrochemical Pathway
  - \$0.10 – 0.30/kWh electrical
  - 6 - 15 \$/kg-H_2
- Baseline Thermochemical Pathway
  - 5.97 \$/kg-H_2



University of Wisconsin

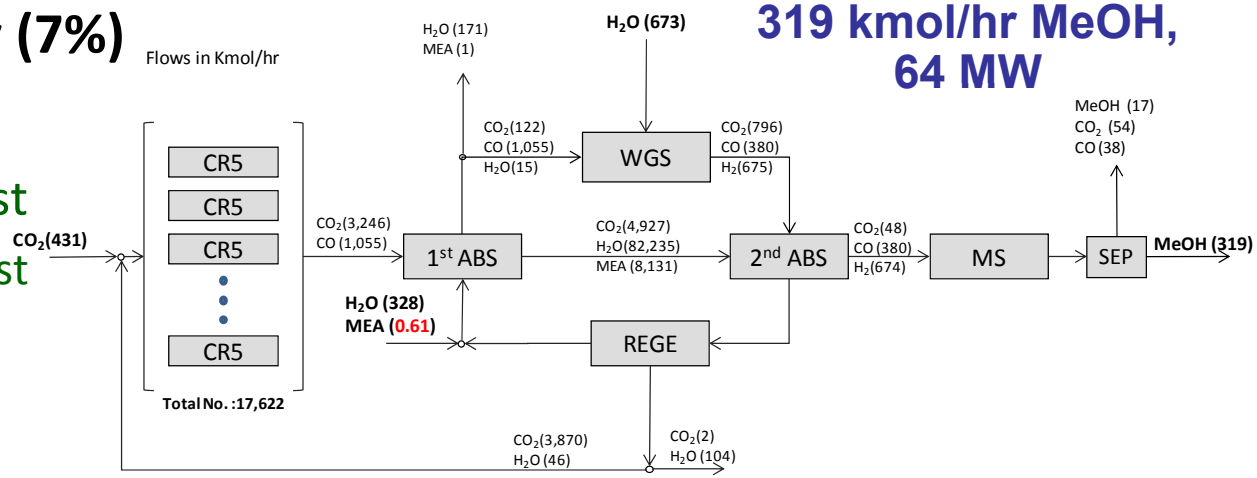
*BOP: Balance of Plant

Baseline System

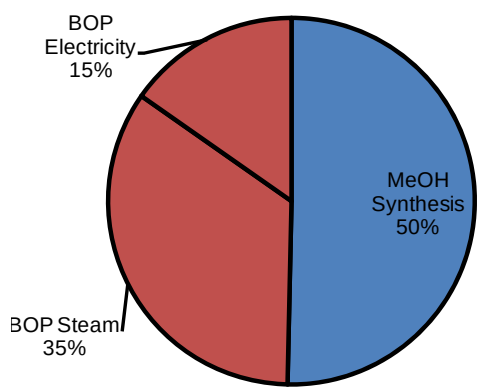
Baseline energy efficiency (7%)

- Dish/CSUs
  - 84% of the capital cost
  - 22.7% of operational cost
- Separations
  - MEA based CO_2
  - 48.7% of operational cost
  - 1.2% of the capital cost
- Water Gas Shift (WGS)
  - Minimal direct cost
  - Increases need for CO_2 separation
- Fuels synthesis
  - Minimal direct cost
  - Transition to higher value FT fuels from methanol

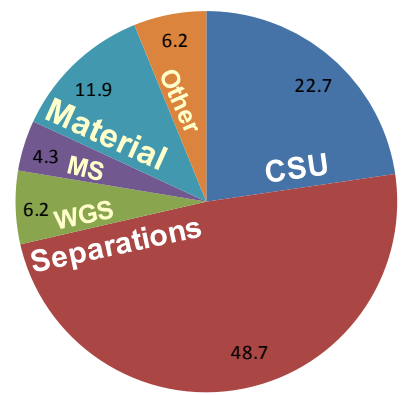
319 kmol/hr MeOH, 64 MW



Energy Balance:



System operating cost:



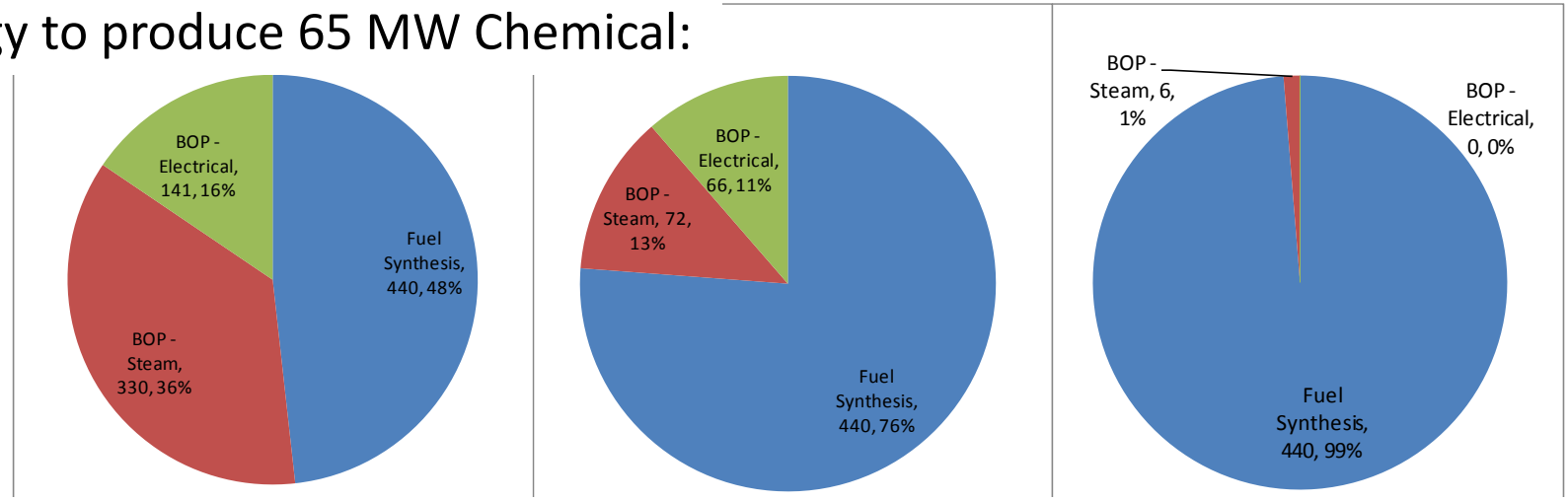
Current market price of methanol:
0.56 $/kg (0.09 $/kW-hr or 3.25 $/GGE)

Cost of methanol from baseline system:
1.70 $/kg (0.27 $/kW-hr or 9.88 $/GGE)

Improving the Balance of System

- The team has shown a pathway that:
  - Doubles the solar to chemical efficiency over the baseline system (from 7.1 to 16.2%)
  - Reduces the solar collection area by 51% (solar only system)
  - Produces end-use fuels at the S2P plant (FT)
  - Sets the stage for technology development, integration, and demonstration once the reactor is mature enough

Energy to produce 65 MW Chemical:

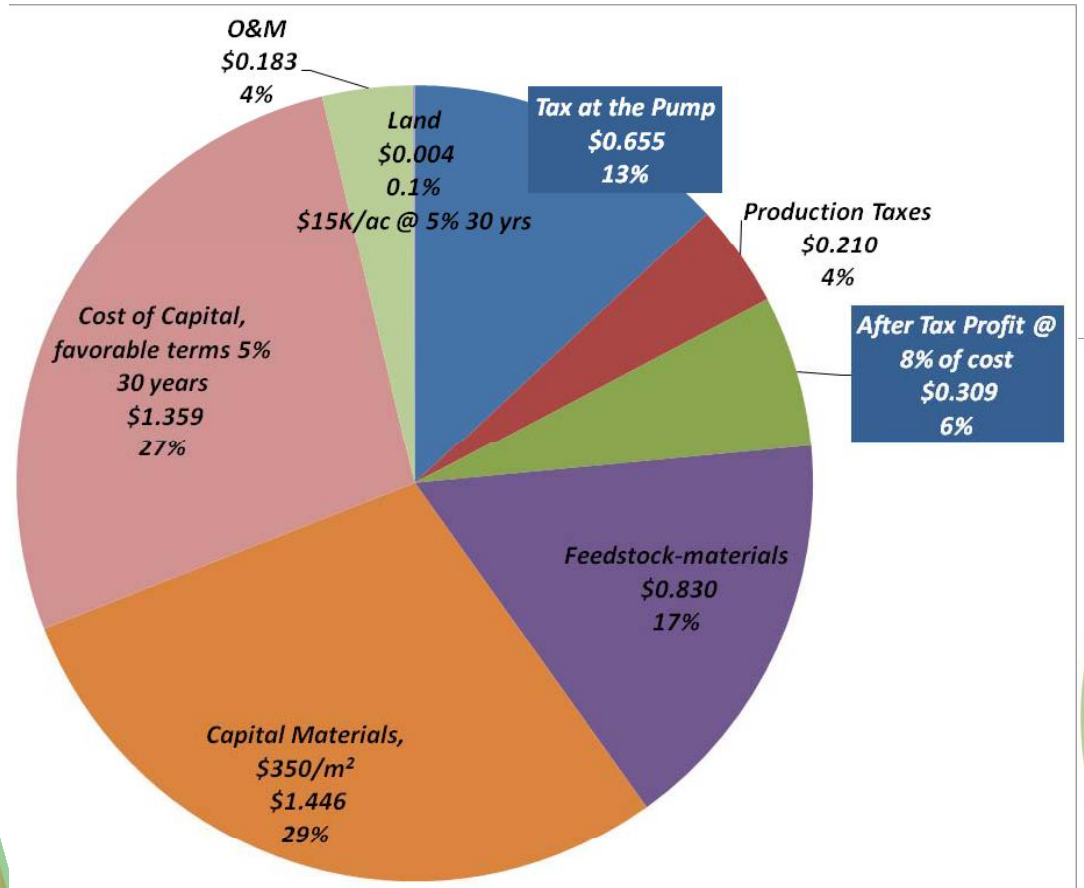


Baseline System 911MW solar | **Mixed Pathway 577MW solar** | **Advanced Sep/CR5 446MW solar**

Next efficiency and cost opportunity: CO_2 and H_2O splitting efficiency

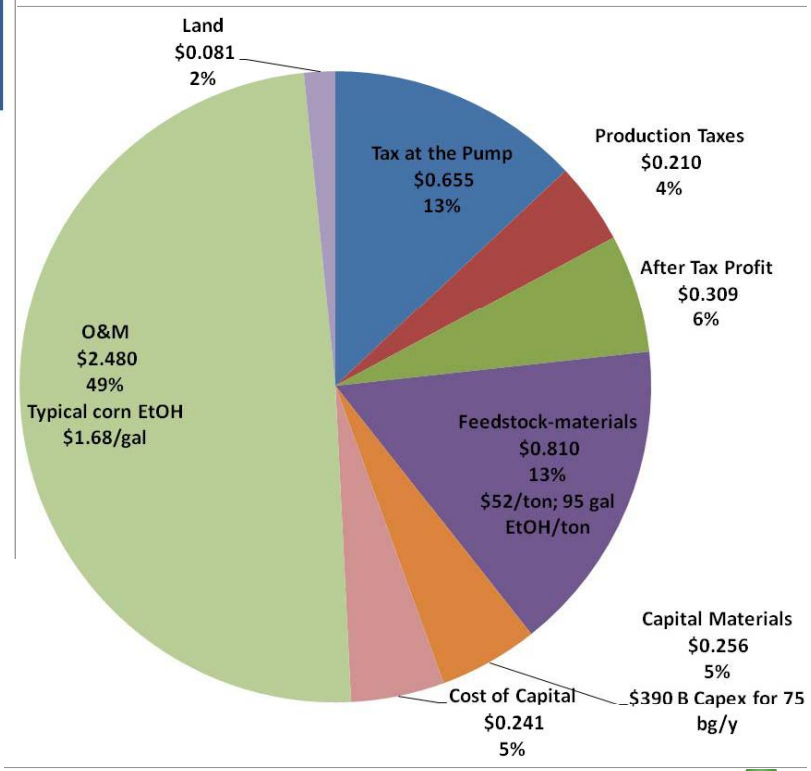
Sunshine to Petrol

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

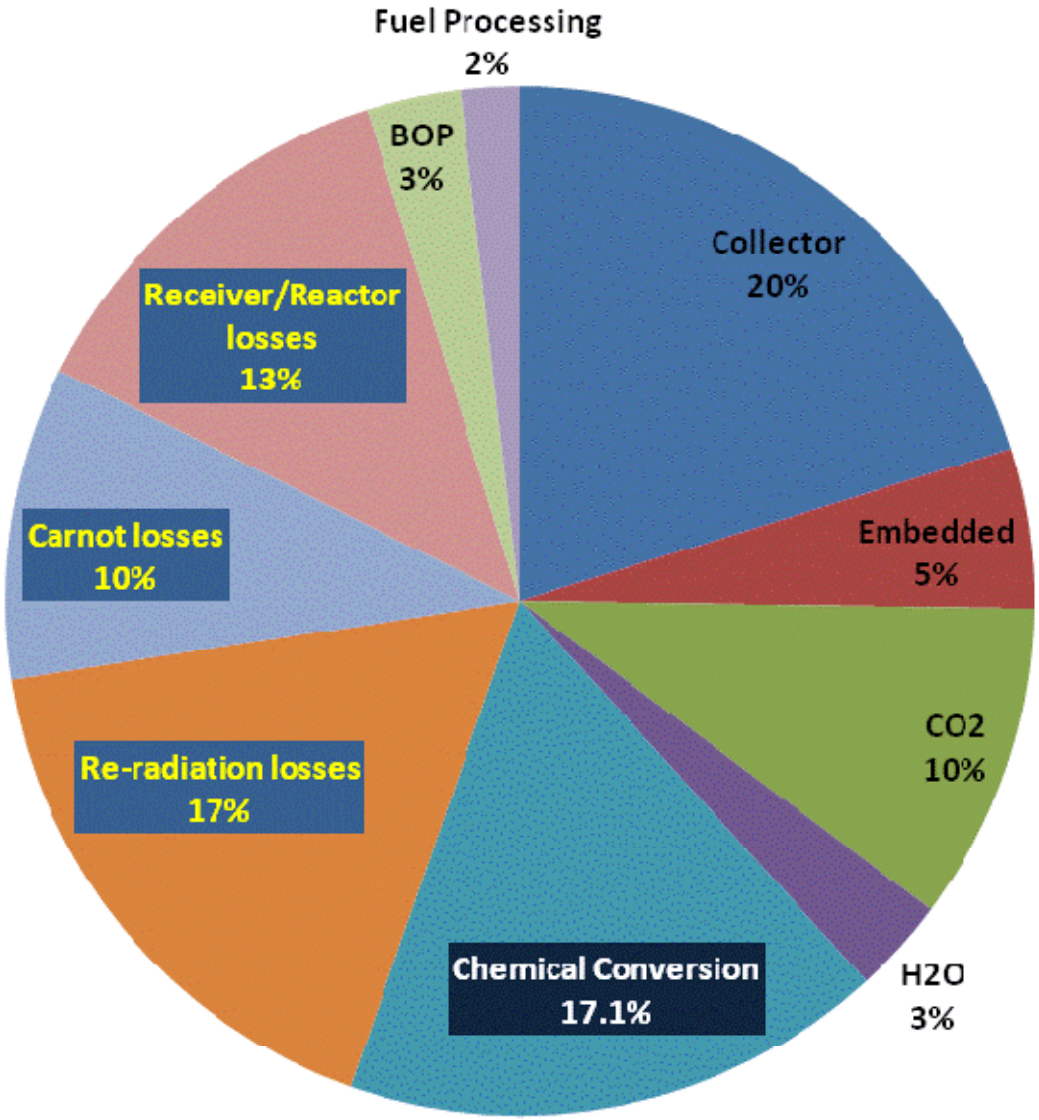


- Costs for S2P are in the ballpark of viability
- Learning curve will reduce the most expensive contributions
- Very sensitive to the cost of capital recovery

- Biofuels generally quote and demonstrate $2-4/GGE
- But, with similar assumptions as for S2P comes to ~$5.00/GGE, despite a very different breakdown



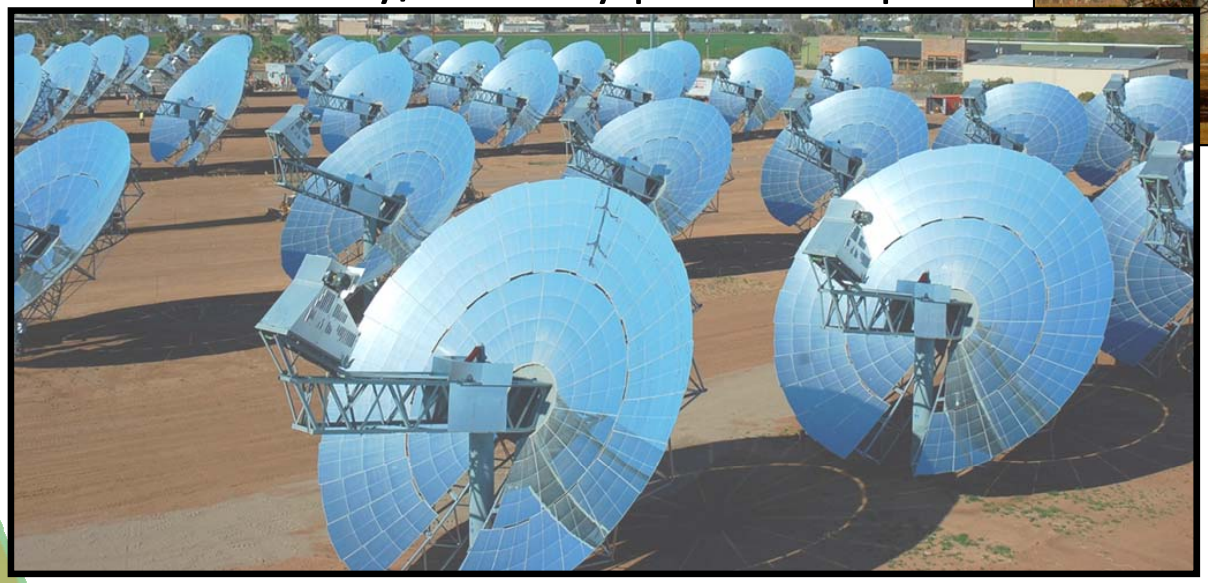
Graphical View of Where the Energy Goes: 12.5% LCE



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

One Path to the Market: Capitalizing on Adjacent Technology and Partnerships

- 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



SES intends to provide a dish for the project and is interested in potential commercialization

The reactor is the heart of the system

First of a kind – new innovative heat engine concept based on recuperation

Differentiating, Distinctive

Steep learning curve and a lot to learn

Builds on Sandia strength in solar engineering

THE REACTOR

The redox active materials are the heart of the technology

Builds on Sandia's core competency in Materials Science and Engineering but takes us into new regimes:

- high temperature materials, materials in extreme environments, complex metal oxides in new functional operating conditions

MATERIALS