ECE 333 – GREEN ELECTRIC ENERGY

17. Concentrated Solar Power Plants

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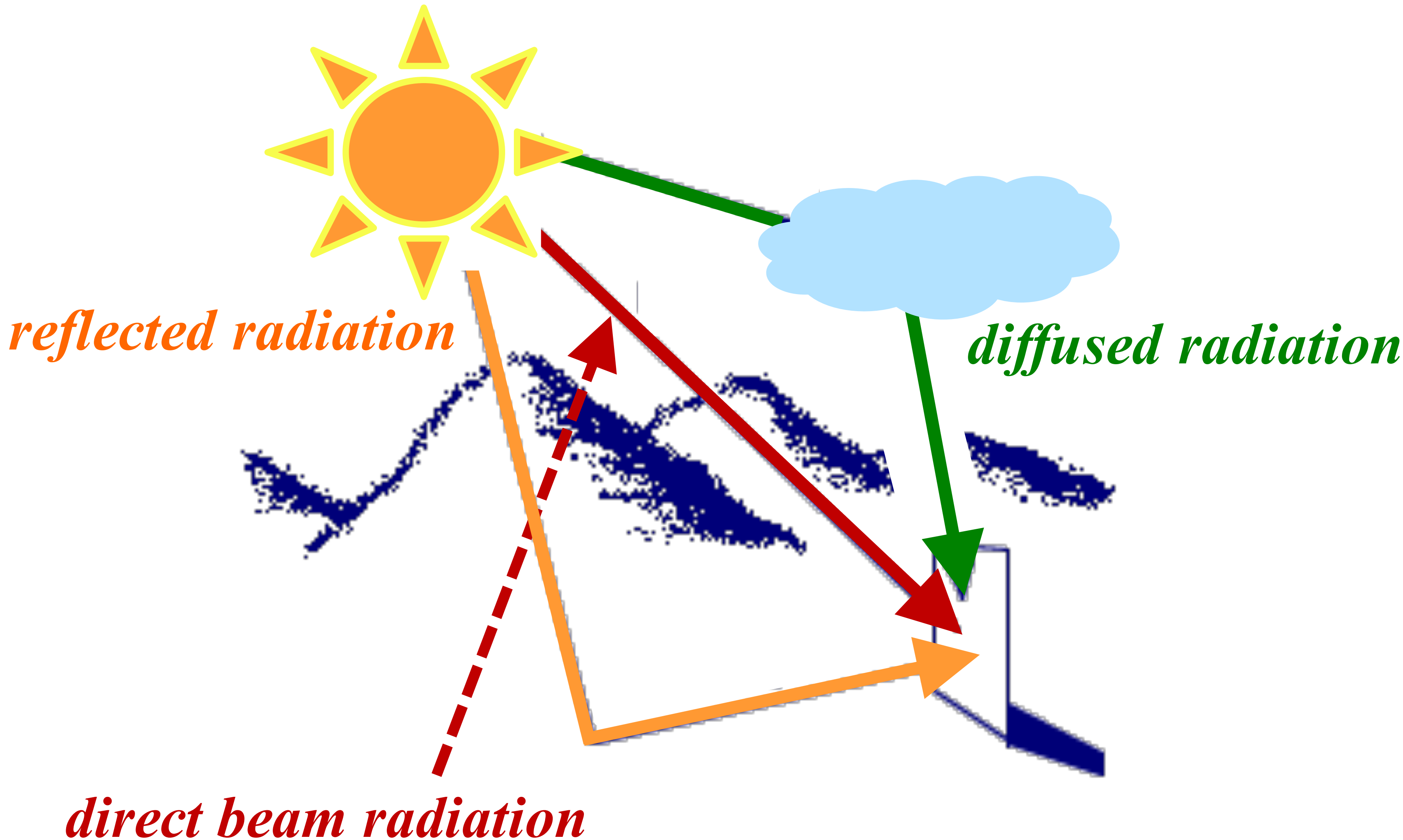
CONCENTRATED SOLAR POWER (*CSP*)

- 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



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*) – to generate electricity

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 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*
  - *Fresnel reflector*
  - *solar tower*
  - *dish Stirling*

PARABOLIC TROUGH *CSP* TECHNOLOGY

Parabolic trough *CSP* technology uses parabolic mirrors to concentrate *DNI* onto the receivers positioned along each mirror's focal line

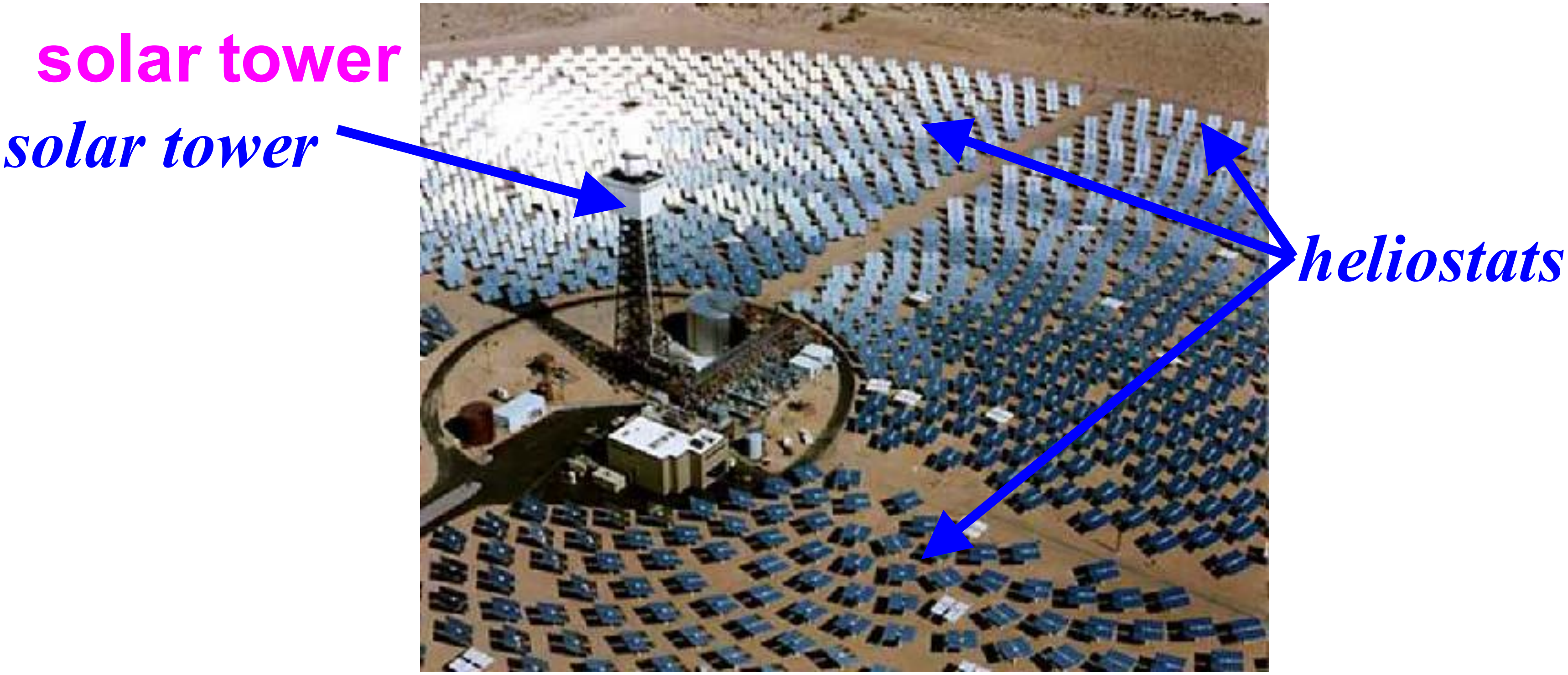
Source: http://www.abengoa.com

CALIFORNIA 354 – *MW* SOLAR ELECTRIC GENERATION SYSTEMS

Source: http://upload.wikimedia.org/wikipedia/commons/4/44/

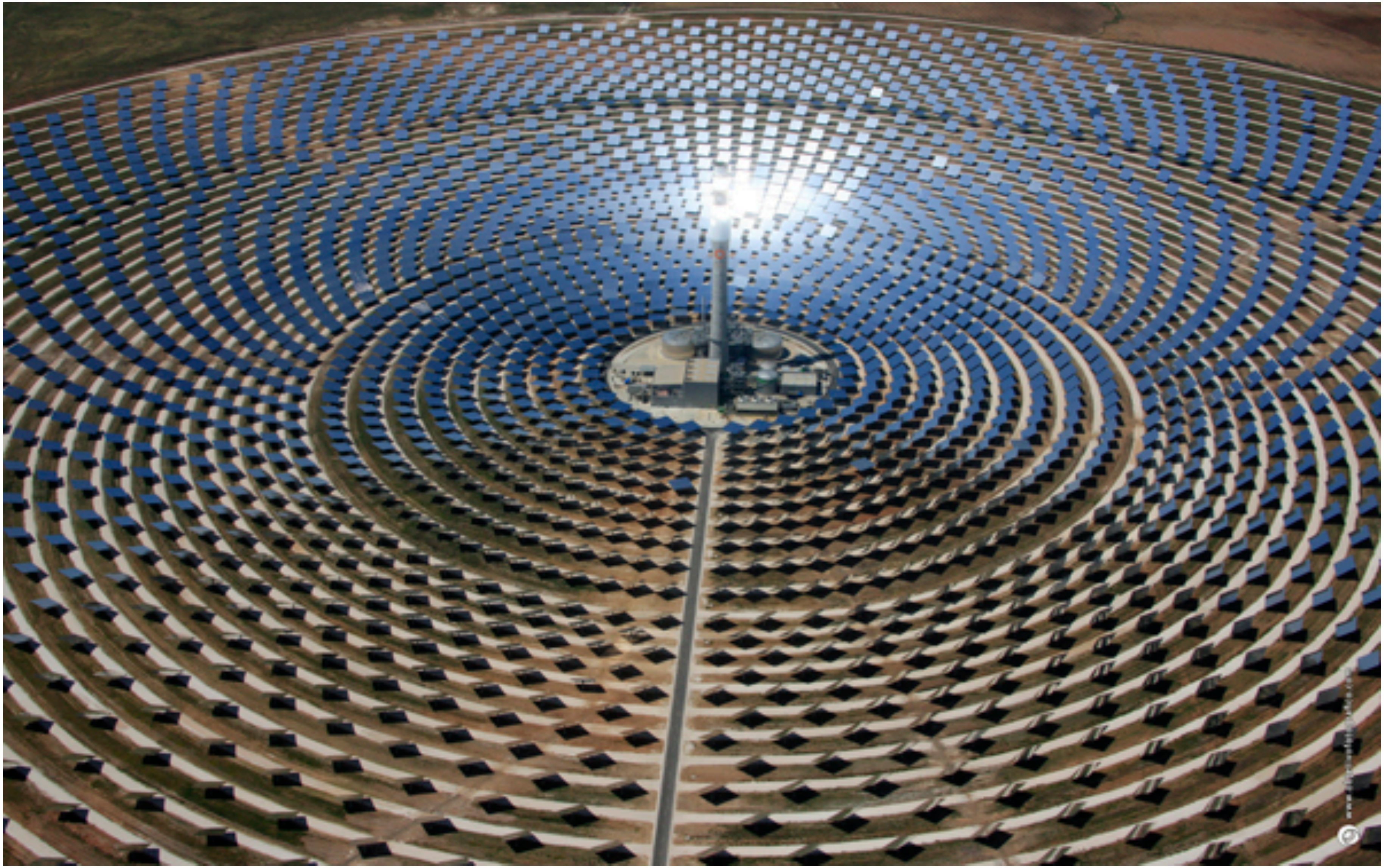
SOLAR TOWER *CSP* TECHNOLOGY

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/f

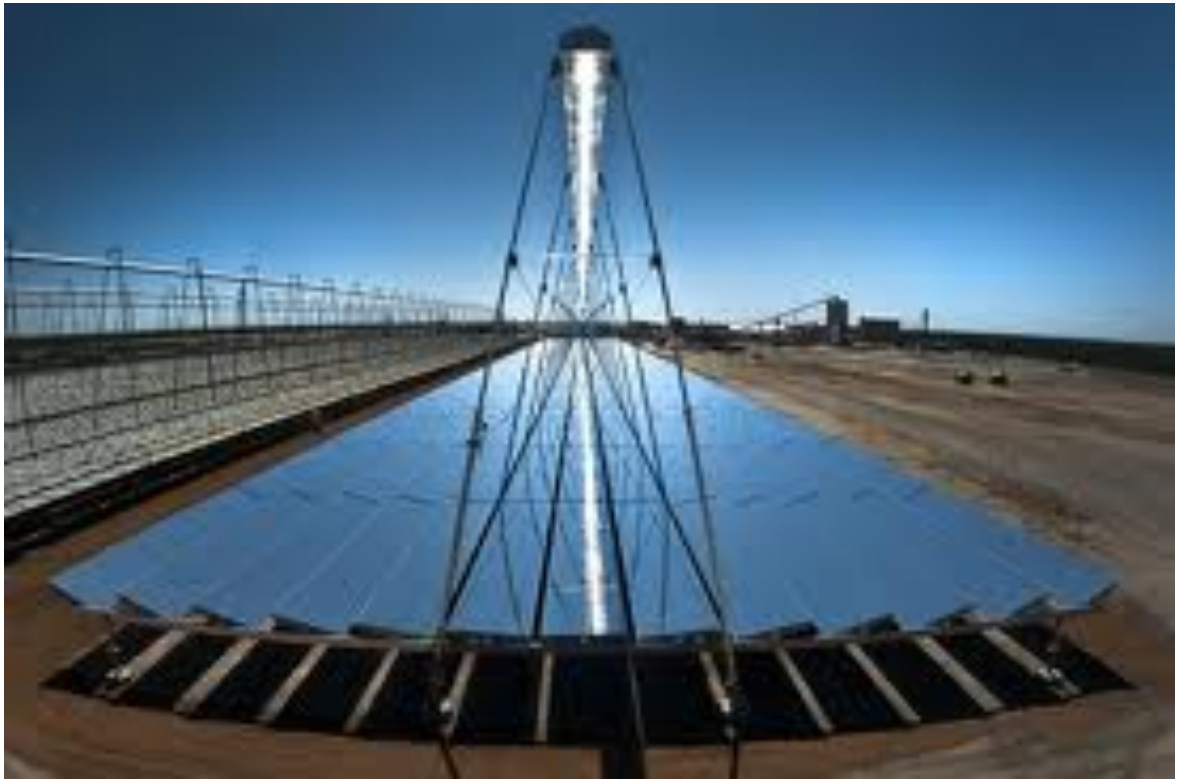
SPAIN 20 – MW GEMASOLAR THERMOSOLAR PLANT



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



Source: https://encrypted-tbn2.gstatic.com

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

Source: http://www.solarserver.com/uploads/pics/ses_suncatchers.jpg

CSP TECHNOLOGY DIFFERENCES

- 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

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 reduction and major efficiency improvement
- We summarize the key attributes of the four categories in a tabular format

COMPARISON OF DIFFERENT *CSP* TECHNOLOGIES

attribute	*parabolic trough*	*solar tower*	*Fresnel collector*	*dish Stirling*
capacity range (MW)	10 – 400	10 – 400	10 – 200	< 2
collector concentration (suns)	70 – 80	> 1,000	> 60	> 1,300
efficiency range (%)	11 – 16	7 – 20	10 – 15	12 – 25
HTF temperature (°C)	350 – 550	250 – 566	390 – 500	550 – 750

COMPARISON OF DIFFERENT *CSP* TECHNOLOGIES

measure	*parabolic trough*	*solar tower*	*Fresnel collector*	*dish Stirling*
c.f. range (%)	25 – 28	27 – 35	22 – 24	25 – 28
land requirements	*large*	*medium*	*medium*	*small*
maturity of technology	*commercial projects*	*pilot commercial projects*	*pilot projects*	*demonstra-tion projects*

TES

- A key advantage of *CSP* technology is the deployment of *thermal energy storage* (*TES*) to store excess thermal energy for later use
- A *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 occurrences

TES

- The storage of energy during the lower demand periods and its use for generation for delivery in higher–demand periods increase the economic value of the *CSP–TES*–produced energy and may offset the additional *TES* investment costs
- The theoretical range of *c.f.*s of *CSP–TES* plants is [35, 90] % – a major 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 the ratio of the physical capability in MWh_t to the largest input from the power block in MWh_t

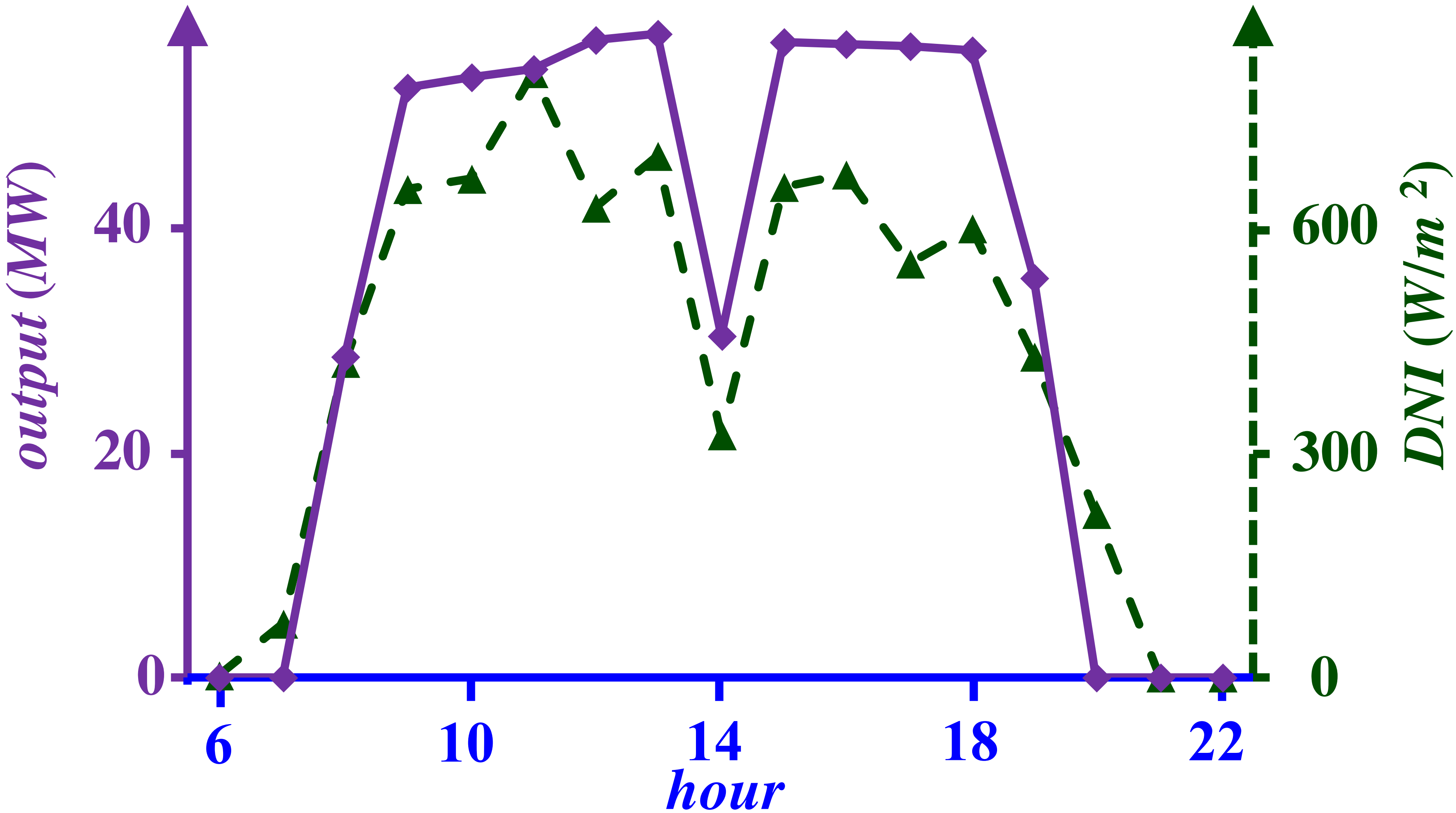
EXAMPLE: *TES* IMPACTS

CSP capacity (MW)		60
maximum input of power block (MW_t)		140
TES	*physical capability* (MWh_t)	140
	storage capability (h)	1

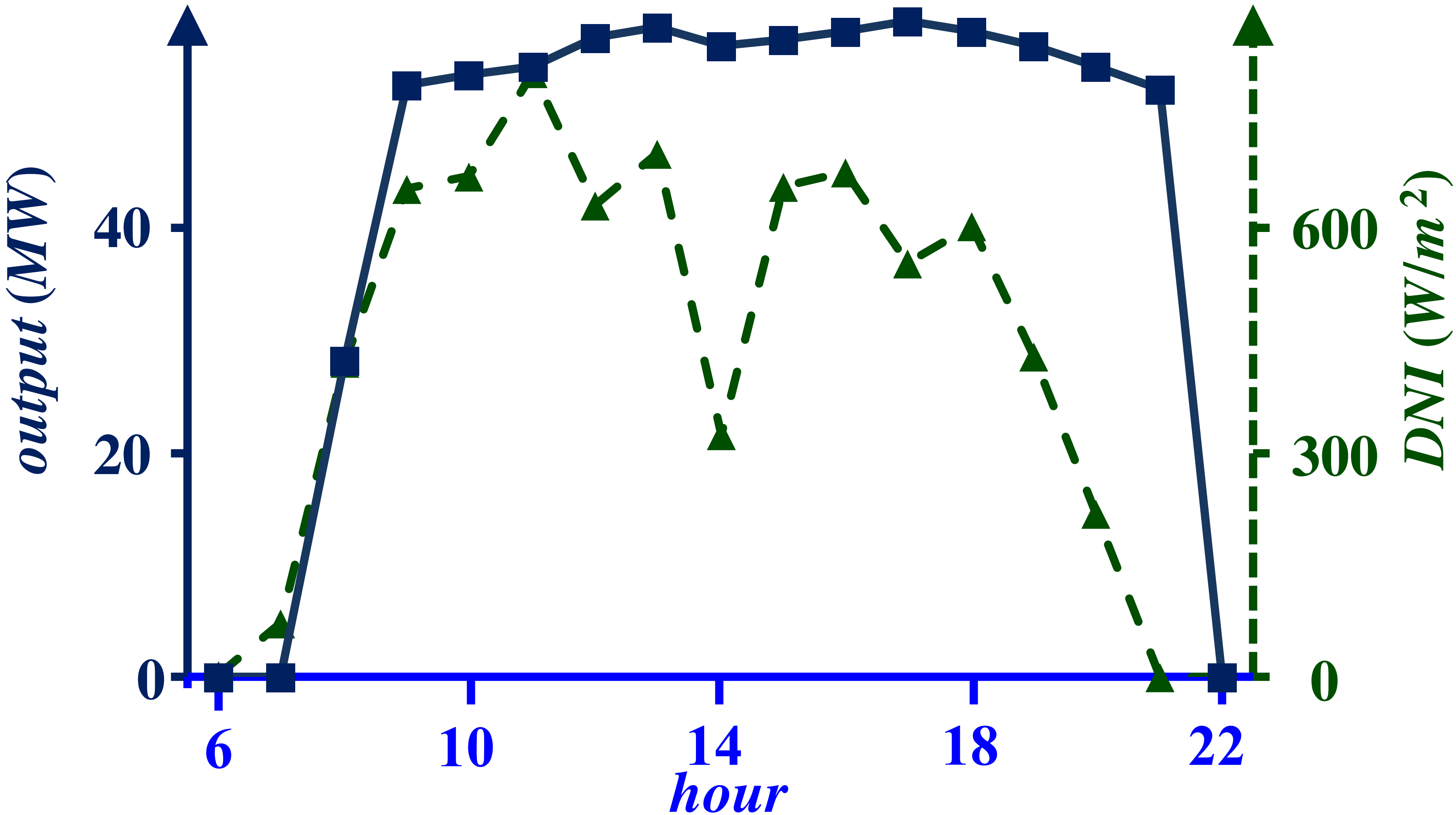
TES SCHEDULER

- 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

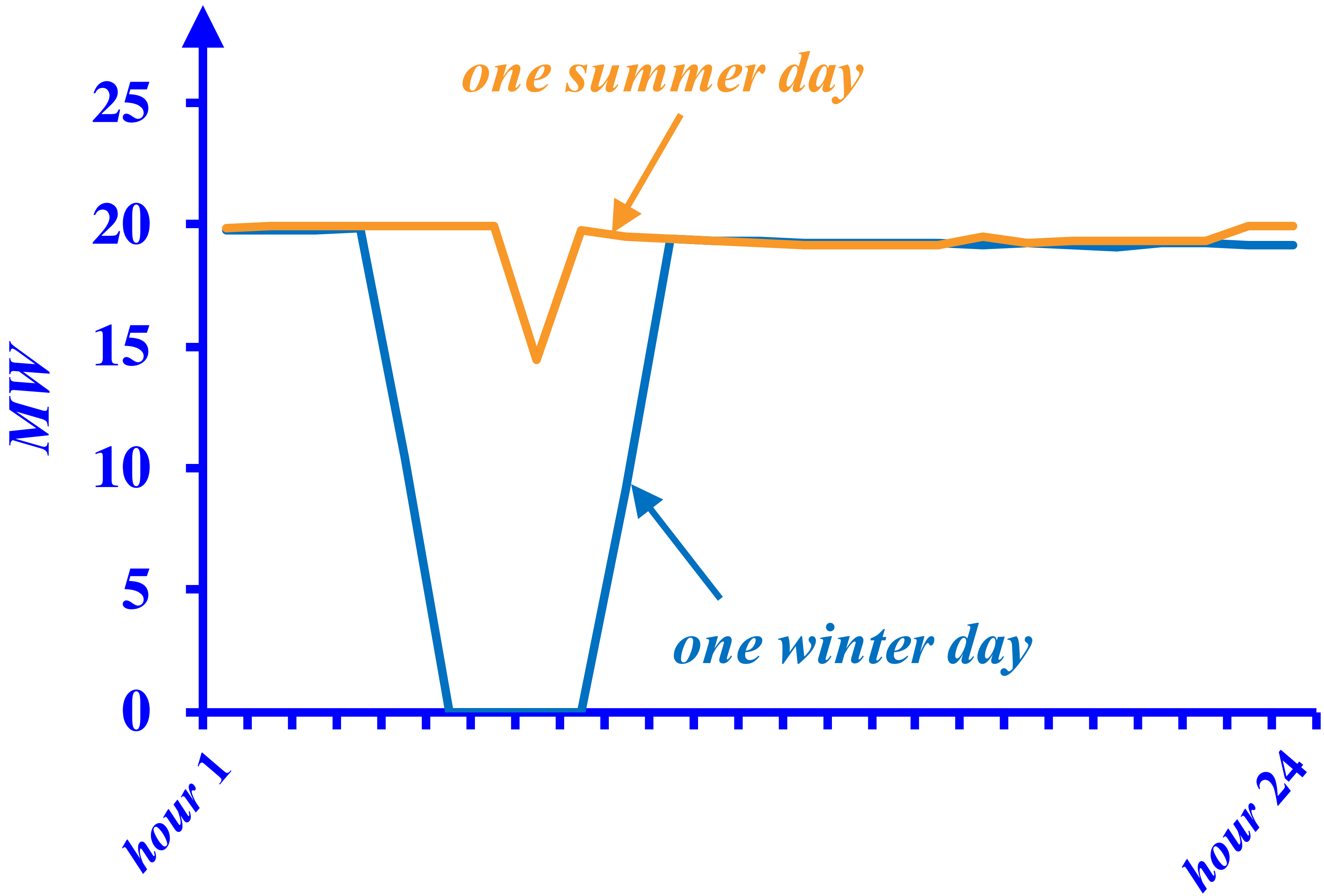
DAILY *CSP* POWER OUTPUT WITHOUT *TES*



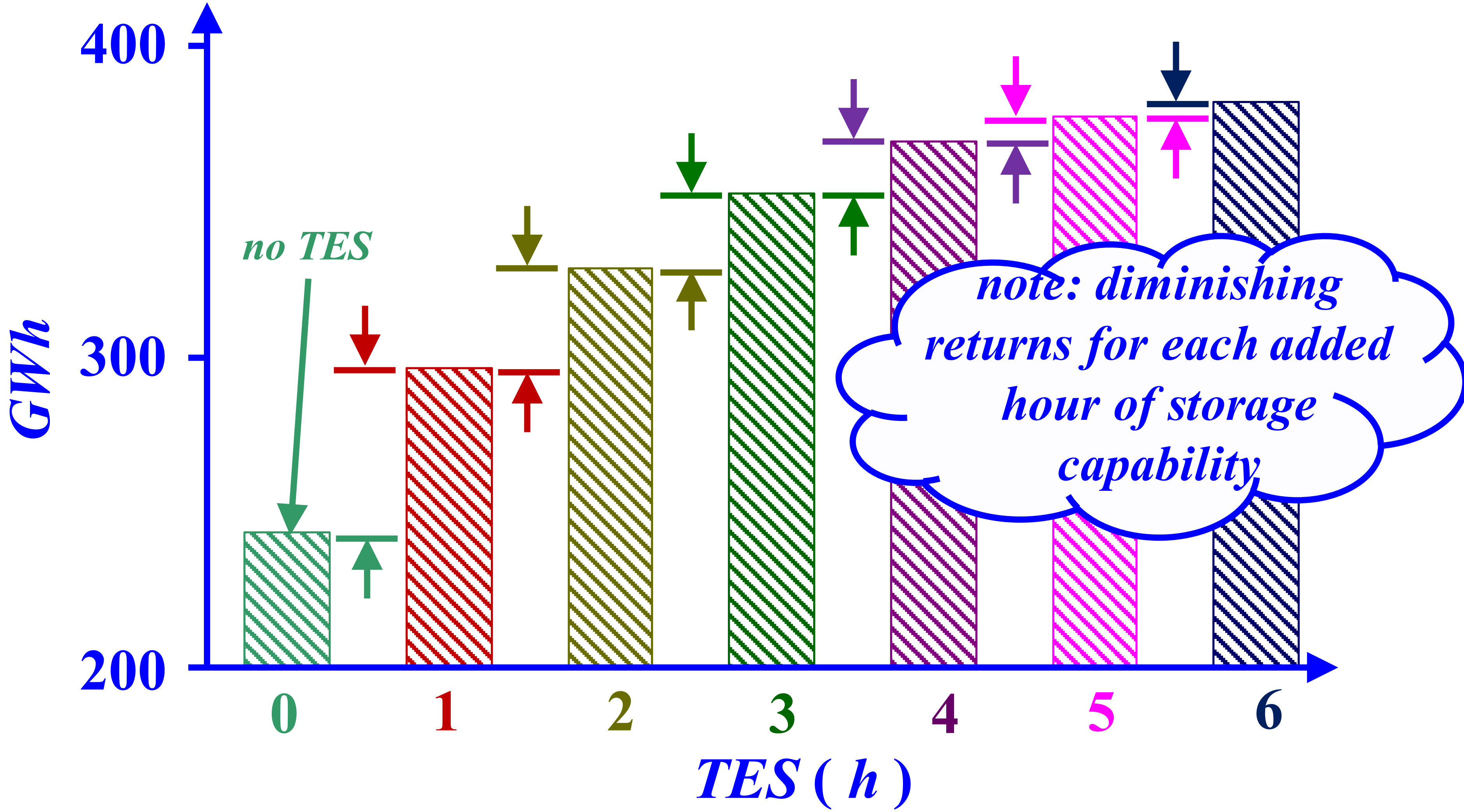
DAILY *CSP* POWER OUTPUT WITH *TES*



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



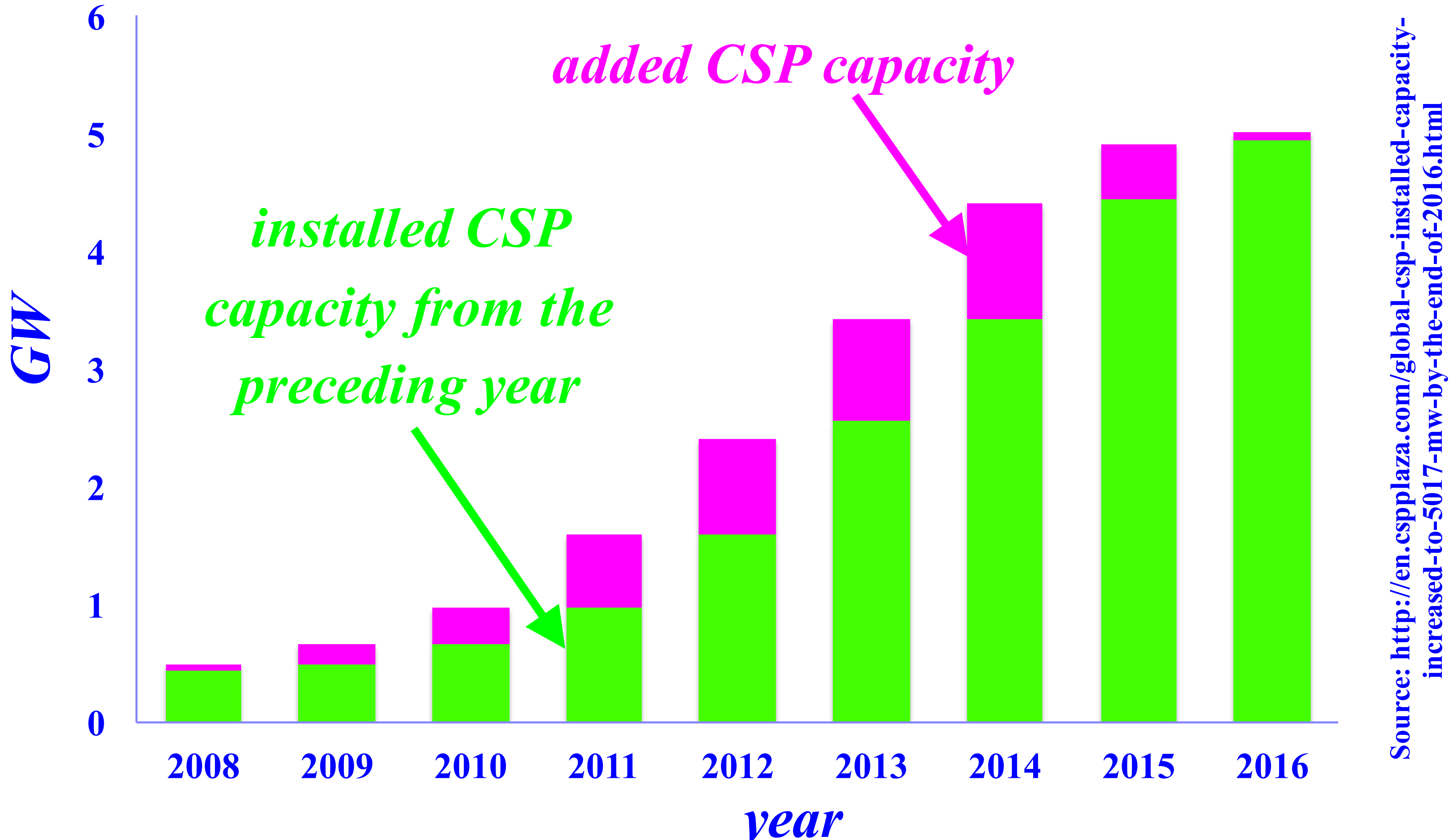
MEAN ANNUAL ENERGY GENERATION BY A 120 – *MW CSP* PLANT



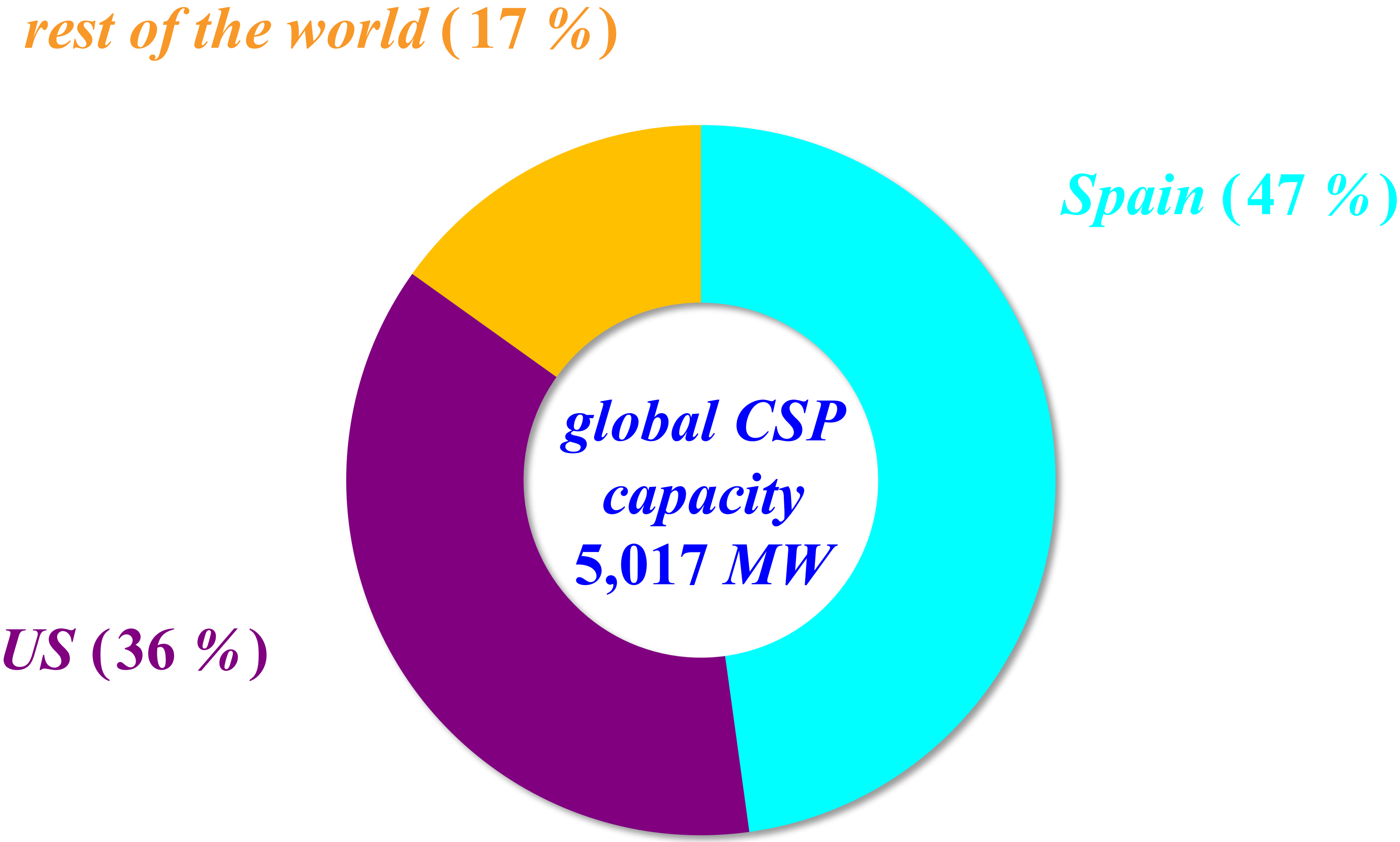
2016 WORLD *CSP* STATUS

- The 2016 global *CSP* capacity increased 76.86 *MW* to reach 5,017 *MW* – 1.56 % above the 2015 figure
- *Spain* is the leading nation in total *CSP* capacity
- *US* added 2–*MW CSP* capacity in 2016
- *South Africa*'s installed *CSP* capacity became noticed in 2016 – a year in which it became the global market leader in annual additions
- In addition to *South Africa, China* and *Australia* also have notable *CSP* resource installations

2006 – 2016 GLOBAL CUMULATIVE *CSP* CAPACITY



2016 *CSP* CAPACITY BY COUNTRY

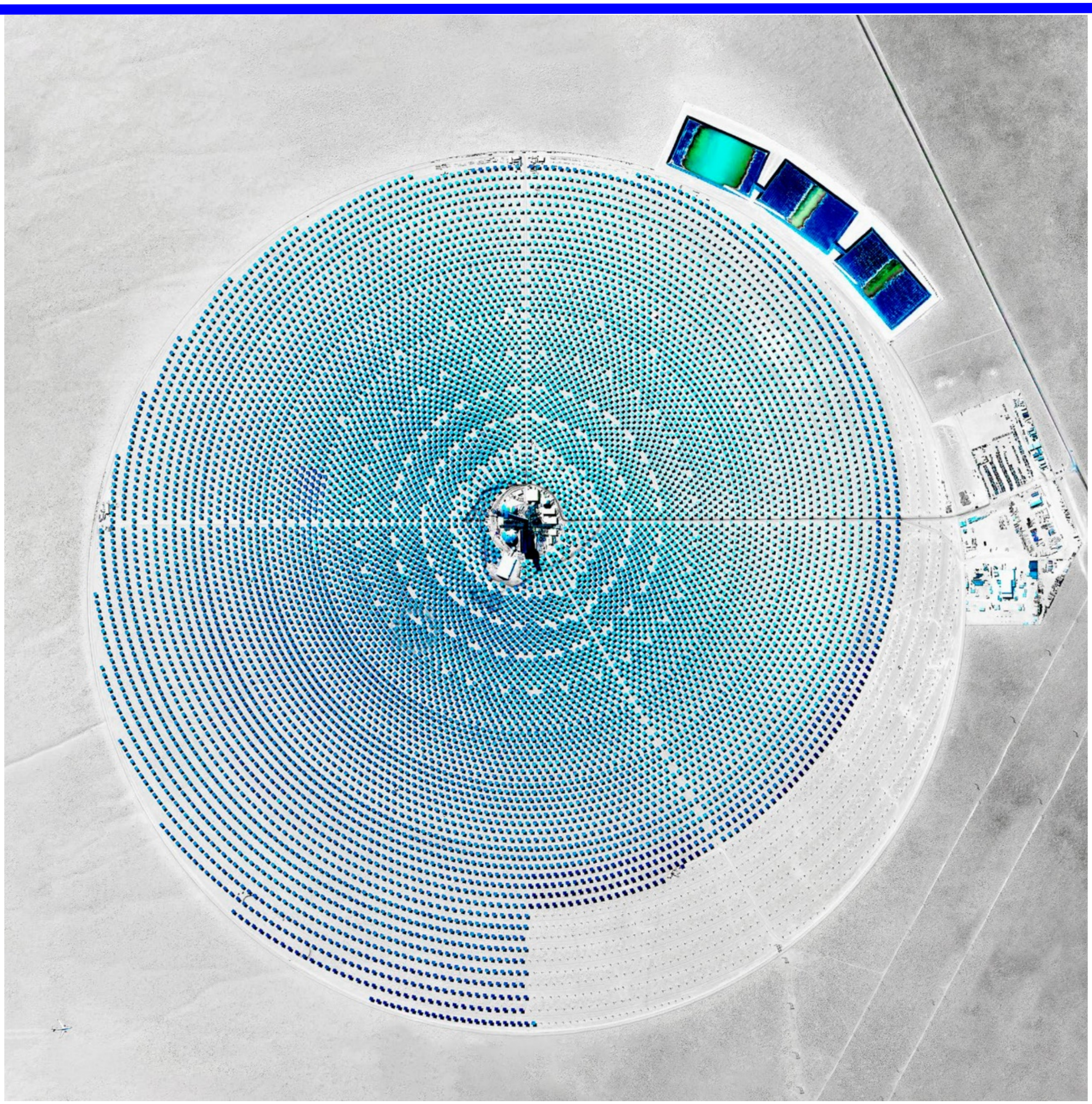


Source: http://en.cspplaza.com/global-csp-installed-capacity-increased-to-5017-mw-by-the-end-of-2016.html

2016 *US* *CSP* STATUS

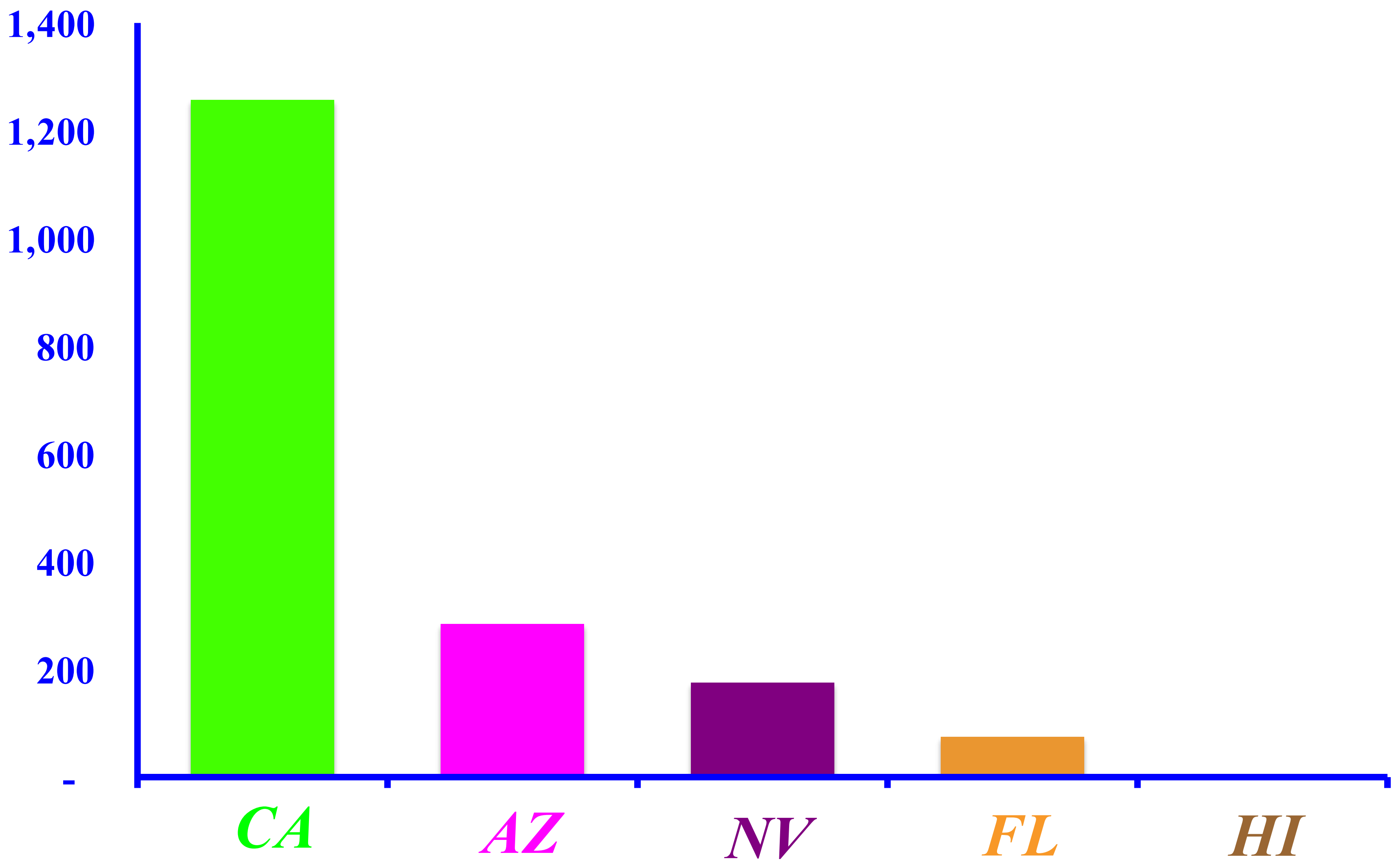
- The *US* remained the second largest *CSP* market in terms of total installed capacity
- Nevada was the only state to install new *CSP* capacity, the 2–*MW* *Stillwater* power plant
- The virtual absence of new *CSP* installed capacity indicates the strong competitive position of *PV* solar, in light of the drastic price reductions

THE *CRESCENT DUNES* SOLAR PROJECT IN *NEVADA*



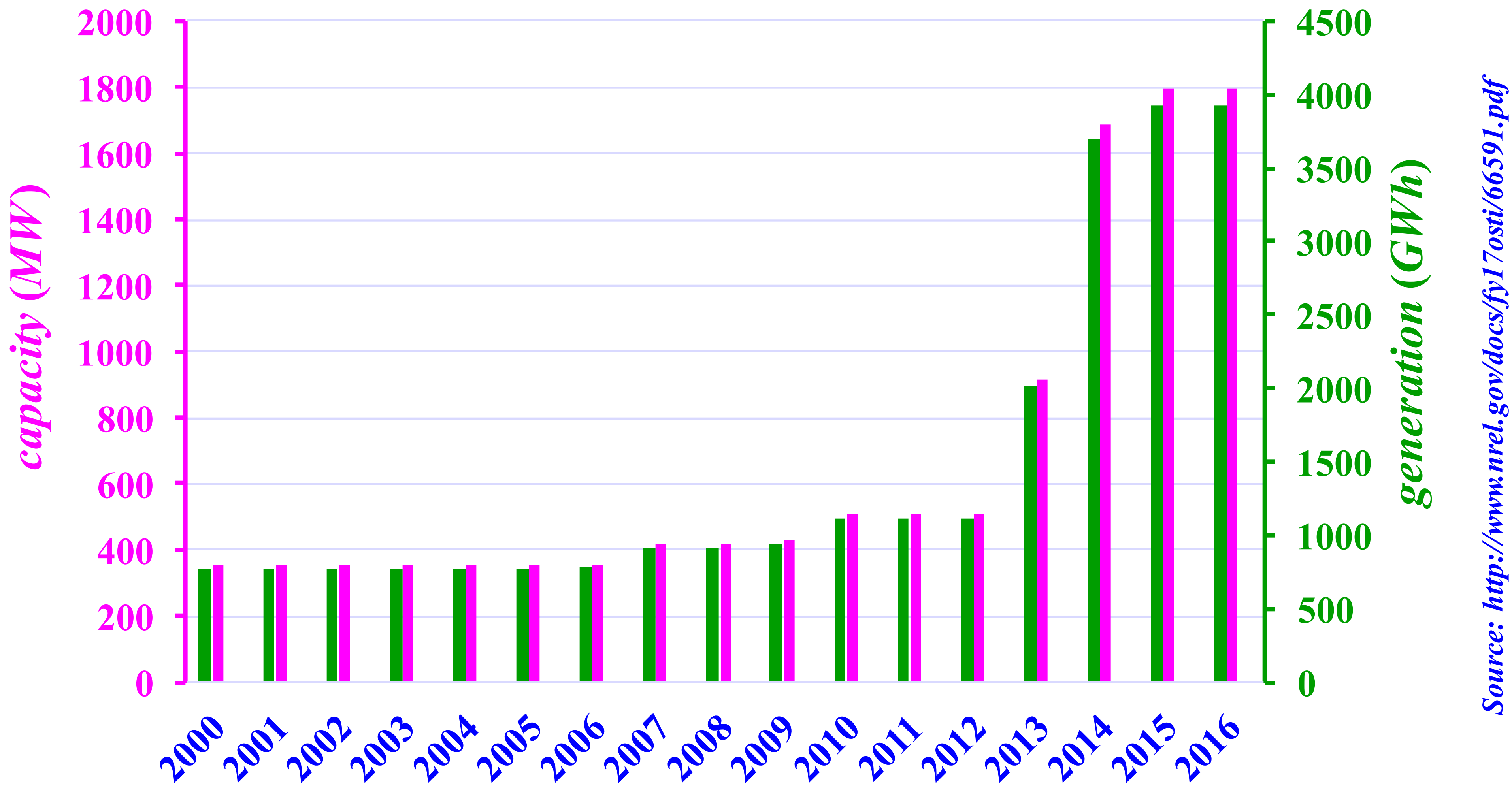
Source: Overview, A New Perspective of Earth, by Benjamin Grant

THE TOP 5 STATES IN CUMULATIVE *CSP* CAPACITY: END OF 2016



Source: http://www.nrel.gov/docs/fy17osti/66591.pdf

US CSP CUMMULATIVE INSTALLED CAPACITY AND ANNUAL GENERATION



IVANPAH SOLAR ENERGY
GENERATION PLANT

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

IVANPAH SOLAR ENERGY GENERATING SYSTEM

- **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 m^2 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

ANDASOL SOLAR POWER STATION

- **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

Source: http://www.bbc.com/news/science-environment-34883224

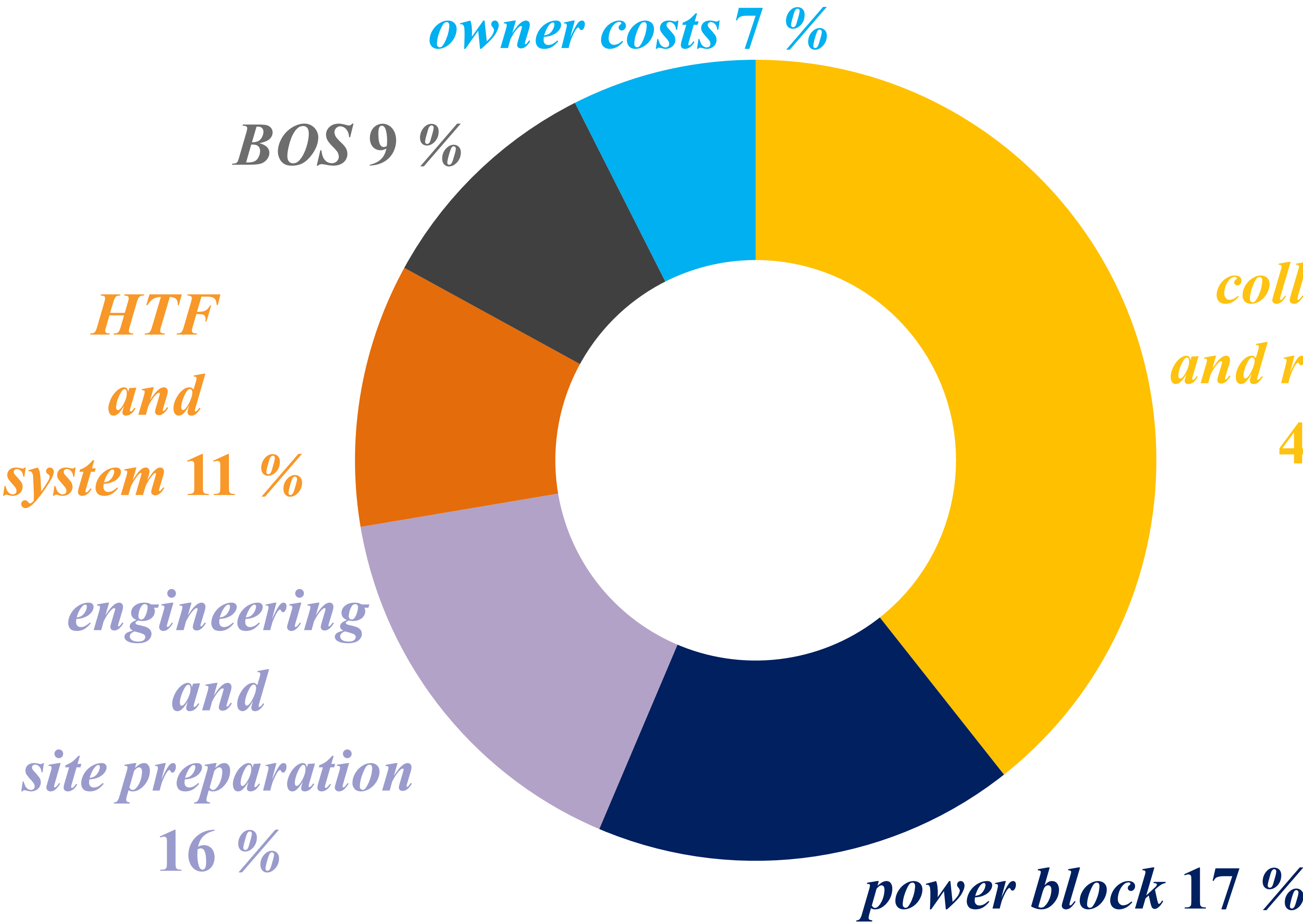
THE *MOROCCAN* SOLAR PLANT

- 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 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

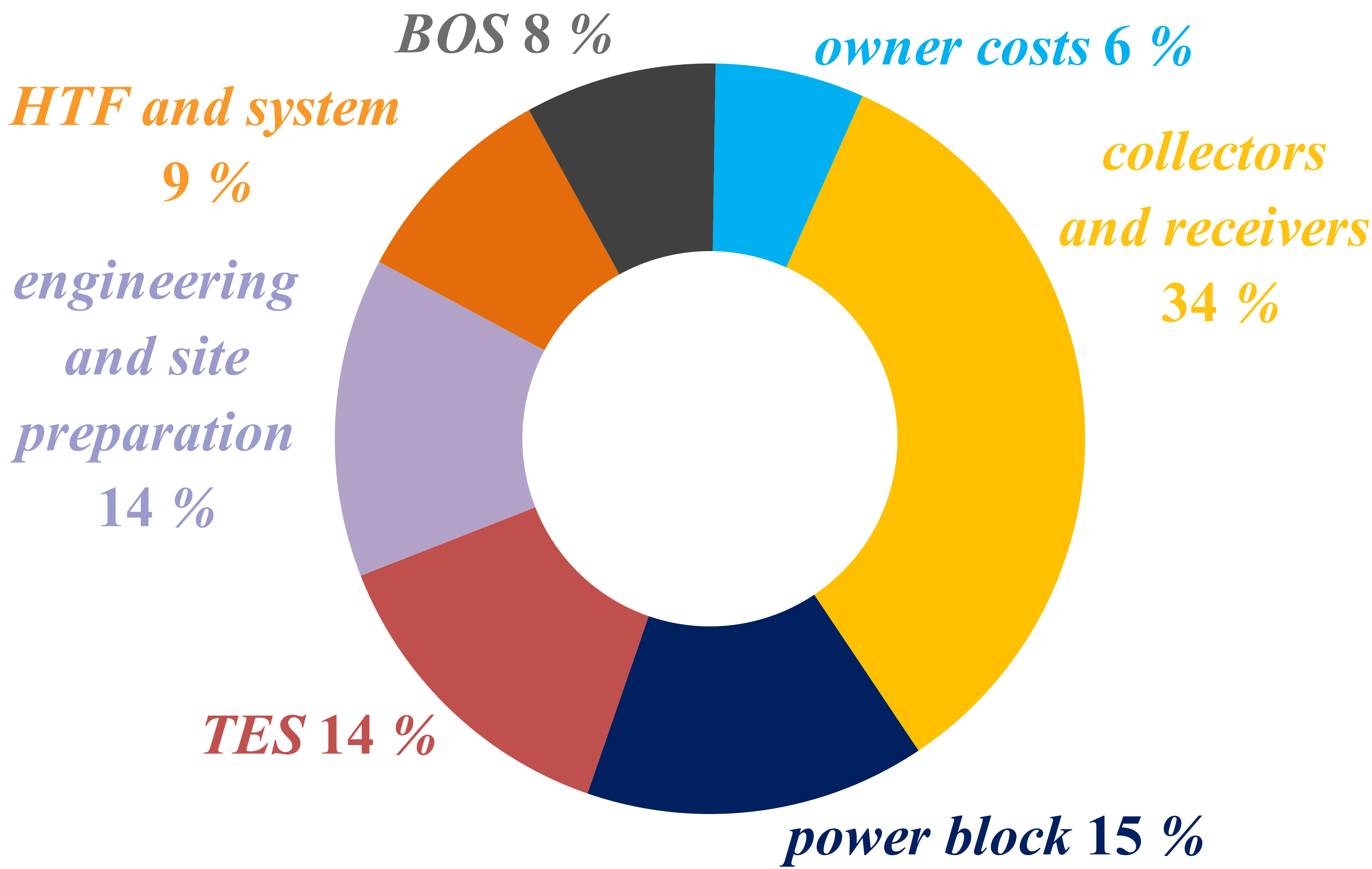
- The current investment costs for parabolic trough and solar tower *CSP* technology without *TES* range from 3.6 to 8.8 *$/kW*
- *CSP* plants with *TES* tend to be more expensive with costs ranging from 5 to 10.5 *$/kW* and have higher *c.f.*s, with the important capability to shift generation outside the sunrise–sunset periods

2012 PARABOLIC TROUGH *CSP* COST BREAKDOWN WITHOUT *TES*



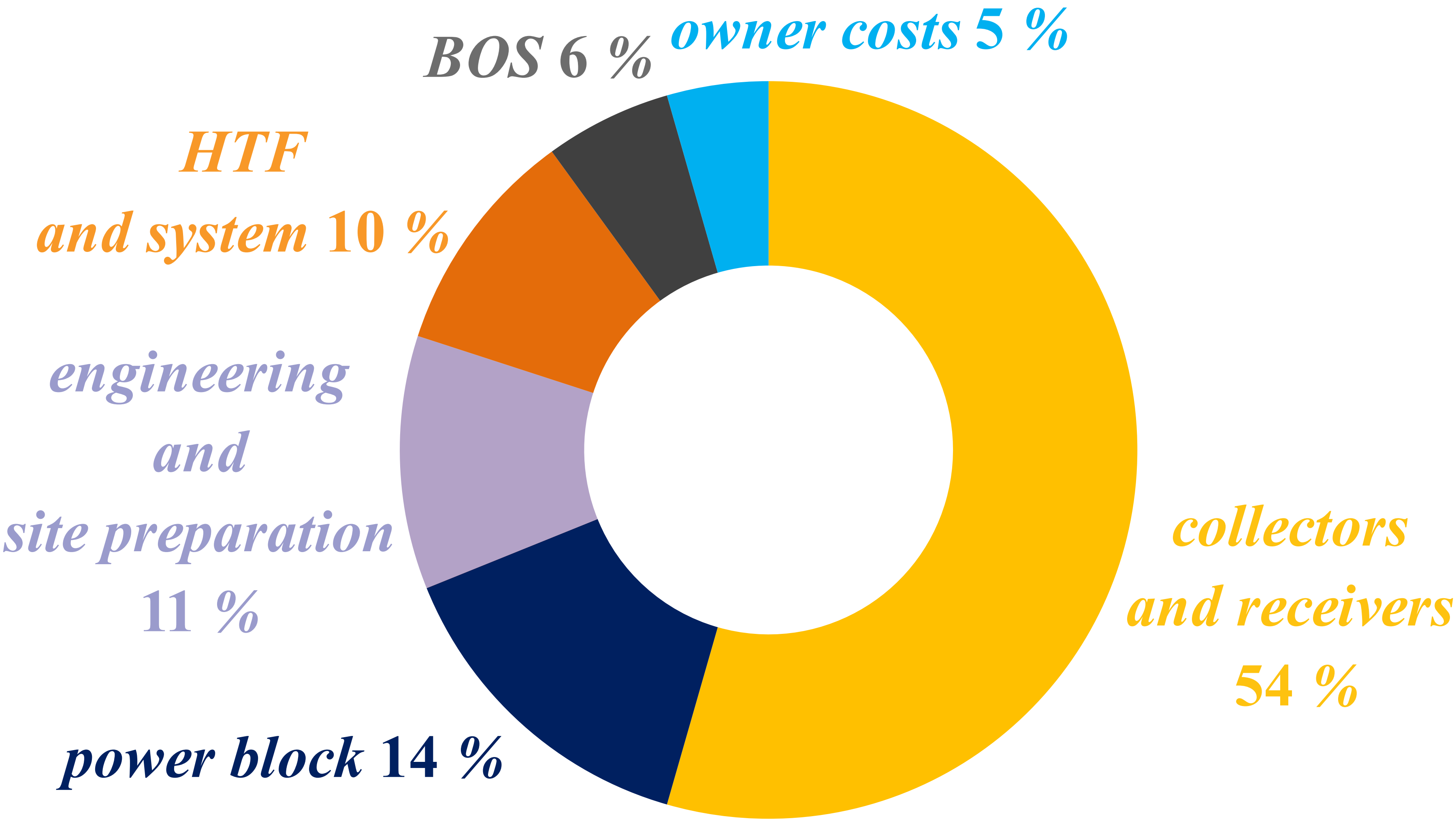
Source: http://www.nrel.gov/

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



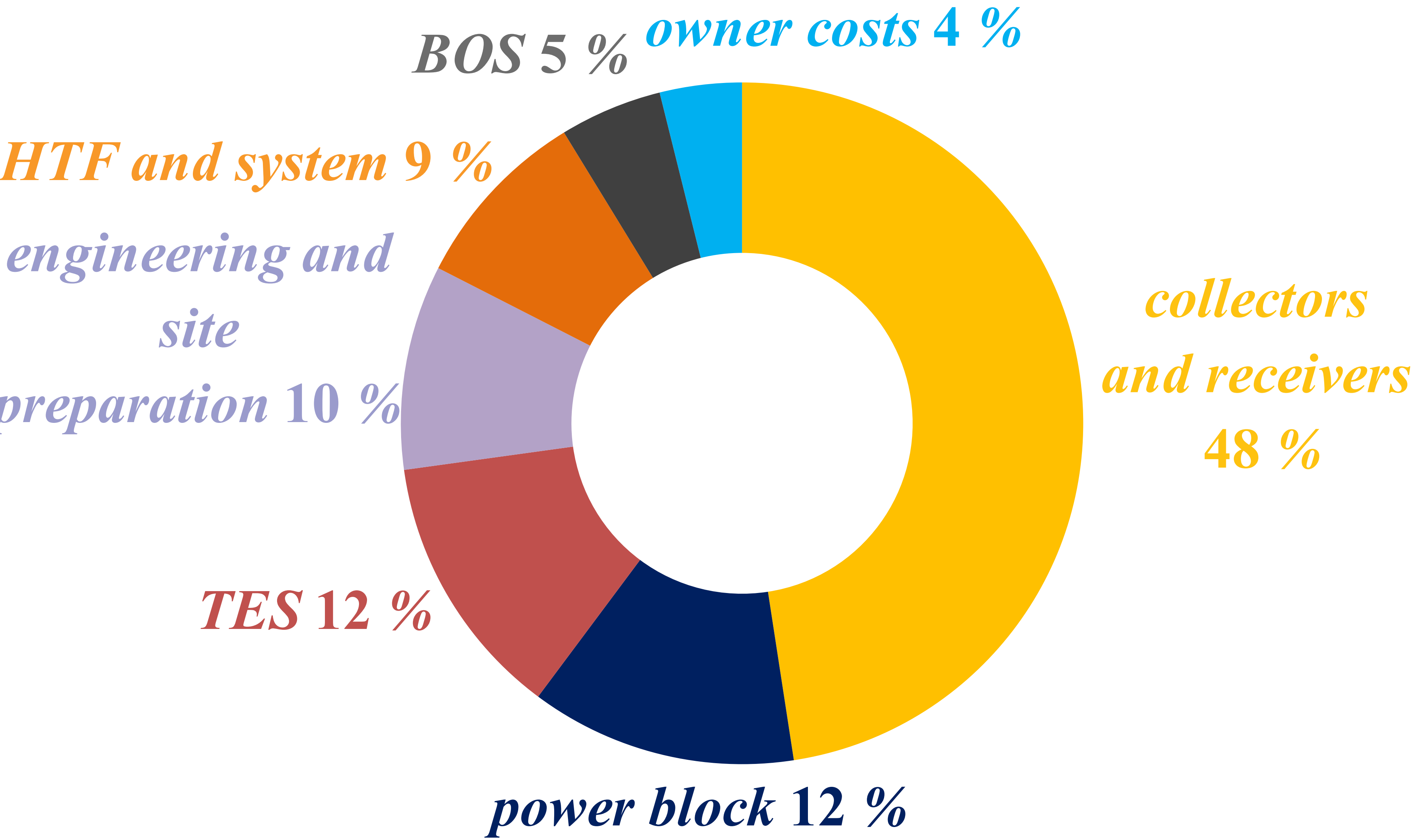
Source: http://www.nrel.gov/

2012 SOLAR TOWER *CSP* COST BREAKDOWN WITHOUT *TES*



Source: http://www.nrel.gov/

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



Source: http://www.nrel.gov/

CSP COST REDUCTION POTENTIAL

- There are multiple approaches under study 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 *HTF*s 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*

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*

- 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

attribute	*PV*	*CSP*
capacity range (MW)	0.1 – 400	0.1 – 400
c.f. range (%)	5 – 25	22 – 35 (*without TES*) 30 – 90 (*with TES*)
investment cost range ($/*W*)	1.98 – 4.01	3.84 – 14.54
average project implementation duration (*y*)	2 – 4	3 – 5
LCOE range ($/*kWh*)	0.11 – 0.29	0.16 – 0.36

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

