17. Concentrated Solar Power Plants
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

Source: http://www.inforse.org/europe/dieret/Solar/solar.html
CSP

- *PV* technology is able to collect all the 3 insolation components for electricity production.

- Unlike *PV*, *CSP* can concentrate only the direct beam radiation – also referred to as *direct normal irradiation* (*DNI*).
CSP

- Specifically, CSP plant uses mirrors with tracking systems to focus DNI to collect the solar energy.
- The solar energy is used to heat up the heat transfer fluid (HTF) and to 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 receivers
  - a receiver that converts solar energy into thermal energy
  - a power block that converts thermal energy into electricity distinct

- The collector configurations are used to classify CSP plants into 4 distinct categories
  - parabolic trough
  - Fresnel reflector
  - solar tower
  - 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
CALIFORNIA 354 – MW SOLAR ELECTRIC GENERATION SYSTEMS

Source: http://upload.wikimedia.org/wikipedia/commons/4/44/
Solar tower CSP technology employs heliostats - collectors with dual-axis trackers – to concentrate DNI onto a central receiver – the solar tower.

Source: http://infohost.nmt.edu/~helio/images/fheliostats.png
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/64aed33b53.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

The four CSP plant categories differ significantly from one another in terms of technical features, economics, technology maturity and operational performance in utility-scale applications.

Parabolic trough CSP plants are commercially widely used and are in many CSP projects being built.

More recently, solar tower CSP plants are being deployed commercially.
There is increasing interest in solar tower CSP using high-temperature molten salt for the HTF—a technology with good potential for marked cost reduction and major efficiency improvement.

We summarize the key attributes of the four categories with a tabular comparison.
## 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>measure</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>small</td>
</tr>
<tr>
<td>maturity of technology</td>
<td>commercial projects</td>
<td>pilot commercial projects</td>
<td>pilot projects</td>
<td>demonstration projects</td>
</tr>
</tbody>
</table>
A key advantage of CSP technology is the deployment of thermal energy storage (TES) to store excess thermal energy for later use.

TES provides flexibility in CSP energy production.

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

Typically, the range of c.f.s of CSP plants with TES is [35, 90] % – a big increase in effective utilization.
EXPLANATION OF TES CAPABILITY

- The TES capability can 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 expressed as the ratio of the physical capability to maximum input of power block for electricity generation.
**EXAMPLE: TES IMPACTS**

<table>
<thead>
<tr>
<th>TES</th>
<th>CSP capacity (MW)</th>
<th>maximum input of power block (MW&lt;sub&gt;t&lt;/sub&gt;)</th>
<th>physical capability (MWh&lt;sub&gt;t&lt;/sub&gt;)</th>
<th>storage capability (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
<td>140</td>
<td>140</td>
<td>1</td>
</tr>
</tbody>
</table>
To optimize the contribution from the CSP, 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:

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

output (MW) vs. hour

6 10 14 18 22

DNI (W/m²)

0 300 600

0 20 40
DAILY POWER OUTPUT OF A 20-MW CSP WITH A 12-HOUR TES

one summer day

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

note: diminishing returns as TES increases

GWh

no TES

TES (h)

0 1 2 3 4 5 6

200 300 400
2015 WORLD CSP STATUS

- The 2015 global CSP capacity increased 0.455 GW to reach 4,940 MW – 10% above the 2014 figure

- Morocco was the global market leader in annual additions, with 160 MW of cumulative CSP capacity by the end of 2015

- Spain, the leader in terms of total capacity, experienced a stagnation in its market

- In addition to Morocco, US and South Africa were the only other countries to bring significant new capacity into commercial operation
2006 – 2015 GLOBAL CUMULATIVE CSP CAPACITY

2015 CSP CAPACITY BY COUNTRY

rest of the world (15 %)

Spain (48 %)

US (37 %)

global CSP capacity
4,940 MW

2015 US CSP STATUS

- The *US* remained the second largest *CSP* market in terms of total installed capacity.

- Nevada was the only state to install new *CSP* capacity, the 110-MW *Crescent Dunes* power plant.

- Another 2,000 *MW CSP* power plant in Nevada was announced by the company *SolarReserve*.
TOP 5 STATES IN CUMULATIVE CSP CAPACITY: END OF 2015

Source: http://www.nrel.gov/docs/fy16osti/64720.pdf
US CSP INSTALLED CAPACITY AND GENERATION

Generation (MWh)

Capacity (MW)

http://www.nrel.gov/docs/fy17osti/66591.pdf
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 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.
ANDASOL SOLAR POWER STATION

- The 150 – MW Andasol solar power station is Europe's first commercial parabolic trough CSP, located in Andalusia, 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 southern–central *Morocco* and is designed to supply power **20 hours** each day.
- The thermal plant harnesses solar heat to melt salt with energy stored by *TES*.
- The plants’ huge parabolic mirrors are moveable so as 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 to get **42 %** of its electricity from renewables by **2020**.
CSP INSTALLATION COSTS

- The current investment costs for parabolic trough and solar tower CSP technology without TES range from 3.6 to 8.8 $/kW.

- CSP plants with TES tend to be more expensive with costs ranging from 5 to 10.5 $/kW and have higher c.f.s with the important capability to shift generation outside the sunrise–sunset periods.
2012 PARABOLIC TROUGH CSP COST BREAKDOWN WITHOUT TES

- **collectors and receivers** 40%
- **power block** 17%
- **site preparation and engineering** 16%
- **HTF and system** 11%
- **BOS** 9%
- **owner costs** 7%

2012 PARABOLIC TROUGH CSP COST BREAKDOWN WITH A 6-h TES

- **BOS 8%**
- **HTF and system 9%**
- **engineering and site preparation 14%**
- **TES 14%**
- **power block 15%**
- **collectors and receivers 34%**
- **owner costs 6%**

2012 SOLAR TOWER CSP COST BREAKDOWN WITHOUT TES

- **power block**: 14%
- **HTF and system**: 10%
- **engineering and site preparation**: 11%
- **collectors and receivers**: 54%
- **BOS**: 6%
- **owner costs**: 5%

2012 SOLAR TOWER CSP COST BREAKDOWN WITH A 6-h TES

- **BOS 5 %**
- **owner costs 4 %**
- **collectors and receivers 48 %**
- **HTF and system 9 %**
- **engineering**
- **site preparation 10 %**
- **TES 12 %**
- **power block 12 %**

There are multiple ways to reduce the costs of CSP plants. The key areas of cost reduction focus on:

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

- *HTF* through the deployment of new *HTFs* capable of being heated up to reach higher temperatures so as to help increase energy conversion efficiency to reduce costs.

- The advances in these areas are expected to reduce substantially the *CSP LCOE*.
The **CSP LCOE** varies significantly with the specific technology deployed.

*CSP* with **TES** decreases the range of **CSP LCOE** from 0.20 to 0.36 $/kWh for parabolic trough *CSP* and from 0.16 to 0.30 $/kWh for solar tower *CSP*.

The **US Department of Energy Sunshot Initiative** aim is to reduce the **CSP LCOE** by 2020 to 0.06 $/kWh.
PV AND CSP

- PV and CSP are the two most mature solar energy technologies for electricity generation.
- By the end of 2014, the US total capacity of solar resources in operation is about 19,990 MW, with 91.5% PV and 8.5% CSP.
- US solar generation from PV and CSP combined totaled nearly 33.6 TWh, approximately 0.8% of total US generation in 2014.
PV AND CSP

- Unlike PV, CSP technology can make use of only the direct 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>0.16 – 0.36</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 questionable.

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