Solar Thermal Technology
for
Climate Change Mitigation

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Can Solar Thermal Technologies play a role in Climate Change Mitigation!

Source: EIA
Fuel prices and current laws and regulations drive growing shares of renewables and natural gas in the electricity generation mix—

- **Fuel prices drive near-term natural gas and coal shares.** As natural gas prices rebound from their 20-year lows which occurred in 2016, coal regains a larger generation share over natural gas through 2020.

- **Federal tax credits drive near-term growth in renewable generation,** displacing growth in natural gas.

- **In the longer term,** policy (Clean Power Plan, renewables tax credits, and California's SB32) and unfavorable economic conditions compared with natural gas and renewables result in declining coal generation and growing natural gas and renewables generation in the Reference case. —as coal's share declines over time in the Reference case.
Battery Storage - Load Leveling, Peak Shaving
Renewable Electricity Cost

Source: BloombergNEF. Note: The global benchmark is a country weighted-average using the latest annual capacity additions. The storage LCOE is reflective of a utility-scale Li-ion battery storage system running at a daily cycle and includes charging costs assumed to be 60% of whole sale base power price in each country.
Solar Electricity Costs

**Concentrating Solar Power**

Typical Cost per kWh: $0.07 – 0.12

**Photovoltaic**

Median electricity

Typical Cost per kWh: $0.07
Annual global irradiation in Europe and USA. (Source: Volker Quascning, DLR & Manuel Blanco Muriel, CIEMAT, Spain)

<table>
<thead>
<tr>
<th>Location</th>
<th>Site Latitude</th>
<th>Annual DNI (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barstow, California</td>
<td>35°N</td>
<td>2,725</td>
</tr>
<tr>
<td>Las Vegas, Nevada</td>
<td>36°N</td>
<td>2,573</td>
</tr>
<tr>
<td>Tucson, Arizona</td>
<td>32°N</td>
<td>2,562</td>
</tr>
<tr>
<td>Alamosa, Colorado</td>
<td>37°N</td>
<td>2,491</td>
</tr>
<tr>
<td>Albuquerque, New Mexico</td>
<td>35°N</td>
<td>2,443</td>
</tr>
<tr>
<td>El Paso, Texas</td>
<td>32°N</td>
<td>2,443</td>
</tr>
<tr>
<td>International</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Mexico</td>
<td>26-30°N</td>
<td>2,835</td>
</tr>
<tr>
<td>Wadi Rum, Jordan</td>
<td>30°N</td>
<td>2,500</td>
</tr>
<tr>
<td>Ouarzazate, Morocco</td>
<td>31°N</td>
<td>2,364</td>
</tr>
<tr>
<td>Crete, Greece</td>
<td>35°N</td>
<td>2,293</td>
</tr>
<tr>
<td>Jodhpur, India</td>
<td>26°N</td>
<td>2,200</td>
</tr>
</tbody>
</table>
DNI Effect CSP Costs

CSP System

Concentrating Solar Thermal Field

Thermal Energy Storage

Power Block

Electricity

Waste Heat
System Efficiency

Graph showing the relationship between useful energy produced, operating temperature, collector subsystem, power generation subsystem, and combined system.
Daily Summer Output Pattern at the SEGS IV Plant in Kramer Junction, CA
Concentration Ratio

Area concentration ratio (geometric):

\[ C = \frac{A_a}{A_r} \]

Optical concentration ratio:

\[ C_O = \frac{1}{A_r} \int I_r dA_r \]

\[ \frac{I_r}{I_a} \]

\[ I_r \] is the averaged irradiance
\[ I_a \] is the insolation incident on the collector aperture

System Efficiency

\[ \eta_{\text{system}} = \eta_{\text{collector}} \times \eta_{\text{process}} \]
Collector Configurations

a) Tubular absorbers with diffusive back reflector; b) Tubular absorbers with specular cusp reflector; c) Plane receiver with plane reflector; d) parabolic concentrator; e) Fresnel reflector f) Array of heliostats with central receiver

Concentration Ratio vs. Receiver Temperature

Lower limit:
thermal losses = absorbed energy

Linear Concentrators: Parabolic Cross Section

Parabolic Trough Technology

Thermal Conversion Efficiency = \frac{\text{net heat collected}}{\text{incident solar radiation}}

Over the last 25 years has been to make larger collectors with higher concentration ratios in order to improve the collector thermal efficiency. However, due to increased material costs, the majority of the initial investment cost is associated with the solar field. Much progress effort is on increasing the efficiency of the plant, it is more useful to find ways to reduce the LEC largely depend on the capital costs. It is useful to think in terms of the cost/energy ratio to determine the viability of the CSP plant. Although much of the recent progress in concentrating solar power (CSP) has been in the areas of improved plant efficiency and reduced capital costs, the CSP industry faces many challenges in order to realize a commercially viable technology. We consider the state of the art in concentrating solar power technology, industrial cost drivers, and the key issues in CSP commercialization.

The typical thermal conversion efficiency (net heat collected/incident solar radiation over the trough aperture area) for a parabolic trough is shown in Fig. 33.10. The efficiency is largely affected by the collector thermal and optical losses. Since the radiation losses are proportional to the fourth power of the temperature, the Rankine cycle, which is the most fundamental and widely used steam-power cycle. The variation of the thermal efficiency of a parabolic collector with operating temperature is approximated by the relation

\[ \text{Thermal Efficiency} = \frac{\text{net heat collected}}{\text{incident solar radiation}} \]

The concentrating parabolic trough systems typically produce power based on the Rankine cycle, which is the most fundamental and widely used steam-power cycle. The cycle starts with superheated steam generated by the heat collected from the parabolic trough field. The superheated vapor expands to lower pressure in a steam turbine that drives a generator to convert the work into electricity. The turbine exhaust steam is then directed to a condenser, where it is cooled to its initial pressure and then returned to the boiler to complete the cycle again. The simple steam cycle thermodynamic efficiency can be as high as 35%, depending on the steam parameters. The thermal efficiency of a parabolic trough plant can vary significantly depending on the specific design and operating conditions. For example, the SEGS system experience shows that the annual solar to electricity conversion efficiency varies from 10.7% to 14.6%, with the higher number corresponding to the majority of the initial investment cost is associated with the solar field. Much progress effort is on increasing the efficiency of the plant, it is more useful to find ways to reduce the LEC largely depend on the capital costs. It is useful to think in terms of the cost/energy ratio to determine the viability of the CSP plant. Although much of the recent progress in concentrating solar power (CSP) has been in the areas of improved plant efficiency and reduced capital costs, the CSP industry faces many challenges in order to realize a commercially viable technology. We consider the state of the art in concentrating solar power technology, industrial cost drivers, and the key issues in CSP commercialization.

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plant produces about 134

The plant uses a supplementary gas heater to provide 2% of the total heat requirement. The electricity efficiency of the plant (such they can produce the equivalent electricity output from a 21 MW plant. The solar to factor of about 0.24. Coal power plants have a capacity factor on the order of 0.74, and as

in a nominal price of about $4.15/W. With medium temperature (250–300

A typical electricity production in a day is depicted in (as compared to an equivalent coal plant) is estimated to be about 100,000 MT/year.

thereby increasing the plant capacity factor. For example, while solar energy availability provide more uniform output over the day and increase annual electricity generation,

renewable energy solutions.

as low as $2.50/W, thus making the parabolic trough systems competitive with many other

troughs and advanced receiver designs, it is anticipated that the installed costs may reach

33

people. This characteristic differentiates CSP from PV technology, as the

solar field to the storage system (Source: www.acciona-na.com). A more desirable option under development is an

a two-tank system; it has an oil-to-salt heat exchanger to transfer thermal energy from the

Fig. 33.13

The ability to provide near-firm power through the use of thermal energy storage is

Fig. 33.16

Utility Load, Trough Plant Output

0.0

0.2

0.4

0.6

0.8

1.0

1.2

1.4

1.6

1.8

900

800

700

600

500

400

300

200

100

0

0

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

Hour Ending

Flow of heat transfer fluid

Solar heated heat transfer fluid

Supplementary gas heater

Solar superheater

Steam generator

Condenser

Cooling tower

Flow of heat transfer fluid

Super heated steam

Water flow

Steam & water

Turbine

Electric generator and transformer

Solar collector field

steam turbine

steam

deaerator

condenser

cooling system

solar evaporator

htf-salt heat exchanger

hot salt tank

cold salt tank

A typical performance graph for a parabolic trough plant is shown in Fig. 33.14. The CO$_2$ emissions from this plant are negligible.

Fig. 33.14

Fig. 33.15

Fig. 33.16

Power Tower Solar Power System

Ivanpah Solar Power Facility
The steam plant was designed for 28.72% gross efficiency.

The local irradiance near the area is about 7.4 kW·h/m²/day (annual average)
Power Tower CSP

Operating Temperature: 565°C; Capacity Factor: 63% (molten salt storage); Gemasolar 19.9 MW - Spain
Dish-Stirling CSP
Operating Temperature Range: 600-940°C

Dish-Stirling system (η~ 20 - 30%), USA
Maximum Receiver Temperature
A hybrid solar thermal/biomass scheme that improves the typical solar thermal capacity factor from 20% to 80%
An organic Rankine cycle (ORC) serves as a bottoming cycle to extract additional energy.
CO₂ Emissions

U.S. energy-related carbon dioxide emissions
billion metric tons of carbon dioxide

2016
history projections

transportation
electric power
industrial
residential
commercial

Can Solar Thermal Technologies play a role in Climate Change Mitigation!

Source: EIA
## Industrial Process Heat

Greatest Potential for Solar Thermal Use

<table>
<thead>
<tr>
<th>Industrial Sector</th>
<th>Process</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food and Beverages</td>
<td>Drying</td>
<td>30 – 90</td>
</tr>
<tr>
<td></td>
<td>Washing</td>
<td>40 – 80</td>
</tr>
<tr>
<td></td>
<td>Pasteurizing</td>
<td>80 – 100</td>
</tr>
<tr>
<td></td>
<td>Boiling</td>
<td>95 – 105</td>
</tr>
<tr>
<td></td>
<td>Sterilizing</td>
<td>140 – 150</td>
</tr>
<tr>
<td></td>
<td>Heat Treatment</td>
<td>40 – 60</td>
</tr>
<tr>
<td>Textile Industry</td>
<td>Washing</td>
<td>40 – 80</td>
</tr>
<tr>
<td></td>
<td>Bleaching</td>
<td>60 – 100</td>
</tr>
<tr>
<td></td>
<td>Dyeing</td>
<td>100 – 160</td>
</tr>
<tr>
<td>Chemical Industry</td>
<td>Boiling</td>
<td>95 – 105</td>
</tr>
<tr>
<td></td>
<td>Distilling</td>
<td>110 – 300</td>
</tr>
<tr>
<td></td>
<td>Various Chemical Processes</td>
<td>120 – 180</td>
</tr>
<tr>
<td>All Sectors</td>
<td>Pre-heating of boiler feed water</td>
<td>30 – 100</td>
</tr>
<tr>
<td></td>
<td>Heating of production halls</td>
<td>30 – 80</td>
</tr>
</tbody>
</table>

Medium Temperature Heat: 80°C – 200°C
Modern Solar Thermal Collectors

Note: adapted from the IEA Solar Heating and Cooling Implementing Agreement.

Concept

Stationary Panel

$CR > 1$

Tracking Receiver

Designed Working Fluid Temperature: 150$^\circ$C

This work was carried out by Dr. John Pandolfini as part of his Ph.D. Dissertation at FSU.
Ray Tracing
Ray Tracing

\[ \gamma \approx \frac{\#Hit}{N} \]
Parabolic Reflector with Moving Receiver

\[ \gamma = F(\theta_i) \]
Concept
Intercept Factor

Fraction of Rays Reaching Receiver with Incident Angle to Parabola
Axis, CR=6, $\theta_{\text{rim}}=60^\circ$
Collector Model

Efficiency for Various Normal Incidence Heat Flux

- Flow: 2 L/min
- Wind: 3 m/s
- $T_{\text{amb}} = 25^\circ \text{C}$

![Graph showing efficiency vs. temperature difference](image_url)
From 2005 to 2016, energy-related carbon dioxide (CO2) emissions fell at an average annual rate of 1.4%. From 2016 to 2040, energy-related CO2 emissions fall 0.2% annually in the Reference case.

In the industrial sector, growth in domestic industries, such as bulk chemicals, leads to higher energy consumption and emissions.

In the electric power sector, coal-fired plants are replaced primarily with new natural gas, solar, and wind capacity, which reduces electricity-related CO2 emissions.

Direct emissions in the residential and commercial building sectors are largely from space heating, water heating, and cooking equipment. The CO2 emissions associated with the use of electricity in these sectors exceed the direct emissions from these sectors.

Energy-related CO2 emissions from the transportation sector surpassed those from the electric power sector in 2016. Transportation CO2 emissions remain relatively flat after 2030 as consumption and the carbon intensity of transportation fuels stay relatively constant.

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Source: EIA
## Energy Density

<table>
<thead>
<tr>
<th>Method</th>
<th>kWh/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>14</td>
</tr>
<tr>
<td>Li-Ion Batteries</td>
<td>0.3</td>
</tr>
<tr>
<td>Hydrostorage</td>
<td>0.3/m³</td>
</tr>
<tr>
<td>Flywheel, Steel</td>
<td>0.05</td>
</tr>
<tr>
<td>Flywheel, Carbon Fiber</td>
<td>0.2</td>
</tr>
<tr>
<td>Flywheel, Fused Silica</td>
<td>0.9</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>38</td>
</tr>
<tr>
<td>Compressed Air</td>
<td>2/m³</td>
</tr>
</tbody>
</table>
Hydrogen Powered Fuel Cell Cars

Typical Range: 585 Km
Top Speeds: 170 km/h
H₂ Storage: 5.5 kg @ 689 bar

Expected cost of fuel cell stack: $50/kW
Expected Hydrogen cost: $6/kg (produced at the point of delivery)
Sustainable Paths to Hydrogen

Renewable Energy

- Heat
  - Mechanical Energy
    - Thermolysis
- Biomass
  - Conversion
    - Electrolysis
      - Hydrogen
    - Photolysis

Source:
D. Brent MacQueen
Brent.macqueen@sri.com
SRI International, Menlo Park CA
Technical grade Hydrogen currently costs about $6/kg

Compressing the gas, delivering it to a filling station, storing it and dispensing it to fuel cell vehicles cost about $13/kg
Energy Efficiency of Electrolysis

\[
\frac{\text{Chemical Potential}}{\text{Electrolysis Potential}} = \frac{1.23}{1.45} = 85\% 
\]

Coupling to a 20% Photo Voltaic array gives a solar to hydrogen efficiency of about 17.5%.

Requirement for Electrolysis: High Purity Water & Electricity
Sun heats redox materials, such as nickel ferrite or cerium oxide, in the interior of the reactor to 1400 degrees Celsius. At these temperatures, the metal oxide is chemically reduced, that is oxygen is released and transported out of the reactor.

The actual water splitting occurs in the second step, which takes place at 800 to 1000 degrees Celsius. Here, the water vapor flow through the reactor. The previously reduced material is reoxidised. As the oxygen is now bound into a metal oxide, it remains in the reactor, whilst the hydrogen is free to be transported out of the reactor. Once the material is completely reoxidised, it is regenerated through the first step of the procedure and the cycle starts again.

CERTH-CPERI-APTL
Hydrogen Production From Biomass

Source: John Dascomb, Ph.D dissertation, FSU, 2013
Hydrogen Production Efficiency

Biomass pellets → Fluidized bed w/ CaO

Steam generator

700 C → 25 C

H X

H2 Enriched Syngas

<table>
<thead>
<tr>
<th></th>
<th>As tested</th>
<th>with single heat exchanger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (mol %)</td>
<td>68.3</td>
<td>68.3</td>
</tr>
<tr>
<td>Total energy efficiency (%)</td>
<td>50</td>
<td>68</td>
</tr>
<tr>
<td>Elemental H2 prod. effic. (%)</td>
<td>29</td>
<td>40</td>
</tr>
</tbody>
</table>
Hydrogen Enriched Synthesis Gas Production Plant

1. Steam injection
2. Biomass screw feeder
3. Ceramic heaters
4. Reactor tube
5. Cyclone filter
6. Heat exchanger
7. Water scrubber/condenser
8. Cooled product gas exhaust

# Steam Gasification with CaO

<table>
<thead>
<tr>
<th>Test #</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor temperature (°C)</td>
<td>657</td>
<td>690</td>
<td>701</td>
</tr>
<tr>
<td>S/B ratio</td>
<td>2.9</td>
<td>2.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Gas residence time (sec)</td>
<td>2.7</td>
<td>2.6</td>
<td>2.7</td>
</tr>
<tr>
<td>Syngas component</td>
<td>Average gas conc. (dry mol %)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>65.5</td>
<td>69.4</td>
<td>68.3</td>
</tr>
<tr>
<td>Methane</td>
<td>11.1</td>
<td>8.8</td>
<td>8.7</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>10.8</td>
<td>7.5</td>
<td>9.3</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>9.4</td>
<td>12.0</td>
<td>11.3</td>
</tr>
<tr>
<td>Ethylene</td>
<td>1.6</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.5</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Acetylene</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Propylene</td>
<td>0.4</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>HHV (dry MJ/m³)</td>
<td>15.6</td>
<td>14.2</td>
<td>14.3</td>
</tr>
</tbody>
</table>

Conclusions

Concentrated Solar Thermal Technologies best suited for energy storage

Multiple Parabolic Reflector Flat Panel Collector design for Industrial process heat

Most Efficient Solar energy to Split Water to Hydrogen is Concentrated Solar Power