The Storage and Utilization of Solar Energy

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Outline

• United States Energy Utilization and Solar Potential
• The Case for Energy Storage
• Concentrating Solar Power Technologies
• System Level Analysis
• Solar Fuels
U.S. Primary Energy Distribution

Annual Total = 94.6 Quads

Supply Sources

- Petroleum¹ 35.3
- Natural Gas² 23.4
- Coal³ 19.7
- Renewable Energy⁴ 7.7
- Nuclear Electric Power 8.3

Demand Sectors

- Transportation 27.0
- Industrial⁵ 18.8
- Residential & Commercial⁶ 10.6
- Electric Power⁷ 38.3

Source: US Energy Information Administration
Future Power Outlook

- Business as usual...
- Total consumption doesn’t change much

Source: Energy Information Administration
U.S. Transportation Fuel Sources

U.S. Petroleum and Other Liquids, Consumption, Production, and Imports (1949-2011)


Sources of U.S. Net Petroleum Imports, 2011

- Western Hemisphere: 52%
- Persian Gulf: 22%
- Africa: 20%
- Other: 6%

U.S. Domestic Solar Resource

58,000 Quads of solar energy fall on the US every year
CSP Potential in the US

Source: http://www.nrel.gov/csp/maps.html
# CSP Technical Potential in the SW USA

<table>
<thead>
<tr>
<th>Region</th>
<th>Solar Resources</th>
<th>Land as % of Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Premium</td>
<td>Excellent</td>
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<tr>
<td><strong>Northwest</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MW</td>
<td>–</td>
<td>1,791</td>
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<tr>
<td>GWh</td>
<td>–</td>
<td>3,529</td>
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<td>Acres (000)</td>
<td>–</td>
<td>9</td>
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<tr>
<td><strong>CO &amp; WY</strong></td>
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<tr>
<td>MW</td>
<td>2,513</td>
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<td>GWh</td>
<td>5,504</td>
<td>36,131</td>
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<td>Acres (000)</td>
<td>13</td>
<td>92</td>
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<tr>
<td><strong>California</strong></td>
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<td>MW</td>
<td>61,617</td>
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<td>GWh</td>
<td>134,942</td>
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<td><strong>Southwest</strong></td>
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<tr>
<td>MW</td>
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<td>GWh</td>
<td>825,956</td>
<td>417,600</td>
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<td>Acres (000)</td>
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<td><strong>Prairie States</strong></td>
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<td>–</td>
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<tr>
<td>GWh</td>
<td>–</td>
<td>4,105</td>
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<td>Acres (000)</td>
<td>–</td>
<td>10</td>
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<tr>
<td><strong>Texas</strong></td>
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<td></td>
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<tr>
<td>MW</td>
<td>38,842</td>
<td>50,681</td>
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<tr>
<td>GWh</td>
<td>85,064</td>
<td>99,892</td>
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<tr>
<td>Acres (000)</td>
<td>194</td>
<td>253</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWh</td>
<td>1,051,466</td>
<td>590,627</td>
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<tr>
<td>2001 Demand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GWh</td>
<td>1,092,160</td>
<td></td>
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</tbody>
</table>

1% of “Lower 48” - 41.5 mi X 41.5 mi

Western Demand

Source: POWERmap and RDI Consulting

Note: Estimate for electric generation assumes 5 acres/MW and capacity factors of 25% for premium, 22.5% for excellent, and 20% for good.
The Case for Energy Storage
Dispatchable Power from Solar

Source: http://www.volker-quaschning.de/articles/fundamentals2/index.php
Renewables and Storage

Study for Wind Power, 16% of supply

Source: Denholm et al, NREL Report: NREL/TP-6A2-47187, 2010
Concentrating Solar Power Technologies
Terminology

- \( MW_e \): Electrical power in megawatts
  - 1 MW supplies 600-1000 houses

- \( MW_{th} \): Thermal (or solar) power in megawatts
  - A central receiver converts solar (\( MW_{th} \)) to electricity (\( MW_e \)) at ~20% efficiency
Solar Energy Utilization

- **Solar to Electricity**
  - PV
  - CSP
  - Electrons
  - Heat
  - Battery
  - Thermal Storage
  - Power Block
  - Electric Power On Demand

- **Solar to Fuel**
  - H₂O/CO₂/Fossil/Biomass
  - Thermal Processes
  - Electrochemical
  - Final Fuel Synthesis
  - Stored Energy
    - H₂/CH₄/Liquid Fuels

Bucknell University
Parabolic Trough

Power Tower

Parabolic Dish

http://www.eere.energy.gov/basics/renewable_energy/csp.html
Parabolic Trough
Parabolic Trough with Storage and Hybridization
Commercial Parabolic Trough Projects

• SEGS:
  – 380 MW_e, Parabolic Trough, California, 1984

• Andasol:
  – 150 MW_e, 7 hours storage, Trough, Spain, 2009

• Nevada Solar One:
  – 65 MW_e, Trough, Nevada, 2007
Central Receiver

Source: Sandia National Laboratories
Gemasolar: 20 MW$_e$

Central Receiver With Storage

Commercial Central Receiver Projects

• PS 10/PS 20:
  – 10/20 MW$_{e}$, steam, Spain, 2007

• Gemasolar:
  – 20 MW$_{e}$, molten salt, 15 hours storage, Spain, 2011

• Ivanpah:
  – 392 MW$_{e}$, steam, no storage, California, 2013

• Crescent Dunes
  – 100 MW$_{e}$, molten salt, 15 hours storage, Nevada, 2013

• 100 MW will run 100,000 single family homes
Parabolic Dish - Stirling

1 MW$_e$ Tessera Solar Plant in Arizona

System Efficiency
Power Cycle Efficiency

Theoretical Carnot Limit

Typical Engineering Limit: 75% of Carnot

Air Brayton Combined Cycle

Supercritical Steam

Current Power Tower (subcritical steam)

Current Parabolic Trough (subcritical steam)

S-CO2 Brayton

Stirling

Ericsson

Trough

Tower

Dish
Solar Collection
Major Efficiency Components

\[ \eta_{collection} = \frac{\text{Energy Collected}}{\text{Energy Incident}} = \eta_{optical} \times \eta_{receiver} \]

**\( \eta_{optical} \)**
- Reflectivity: <93%
- Dirt: <95%
- Track: ~99%
- Window: 95%
- Intercept: 95%

**Total: 79%**

**\( \eta_{receiver} \)**
- \[ \sim \frac{\sigma T^4}{\text{DNI} \times \text{CR}} \]
  - Target: >80%

**\( \eta_{collection} > 60\% \)**
Annual System Efficiency

\[ \eta_{sys} = \sum_{Annual} \frac{Electricity}{Solar \ Incident} = \eta_{optical} \times \eta_{receiver} \times \eta_{conversion} \]

- Parabolic Trough: 15%
- Central Receiver: 18%
- Dish Stirling: 24%
  - World record at Sandia: 32% over one hour
- c-Si PV: 12% (15% module w/ 83% derate)
Solar Fuels
## Transportation Fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Energy per Unit Mass</th>
<th>Energy per Unit Volume</th>
<th>Temp. °C</th>
<th>Mass (per unit volume)</th>
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</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>1.0</td>
<td>1.0</td>
<td>25</td>
<td>1.0</td>
</tr>
<tr>
<td>JP-5</td>
<td>.97</td>
<td>1.1</td>
<td>25</td>
<td>1.0</td>
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<tr>
<td>Methanol</td>
<td>.44</td>
<td>.51</td>
<td>25</td>
<td>1.1</td>
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<tr>
<td>Ethanol</td>
<td>.61</td>
<td>.69</td>
<td>25</td>
<td>1.1</td>
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<tr>
<td>Liquid hydrogen</td>
<td>2.6</td>
<td>.27</td>
<td>-253</td>
<td>.1</td>
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<tr>
<td>Metal hydride</td>
<td>.046</td>
<td>.36</td>
<td>25</td>
<td>2.5</td>
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<tr>
<td>Methane @3,000 psi</td>
<td>1.1</td>
<td>.29</td>
<td>25</td>
<td>.25</td>
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<tr>
<td>Hydrogen gas @3000 psi</td>
<td>2.6</td>
<td>.06</td>
<td>25</td>
<td>.02</td>
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<tr>
<td>Liquid propane @125 psi</td>
<td>1.0</td>
<td>.86</td>
<td>25</td>
<td>.73</td>
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<td>Methane @10,000 psi</td>
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<td>.97</td>
<td>25</td>
<td>.81</td>
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<tr>
<td>Hydrogen gas @10,000 psi</td>
<td>2.6</td>
<td>.2</td>
<td>25</td>
<td>.08</td>
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<tr>
<td>Lithium ion battery</td>
<td>.019</td>
<td>.035</td>
<td>25</td>
<td>2.03</td>
</tr>
</tbody>
</table>
Artificial Pathways to Solar Fuels

Solar Energy

Solar to Electricity

H₂O/CO₂

PEC
PV
CSP

Electrolysis

Solar to Heat

H₂O/CO₂

Thermolysis
Thermochemical

H₂O/CO₂/Fossil/Biomass

Reforming
Cracking
Gasification/Pyrolysis

Intermediate Products – H₂/CO/CO₂/CH₃OH

Additional Inputs (e.g. biomass)

CO₂/H₂O/O₂

Fuel Synthesis

H₂/CH₄/Liquid Fuels
The Solar Fuel Equation

Solar Energy + xCO₂ + (x + 1)H₂O
→ CₓH₂ₓ+₂(liquid fuel) + (1.5x + 0.5)O₂

• Applicable to natural and artificial pathways
• One equation embodies many intermediate steps
The Building Blocks of Liquid Fuel

Solar Energy + CO$_2$ $\rightarrow$ $\frac{1}{2}$O$_2$ + CO

Solar Energy + H$_2$O $\rightarrow$ $\frac{1}{2}$O$_2$ + H$_2$

Solar Energy + CH$_4$ + O$_2$ + 2H$_2$O $\rightarrow$ 10H$_2$ + 4CO

• CO and H$_2$ can be combined to make a synthetic fuel (e.g. Fischer-Tropsch)
• CO and H$_2$ can be “traded” via water gas shift
  – Downstream advantages for CO production
Gas to Liquids

Natural gas (or biogas/trash gas) can be converted to liquid fuel via a series of reactions. The first is steam methane reforming:

1. **EXTRACT GAS**
   - Gas rigs
   - Gas field

2. **REFORM GAS TO SYNGAS**
   - Natural gas converted to syngas
   - Reactors
   - Refinery

3. **TRANSFORM SYNGAS TO WAX**
   - Steam is recovered to make power

4. **SHIP AND DISTRIBUTE**
   - Fuel

5. **REFINERY TO END PRODUCTS**
   - Liquified wax is refined into fuel products
   - Refinery

**HOW IT WORKS**

1. Extract natural gas from the ground. Any gas works, but prolific new “shale gas” fields, which require new technology to extract, are especially promising.

2. Syngas is a mix of carbon monoxide and hydrogen. It’s made by adding pure oxygen to natural gas, heating it up to hundreds of degrees Celsius, mixing it with steam and passing it over a catalyst. The resulting chemical reaction produces syngas.

3. Using heat, pressure and a different catalyst – often cobalt – the small, simple molecules in syngas are transformed into much larger, more complex “paraffinic” – or wax – molecules. Carbon monoxide has just one carbon per molecule. The wax produced in this step, which resembles what you would see in a candle, can have 30.

4. The wax, which flows like a liquid when it’s hot, is brought into a refinery. The process from there is much like any other refinery, where more heat, pressure and catalysts are used to rearrange the big wax molecules into ones that are generally smaller – and thus constitute diesel and other fuels.

5. Most of the product is an ultra-clean biodegradable diesel that’s very low in sulphur, and sells at a premium to crude oil diesel. Much of the remainder is naphtha, which can be used to make thick oil sands bitumen flow.

**END FUEL PRODUCTS**

- Diesel: 75%
- Naphtha: 24%
- Propane: 1%
Solar Thermochemical Reactions

- "Thermolysis"
  \[ \text{CO}_2 \rightarrow \frac{1}{2} \text{O}_2 + \text{CO} \]
  \[ \Delta G = 0 \text{ at } \sim 3000^\circ \text{C} \]

- High temperature
- Recombination (quench)
Multi-Step Reactions

Thermal Reduction \([T_{\text{high}}]\):

\[
\frac{1}{\delta} \text{MO}_x \rightarrow \frac{1}{\delta} \text{MO}_{x-\delta} + \frac{1}{2} \text{O}_2 \quad (A)
\]

Oxidation \([T_{\text{low}}]\):

\[
\frac{1}{\delta} \text{MO}_{x-\delta} + \text{CO}_2 \rightarrow \frac{1}{\delta} \text{MO}_x + \text{CO} \quad (B)
\]

\[
\text{CO}_2 \rightarrow \text{CO} + \frac{1}{2} \text{O}_2
\]

- A+B=CDS
- Lower temperature
  - \(~1500^\circ\text{C}\)
- Product separation
  - (no quench)
- Solid gas reaction
  - \(\text{Fe}_3\text{O}_4 : \text{YSZ}, \text{CeO}_2\)
Reactor Prototype: The CR5

Uses a two step solar- thermochemical process based on a metal-oxide to split water or carbon dioxide:

1) \( \text{Fe}_3\text{O}_4 + \text{Heat} \rightarrow 3\text{FeO} + \frac{1}{2}\text{O}_2 \)

2) \( 3\text{FeO} + \text{CO}_2 \rightarrow \text{Fe}_3\text{O}_4 + \text{CO} \)

Net: \( \text{CO}_2 \rightarrow \text{CO} + \frac{1}{2}\text{O}_2 \)

Sources: Sandia National Labs
Reactive Structures

Sources: Sandia National Labs
System Level Energy Walkthrough

Resource eff. = (Resource > 300 DNI) / Resource = 95% for Daggett

Operational ~ 94%
- Equip. Availability = 97%, B&S = 98%, Wind Outage = 99%

Optical ~ 79%
- Reflectivity = 93% (two reflections), Dirt = 95%, Window = 95%
- Tracking = 99%, Intercept = 95%

Receiver ~ 82%
- Radiation = 82%
- Conduction/Convection = 0%

Reactors/Thermochemical ~ 40%
- Pumping ~ 96% (100 Pa)

Solar to Available Heat = 58%

$H_2 \ @ \ \eta_{sys} = 23\%$

To Fuel

To Power

Thermal Power Conversion ~ 50%

$\text{Electricity} \ @ \ \eta_{sys} = 29\%$
## Solar Power and Fuel “Today”

<table>
<thead>
<tr>
<th>Technology</th>
<th>Solar to electricity(^b)</th>
<th>Electricity to hydrogen(^c)</th>
<th>Solar to hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic/AE(^a)</td>
<td>15%</td>
<td>73%</td>
<td>11%</td>
</tr>
<tr>
<td>Molten Salt Tower/AE</td>
<td>18%</td>
<td>73%</td>
<td>13%</td>
</tr>
<tr>
<td>Dish Stirling/AE</td>
<td>24%</td>
<td>73%</td>
<td>18%</td>
</tr>
</tbody>
</table>

### Future Electricity @ $\eta_{sys} = 29\%$

### Future $H_2$ @ $\eta_{sys} > 23\%$

$$\text{Annual Efficiency} = \sum_{\text{annual}} \frac{Q_{\text{product}}}{Q_{\text{solar,a}}}$$
Conclusions

• Domestic solar resource is large and undeveloped
  – But commercial projects are on the move
• Storage is important to the continued growth of renewable energy systems
  – Dispatchable power
  – Grid stability
  – Transportation fuels
• Natural gas can enable solar technologies in the near term
• Higher temperature/higher efficiency on the horizon
Thank You

• Questions?
Additional Resources
DIY Solar

- http://www.heliotrack.com/Parabolic.html
- http://www.redrok.com
Solar Research Archives

• Sandia Report Server

• NTIS
  – http://www.ntis.gov/

• OSTI
  – http://www.osti.gov/home/
GIS and Maps

- Geographic Information System (GIS) Data and Maps
  - NREL’s main site:
  - Renewable Technical Potential
    - [http://www.nrel.gov/gis/re_potential.html](http://www.nrel.gov/gis/re_potential.html)
  - Solar Maps
  - Other Tools
Measured Data

• Cooperative Networks for Renewable Resource Measurements
  – Data files, format, realtime display.

• NOAA
  – http://rredc.nrel.gov/solar/old_data/noaa/

• NREL Measurement and Instrumentation Data Center
  – http://www.nrel.gov/midc/
TMY Data

- TMY2 Data is based on measurements from 1961-1990
- TMY3 is based on measurements from 1991-2005.
- Both formats contain hourly data for every day of a typical year.

- You can get them here:

- These data are the foundation of many system level or annual performance calculations
Sun Position Calculators

- Instantaneous position calculation
  - [http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html](http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html)
- Map output
  - [http://www.esrl.noaa.gov/gmd/grad/solcalc/index.htm](http://www.esrl.noaa.gov/gmd/grad/solcalc/index.htm)
- Tabulated solar position
    - Valid to 2050 CE at +/- 0.01 degrees accuracy
    - Valid to 6000 CE at +/- 0.0003 degrees accuracy
Residential Solar Power Calculators

• PVWatts:

• In My Backyard: