17. Concentrated Solar Power Plants

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CONCENTRATED SOLAR POWER (CSP)

- Many conventional power plants use heat to boil water to produce high-pressure steam, which expands through the turbine to spin the generator rotor and results in the production of electricity.

- CSP technology extracts the heat from the solar irradiation and its operation resembles the steam generation plants that burn fossil fuels or use uranium to produce electricity.
REVIEW OF INSOLATION COMPONENTS

- reflected radiation
- diffused radiation
- direct beam radiation

PV technology is able to collect and deploy all the 3 insolation components for electricity production.

Unlike PV, CSP can concentrate only the direct beam radiation – often called direct normal irradiation (DNI) – to generate electricity.

Specifically, CSP plant uses mirrors with tracking systems to focus DNI and collect the solar energy.
CSP

- The solar energy is used to heat up the heat transfer fluid (HTF) and convert HTF into thermal energy.

- Subsequently, the absorbed thermal energy is utilized to generate steam which drives a steam turbine to produce electricity.

- Some CSP plants incorporate thermal storage devices.
KEY COMPONENTS OF A CSP PLANT

❑ A typical CSP plant set-up includes

- collectors that reflect solar rays to a receiver
- a receiver that converts solar energy into thermal energy
- a power block that converts thermal energy into electricity

❑ The collector configurations are used to classify CSP plants into 4 distinct categories

- parabolic trough
- solar tower
- Fresnel reflector
- dish Stirling
Parabolic trough CSP technology uses parabolic mirrors to concentrate DNI onto the receivers positioned along each mirror’s focal line.

Source: http://www.abengoa.com
Solar tower CSP technology employs *heliostats* – collectors with dual-axis trackers – to concentrate *DNI* onto a central receiver – the solar tower
SPAIN 20 – MW
GEMASOLAR THERMOSOLAR PLANT

Source: http://www.torresolenergy.com/TORRESOL
FRESNEL REFLECTOR CSP TECHNOLOGY

Fresnel reflector CSP utilizes the independently controlled, long and flat mirrors placed along a horizontal axis for solar energy collection.
SPAIN 30 – MW PUERTO ERRADO 2 PLANT

Source: http://www.estelasolar.eu/typo3temp/pics/64aedd3b53.jpg
DISH STIRLING CSP TECHNOLOGY

- Dish Stirling CSP technology uses mirrors to approximate a parabolic dish to effectively reflect \( DNI \) onto the receiver.

- The absorbed thermal energy is used to power a special type of heat engine, called a Stirling engine.
1.5 – MW MARICOPA SOLAR PROJECT


Stirling engine
CSP TECHNOLOGY DIFFERENCES

- The four CSP plant categories differ significantly from one another in terms of their technical features, economics, technology maturity and operational performance in utility-scale applications.
- **Parabolic trough CSP** plants are commercially widely deployed in various CSP projects.
- More recently, the commercial implementation of **solar tower CSP** is pursued on a broader scale.
CSP TECHNOLOGY DIFFERENCES

- There is increasing interest in solar tower CSP using high-temperature molten salt for the HTF – a technology with good potential for marked cost reductions and major efficiency improvements.

- We summarize the salient attributes of the four CSP technology categories in a tabular format.
# COMPARISON OF DIFFERENT CSP TECHNOLOGIES

<table>
<thead>
<tr>
<th>attribute</th>
<th>parabolic trough</th>
<th>solar tower</th>
<th>Fresnel collector</th>
<th>dish Stirling</th>
</tr>
</thead>
<tbody>
<tr>
<td>capacity range (MW)</td>
<td>10 – 400</td>
<td>10 – 400</td>
<td>10 – 200</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>collector concentration (suns)</td>
<td>70 – 80</td>
<td>&gt; 1,000</td>
<td>&gt; 60</td>
<td>&gt; 1,300</td>
</tr>
<tr>
<td>efficiency range (%)</td>
<td>11 – 16</td>
<td>7 – 20</td>
<td>10 – 15</td>
<td>12 – 25</td>
</tr>
<tr>
<td>HTF temperature (°C)</td>
<td>350 – 550</td>
<td>250 – 566</td>
<td>390 – 500</td>
<td>550 – 750</td>
</tr>
</tbody>
</table>
## COMPARISON OF DIFFERENT CSP TECHNOLOGIES

<table>
<thead>
<tr>
<th>Metric</th>
<th>Parabolic Trough</th>
<th>Solar Tower</th>
<th>Fresnel Collector</th>
<th>Dish Stirling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land requirements</td>
<td>Large</td>
<td>Medium</td>
<td>Medium</td>
<td>Very small</td>
</tr>
<tr>
<td>Maturity of technology</td>
<td>Commercial projects</td>
<td>Pilot commercial projects</td>
<td>Demonstration projects</td>
<td>Demonstration projects</td>
</tr>
</tbody>
</table>
A key advantage of CSP technology is the ability to deploy thermal energy storage (TES) to store excess thermal energy for its use at a later time.

A TES provides flexibility in CSP energy production.

TES enables a CSP plant to produce electricity even outside the sunrise–sunset periods and also enables smoothing of the CSP power output in cases of cloud cover.
The storage of energy during the lower demand periods and its later use for generation in higher-demand periods increase the economic value of the CSP–TES–produced energy and may offset the additional investment costs incurred in TES.

The theoretical range of c.f.s of CSP–TES plants is [35, 90] % – a big increase in effective solar utilization.
The *TES* capability may be expressed in terms of either physical or storage capability in $MWh_t$ or in hours:

- The *physical capability* refers to the maximum amount of stored thermal energy.
- The *storage capability* is the ratio of the physical capability in $MWh_t$ to the largest input by the power block expressed in $MW_t$ units.
**EXAMPLE: TES IMPACTS FOR CSP**

<table>
<thead>
<tr>
<th>CSP-TES feature (unit)</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CSP capacity (MW)</strong></td>
<td>60</td>
</tr>
<tr>
<td><strong>maximum input of power block (MW$_t$)</strong></td>
<td>140</td>
</tr>
<tr>
<td><strong>physical capability (MWh$_t$)</strong></td>
<td>140</td>
</tr>
<tr>
<td><strong>storage capability (h)</strong></td>
<td>1</td>
</tr>
</tbody>
</table>
To optimize the contribution the CSP makes, the TES requires the use of an efficient scheduler.

The TES schedule optimization problem has the specific objective to maximize the CSP energy value with the consideration of the following factors:

- the impacts of charge/discharge on the thermal energy stored in the TES
- the charge/discharge limits
- the TES physical capability
- the power block capacity
DAILY CSP POWER OUTPUT
WITHOUT TES

output (MW)

hour

DNI (W/m²)

0  10  14  18  22

0  20  40  60  80  100

300  600

0  300  600
DAILY CSP POWER OUTPUT WITH TES

(output (MW))

hour

DNI (W/m^2)

0  6  10  14  18  22

0  20  40

0  300  600

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DAILY POWER OUTPUT OF A 20-MW CSP WITH A 12-HOUR TES

one summer day

one winter day
MEAN ANNUAL ENERGY GENERATION BY A 120–MW CSP PLANT

Note: diminishing returns for each added hour of storage capability.
2020 WORLD CSP STATUS

- Spain has the largest CSP capacity at 2,304 MW followed by US – 1,738 MW, Morocco – 516 MW, South Africa – 500 MW, China – 570 MW, Israel – 240 MW, India – 225 MW, and UAR – 100 MW

- Israel, Kuwait and France saw the implementation of their first commercial CSP capacity in 2019

- Dubai’s 700 MW CSP project starts to operate as the world’s largest CSP plant in 2021
2006 – 2020 GLOBAL CUMULATIVE CSP CAPACITY

GW

0 1 2 3 4 5 6 7

year


added CSP capacity

installed CSP capacity from the preceding year

in 2020, 150 MW of new capacity was added in China
2020 CSP CAPACITY BY COUNTRY

rest of the world (36.5 %)

Spain (36.1 %)

US (27.3 %)

global CSP capacity 6,360 MW

GLOBAL CSP THERMAL ENERGY STORAGE CAPABILITY 2009 – 2020

THE TOP 3 STATES IN CUMULATIVE CSP CAPACITY: END OF 2020

Source: https://www.nrel.gov/docs/fy20osti/75284.pdf
THE CRESCEnt DunEs sOLAR pROJECT IN NEVADA

Source: Overview, A New Perspective of Earth, by Benjamin Grant
IVANPAH SOLAR ENERGY GENERATION PLANT

http://graphics.latimes.com/media/flatgraphics/towercard/15/la-me-solar-desert-tower1

- Phase I
- Phase II
- Phase III

- Power tower
- Primm, Nev. (casinos and retail outlets at the state line)
- I-15 (to Las Vegas)
- Primm Valley Golf Course

- 173,500 heliostats (each has 2 mirrors)
- Each heliostat is 7 feet wide x 10 feet high
The Ivanpah Solar Energy Generating System – owned by NRG Energy, Google and BrightSource Energy – is the largest CSP development in the world with a total capacity of 395 MW.

Located near Ivanpah Dry Lake, California, the 3–unit plant is built on approximately 14,164,000 m² or 3,500 acres of desert public land.
THE IVANPAH SOLAR ENERGY GENERATING SYSTEM

- The plant uses the BrightSource Energy solar tower technology to produce about 1,080 $GWh$ annually to serve the consumption of over 140,000 homes.

- Ivanpah Solar Energy Generating System is estimated to reduce $CO_2$ emissions by over 13.5 million tons over its 30–year life time.
IVANPAH SOLAR ENERGY GENERATING SYSTEM

Source: http://www.youtube.com/watch?v=bxCUYPzHsug
ANDASOL SOLAR POWER STATION

Source: http://images.nationalgeographic.com/wpf/media-live/photos/000/493/cache
The 150 – MW Andasol solar power station is Europe's first commercial parabolic trough CSP, located in Andalucia, Spain.

Equipped with a 7.5 – h TES, Andasol solar power station produces around 495 GWh annually with an annual c.f. of 0.41.
THE MOROCCAN SOLAR PLANT

THE MOROCCAN SOLAR PLANT

- The Moroccan solar thermal plant is located at Ouarzazate, in the central southern Morocco and is designed to supply power 20 hours each day.
- The thermal plant harnesses solar heat to produce molten salt with energy stored in its TES.
- The plants’ huge parabolic mirrors are moveable in order to track the sun from sunrise to sunset and occupy an area as large as Rabat, the capital.
- The solar plant is part of the country’s vision for a 42% share of its 2020 electricity from renewables.
CSP INSTALLATION COSTS

- In 2020, 150 MW of new CSP was installed at costs of 4581 $/kW; the 2018 – 2019 CSP projects with 8 or more hours TES cost range from 4126 to 5945 $/kW.

- CSP plants with TES tend to be more expensive with but have higher c.f.s, with the significant ability to shift generation outside the sunrise–sunset periods.
### 2020 CSP COST COMPONENTS


<table>
<thead>
<tr>
<th>cost component</th>
<th>share in % of the total costs of parabolic trough</th>
<th>solar tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>owner borne</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>indirect EPC cost</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>thermal storage</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td><strong>power block</strong></td>
<td><strong>18</strong></td>
<td><strong>16</strong></td>
</tr>
<tr>
<td>tower</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>receiver</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td><strong>solar field</strong></td>
<td><strong>39</strong></td>
<td><strong>28</strong></td>
</tr>
</tbody>
</table>

GLOBAL WEIGHTED – AVERAGE UTILITY–SCALE LCOEs: 2010 – 2020


US $/kWh

PV

CSP

offshore wind

geothermal

biomass

hydro

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.381
0.340
0.162
0.039
0.089
0.076
0.049
0.038
0.084
0.076
0.071
0.057
0.044
0.039
0.108

GLOBAL WEIGHTED-AVERAGE TOTAL INSTALLED COSTS TRENDS: 2010 – 2020

The CSP LCOE varies significantly with the specific technology deployed and the TES capability.

The global weighted-average LCOE declined from 2010 to 2020 by 0.24 $/kWh.

The US Department of Energy Sunshot Initiative aim is to reduce the CSP LCOE by 2020 to 0.06 $/kWh.
CSP LCOEs FOR 2010 – 2020


- Linear Fresnel
- Parabolic trough
- Solar tower
- Storage (hours):
  - No storage
  - 0 to 4
  - 4 to 8
  - 8 to 10
  - 10+
- Capacity (MW):
  - 1
  - 100
  - 200
  - ≥ 300
PROJECT AND GLOBAL WEIGHTED-AVERAGE LCOE AND PPA/AUCTION PRICES: 2010 – 2023


PV  CSP  wind  offshore wind

2020 USD/kWh

0.4

0.381

0.340

0.3

0.2

0.1

0.057

0.043

0.039

0.04

0.076

0.069

0.108

Fossil fuel cost range


Auction database  LCOE database
CSP INSTALLED COSTS, c.f.s AND LCOEs: 2010 – 2120

There are multiple approaches under study to lower the investment costs of CSP plants.

The key areas of cost reduction focus on the:

- collectors and receivers through mass production and cheaper components;
- plant design improvements to reduce parasitic loss and increase efficiency; and,
CSP COST REDUCTION POSSIBILITIES

- the deployment of new HTFs capable to be heated up to reach higher temperatures in order to help increase energy conversion efficiency to reduce costs

- The advances in these areas are expected to reduce substantially the CSP LCOE
PV AND CSP

- Unlike PV, CSP technology can make use of only the direct beam component of the insolation.
- However, the utilization of TES, to allow CSP to produce electricity outside the sunrise–to–sunset periods, is a major advantage of CSP deployment over the nondispatchable PV.
- We summarize some key comparative aspects of PV and CSP technologies in the table below.
### PV AND CSP COMPARISON

<table>
<thead>
<tr>
<th>attribute</th>
<th>PV</th>
<th>CSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>capacity range (MW)</td>
<td>0.1 – 400</td>
<td>0.1 – 400</td>
</tr>
<tr>
<td>c.f. range (%)</td>
<td>5 – 25</td>
<td>22 – 35 (without TES) 30 – 90 (with TES)</td>
</tr>
<tr>
<td>investment cost range ($/W)</td>
<td>1.98 – 4.01</td>
<td>3.84 – 14.54</td>
</tr>
<tr>
<td>average project implementation duration (y)</td>
<td>2 – 4</td>
<td>3 – 5</td>
</tr>
<tr>
<td>LCOE range ($/kWh)</td>
<td>0.11 – 0.29</td>
<td>0.11 – 0.34</td>
</tr>
</tbody>
</table>
PV AND CSP

- CSP with the additional benefits from TES is a promising technology to harness solar energy but as PV prices continue to drop drastically, its economic competitiveness becomes problematic.

- Instead of direct PV and CSP competition, the two technologies may work symbiotically to deepen solar penetration in future grids.