ECE 333

GREEN ELECTRIC ENERGY

18. Concentrated Solar Plants

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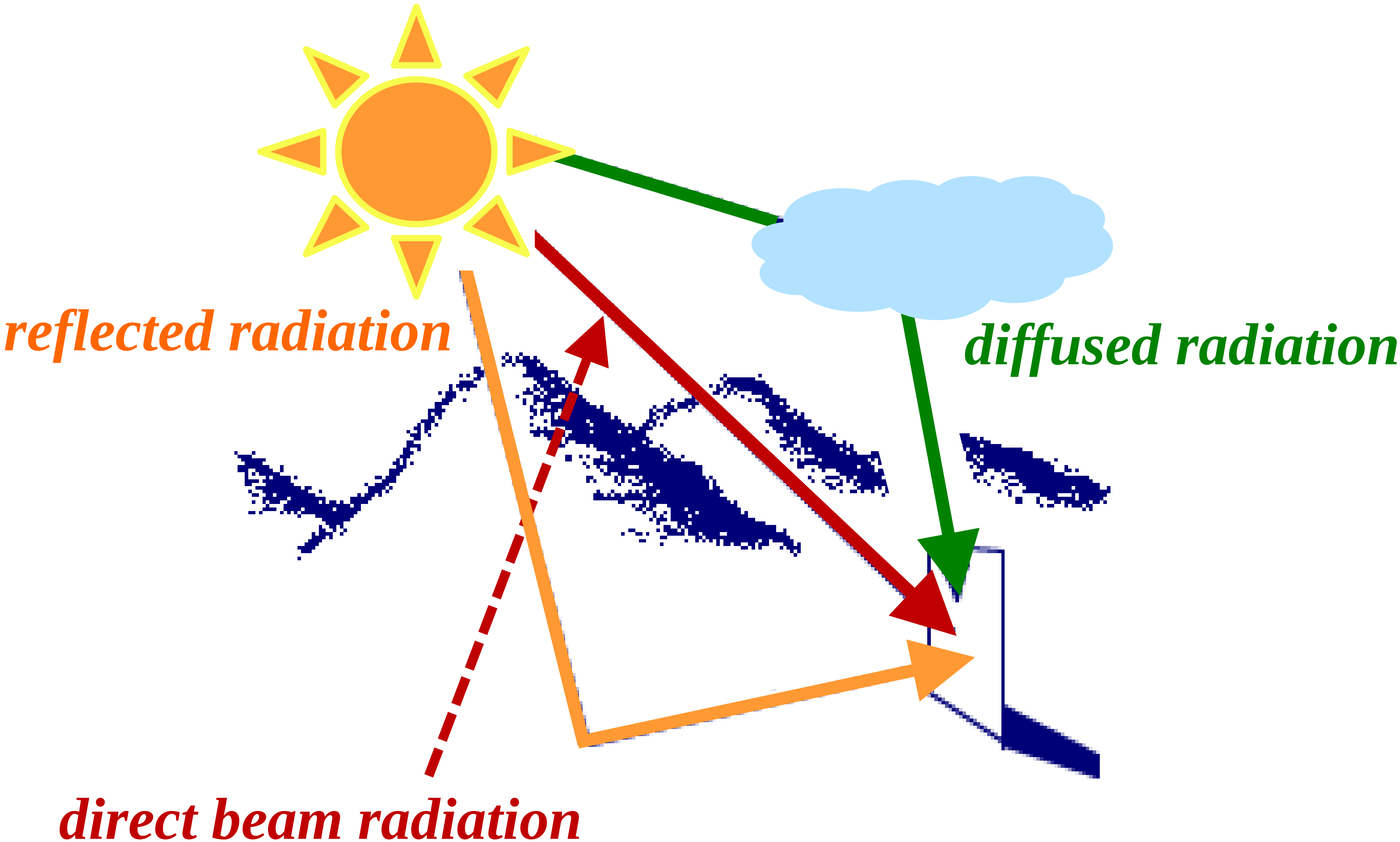
CONCENTRATED SOLAR PLANT (*CSP*)

- 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 only concentrate the direct beam radiation – also referred to as direct normal irradiation (*DNI*) – to generate electricity**

CSP

- **Specifically, *CSP* utilizes mirrors with tracking systems to focus *DNI* to collect the solar energy**
- **The collected solar energy is used to heat up the *heat transfer fluid* (*HTF*) to convert into *thermal energy***
- **Subsequently, the absorbed thermal energy is utilized to generate steam which drives a steam turbine to produce electricity**
- **A *CSP* may also incorporate a *thermal storage* device**

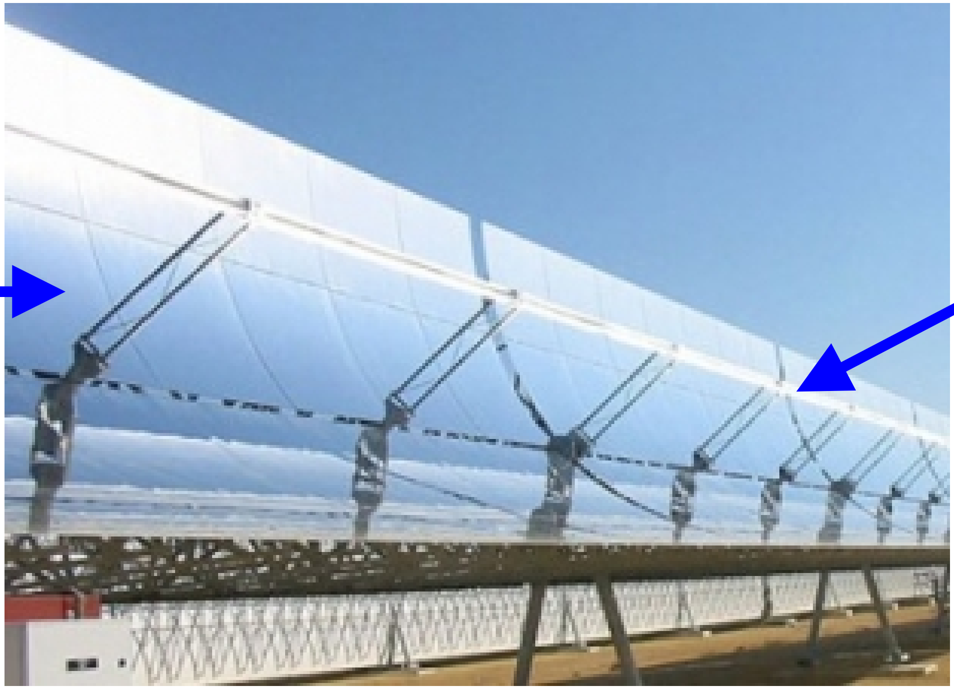
KEY COMPONENTS OF *CSP*

- A typical *CSP* 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
- The collector configurations are used to classify *CSP*s into 4 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

parabolic mirrors



receiver

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

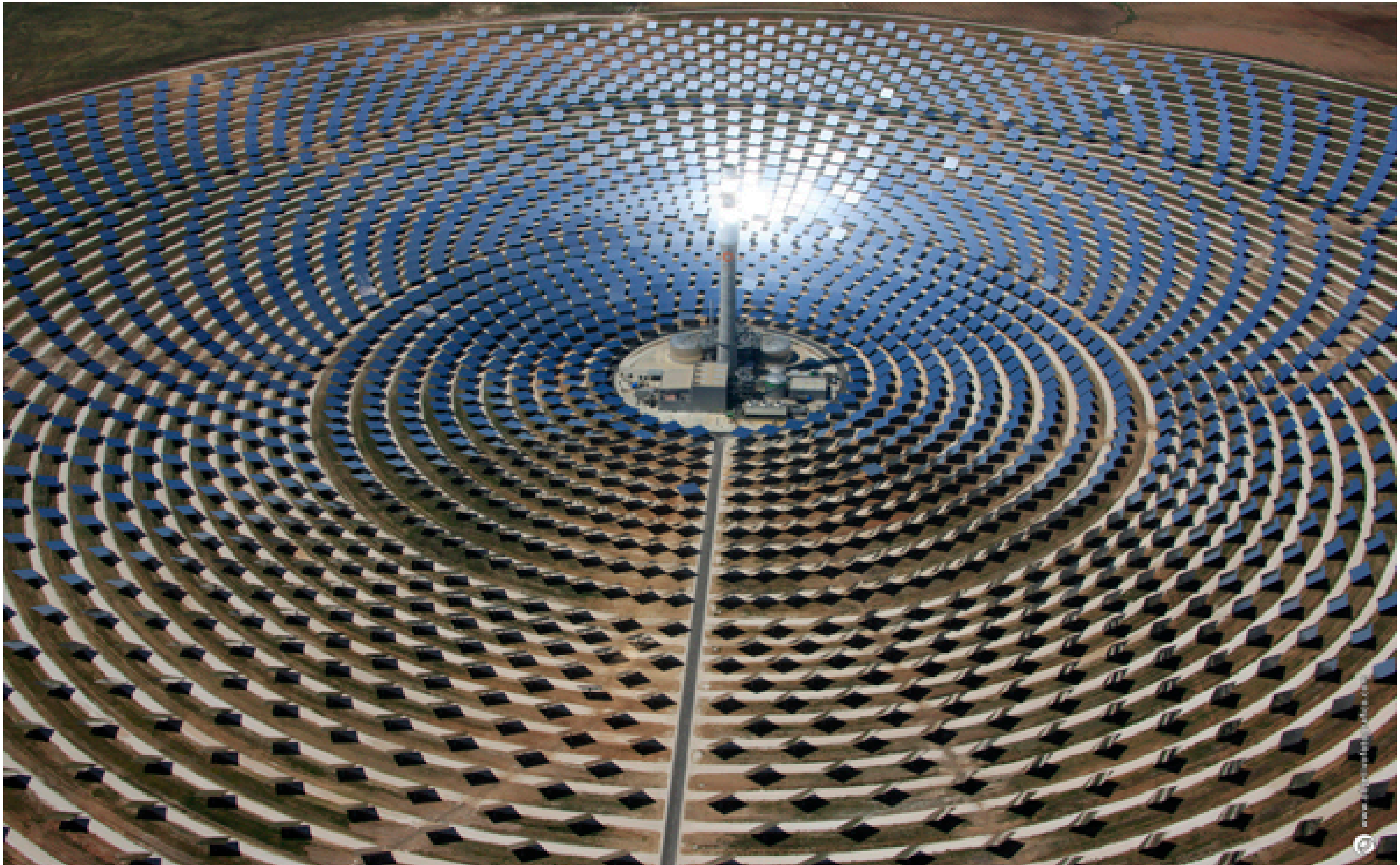
Solar tower *CSP* technology employs *heliostats* - collectors with dual-axis trackers – to concentrate *DNI* onto a central receiver – the solar tower

solar tower

heliostats

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* categories differ significantly from one another in terms of technical features, economics, technology maturity and operational performance in utility-scale applications
- Parabolic trough *CSP* is commercially widely used and is in many *CSP* projects under construction
- More recently, solar tower *CSP* is being deployed commercially

CSP TECHNOLOGY DIFFERENCES

- There are increasing interests in solar tower *CSP* using high-temperature molten salt as the *HTF* – a technology with the potential for marked cost reduction and considerable efficiency improvement
- We summarize the key attributes of the four categories in a tabular comparison

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* 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 *CSP* to produce electricity outside the sunrise – sunset periods and also provides smoothing of the *CSP* power output in cases of cloud cover uncertainty

TES

- 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.* values of *CSP* with *TES* is from 35 to 90 % – a major increase in utilization

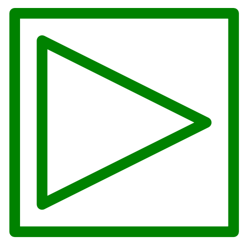
EXPLANATION OF *TES* CAPABILITY

- **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

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

CSP OPERATIONS

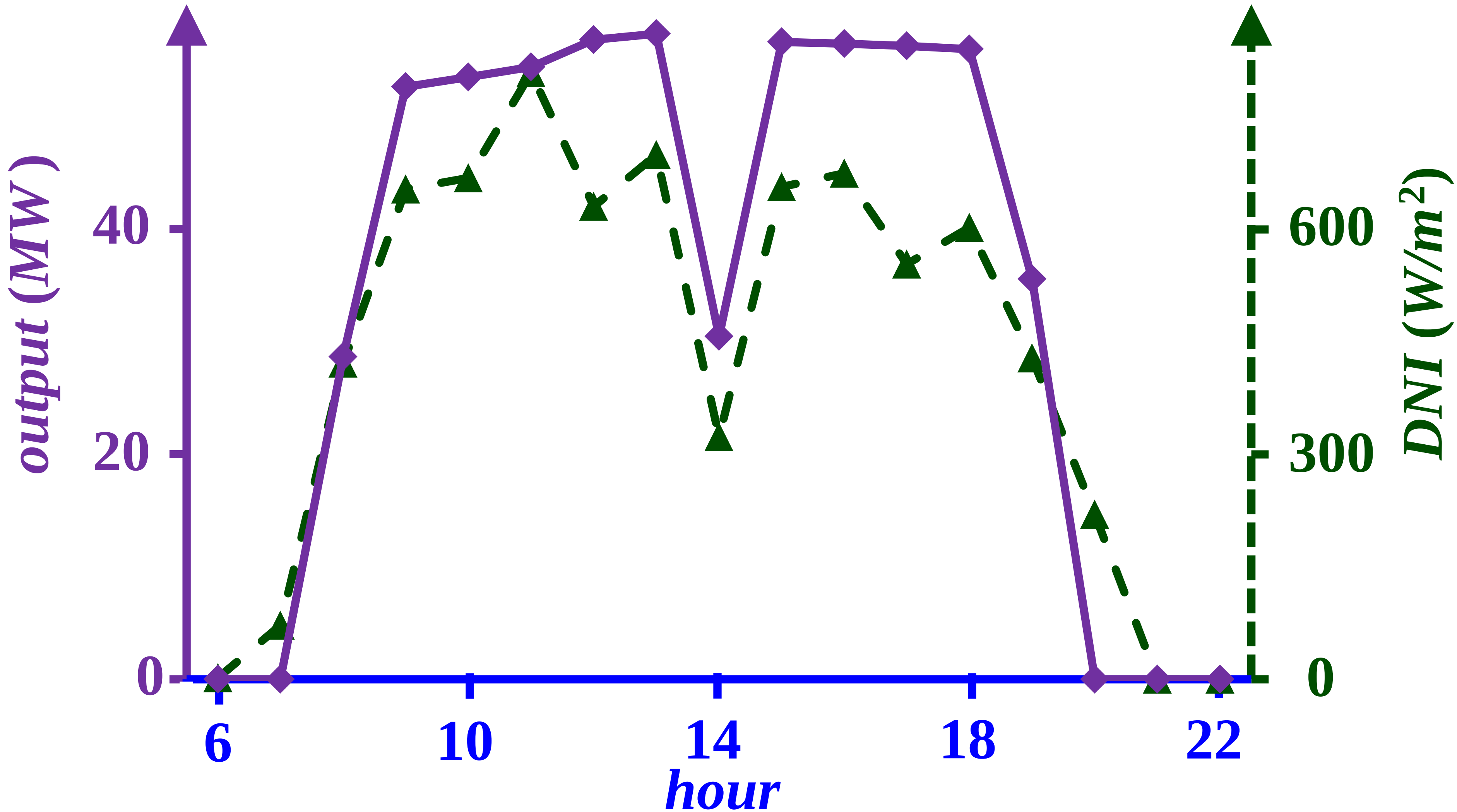


Source: http://www.youtube.com/watch?v=73SNIuZ333s

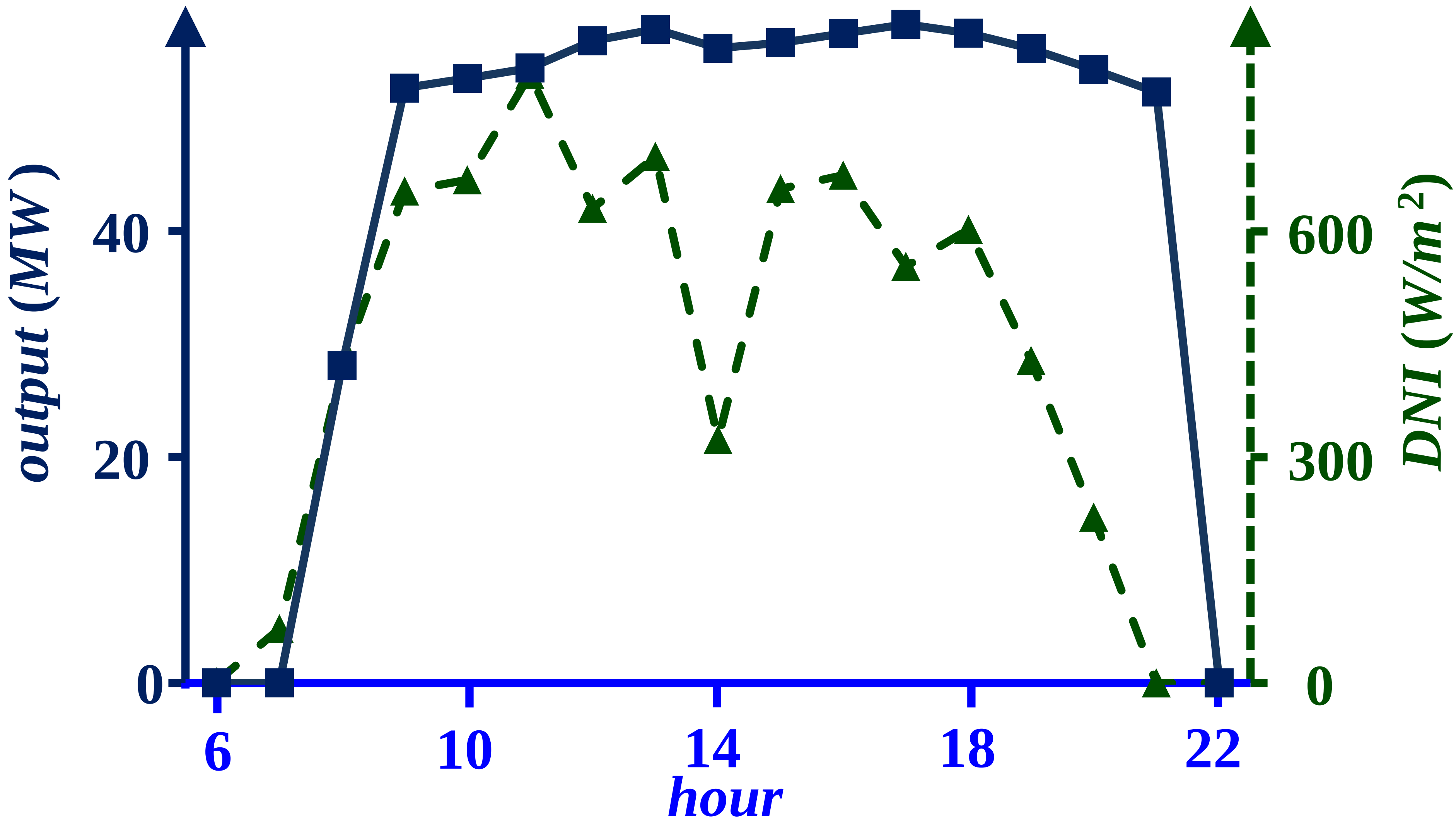
TES SCHEDULER

- 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 following considerations accounted for:
  - impacts of charge/discharge on the thermal energy stored in the *TES*
  - charge/discharge limits
  - *TES* physical capability
  - power block capacity

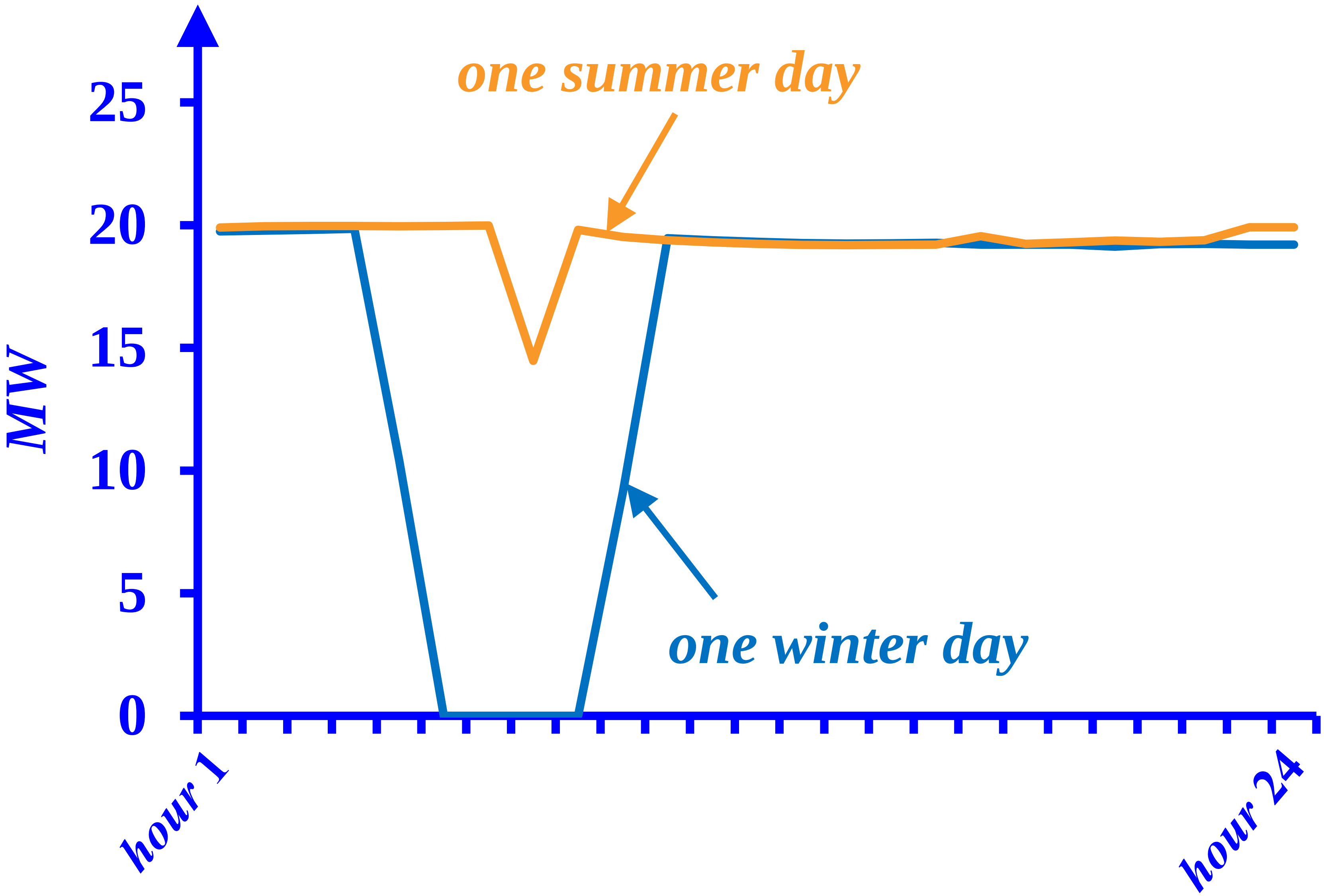
DAILY *CSP* POWER OUTPUT WITHOUT *TES*



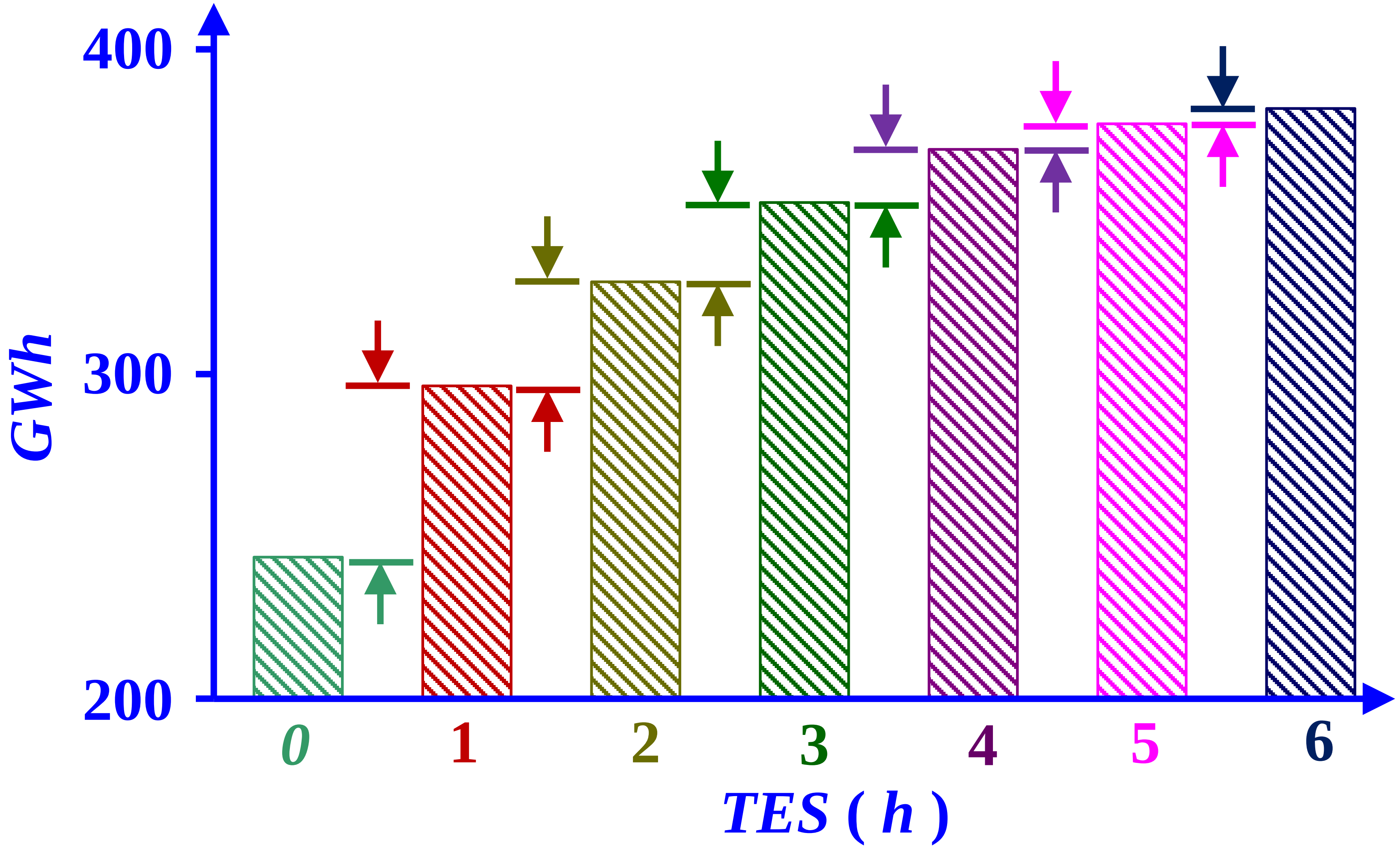
DAILY *CSP* POWER OUTPUT WITH *TES*



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



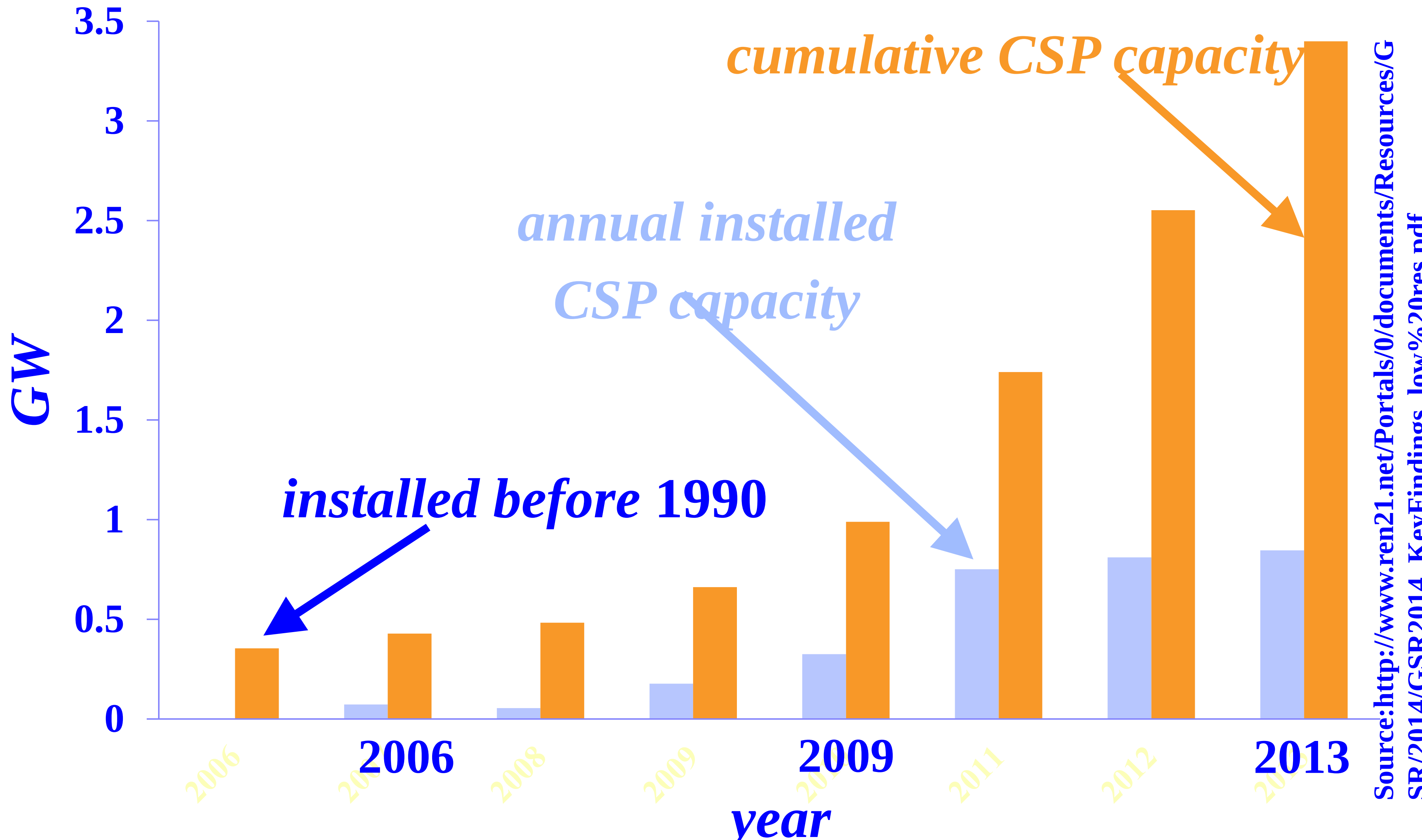
EXPECTED ANNUAL ENERGY PRODUCTION OF A 120 – *MW CSP*



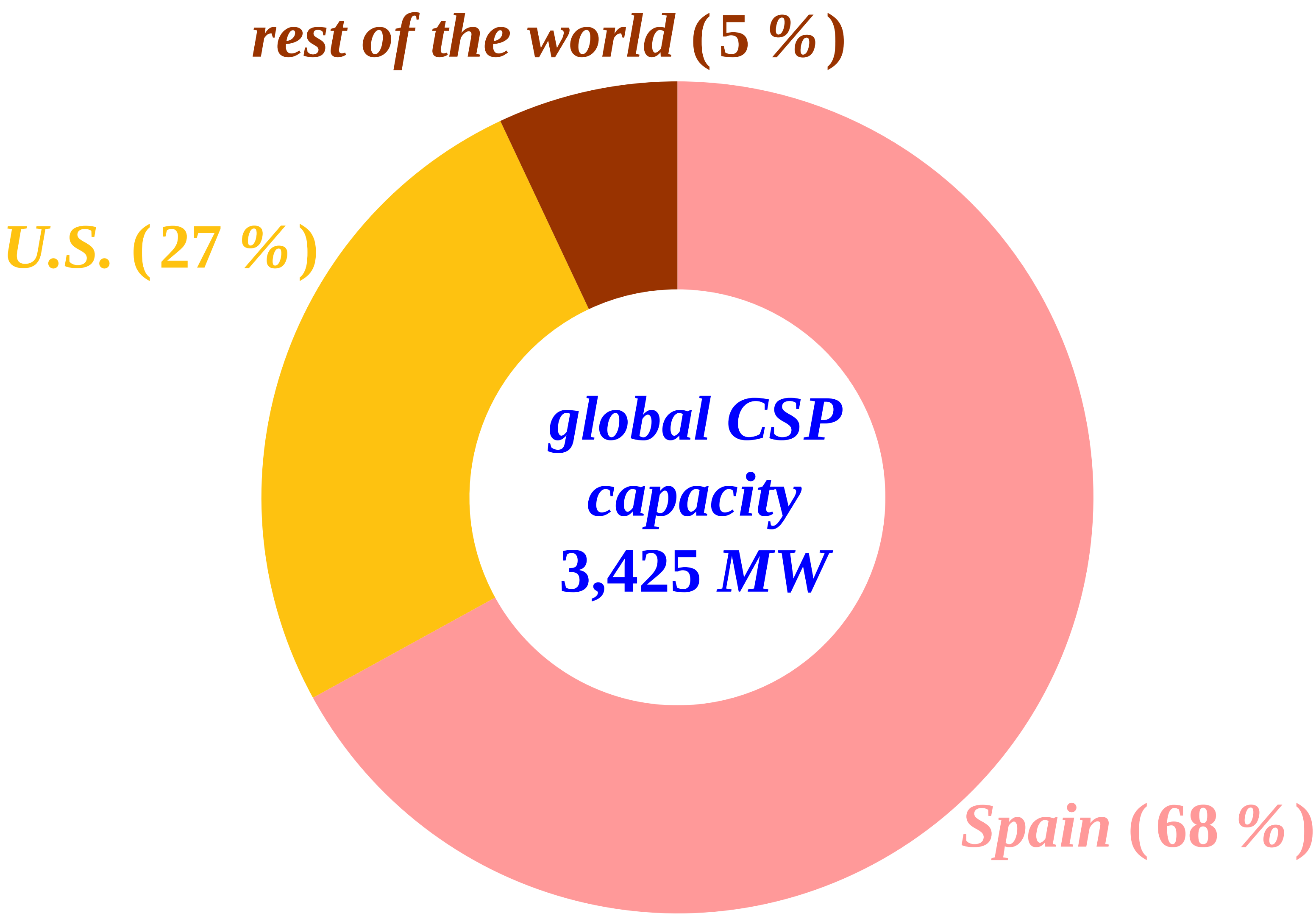
2013 WORLD *CSP* STATUS

- The 2013 global *CSP* capacity increased by 0.9 *GW* to reach 3,425 *MW* – 36 % above the 2012 figure
- While *US* and *Spain* remained the market leaders in annual additions with *Spain* being the leader in terms of total capacity, markets continued to shift towards countries with higher levels of insolation
- Capacity nearly tripled with projects coming on line in countries such as *UAE*, *India* and *China*

2006-2013 CUMULATIVE *CSP* CAPACITY



2013 *CSP* CAPACITY BY COUNTRY



Source:http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_KeyFindings_low%20res.pdf

2013 *U.S. CSP* STATUS

- The *US* remained the second largest *CSP* market in terms of total installed capacity, ending the year with 882 *MW* in operation
- With the start of operations of the *Ivanpah Solar Energy Generation Station* in *San Bernardino, California* in 2013, *US* led in annual *CSP* installation capacity

IVANPAH SOLAR ENERGY GENERATION PLANT

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

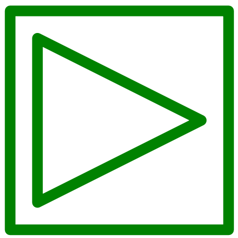
IVANPAH SOLAR ENERGY GENERATING SYSTEM

- **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

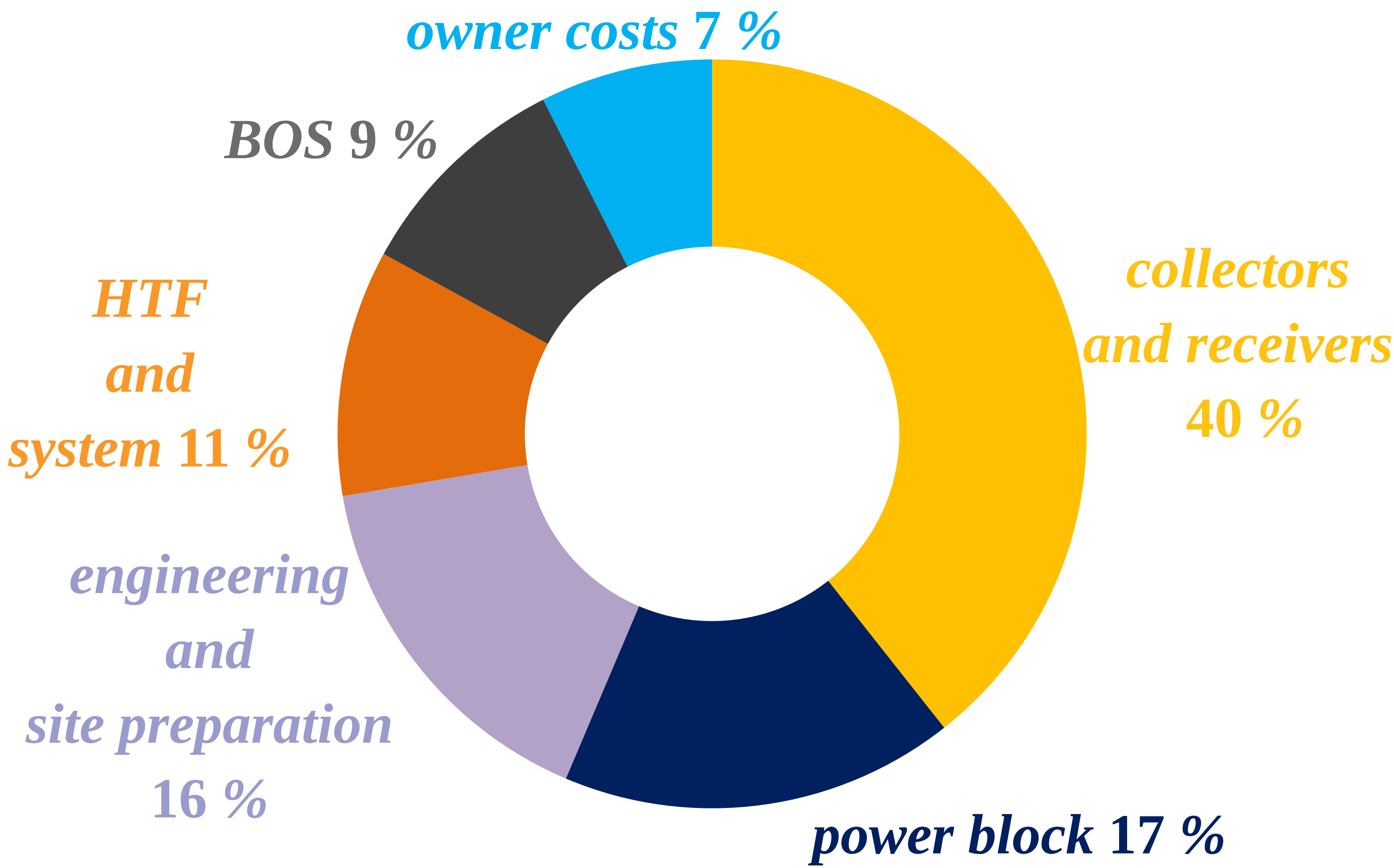
- **The 150 – *MW Andasol solar power station* is Europe's first commercial parabolic trough *CSP*, located in Andalusia, Spain**

- **Equipped with a 7.5 – *h TES*, *Andasol solar power station* is expected to produce 540 *GWh* annually with an annual *c.f.* of 0.41**

CSP INSTALLATION COSTS

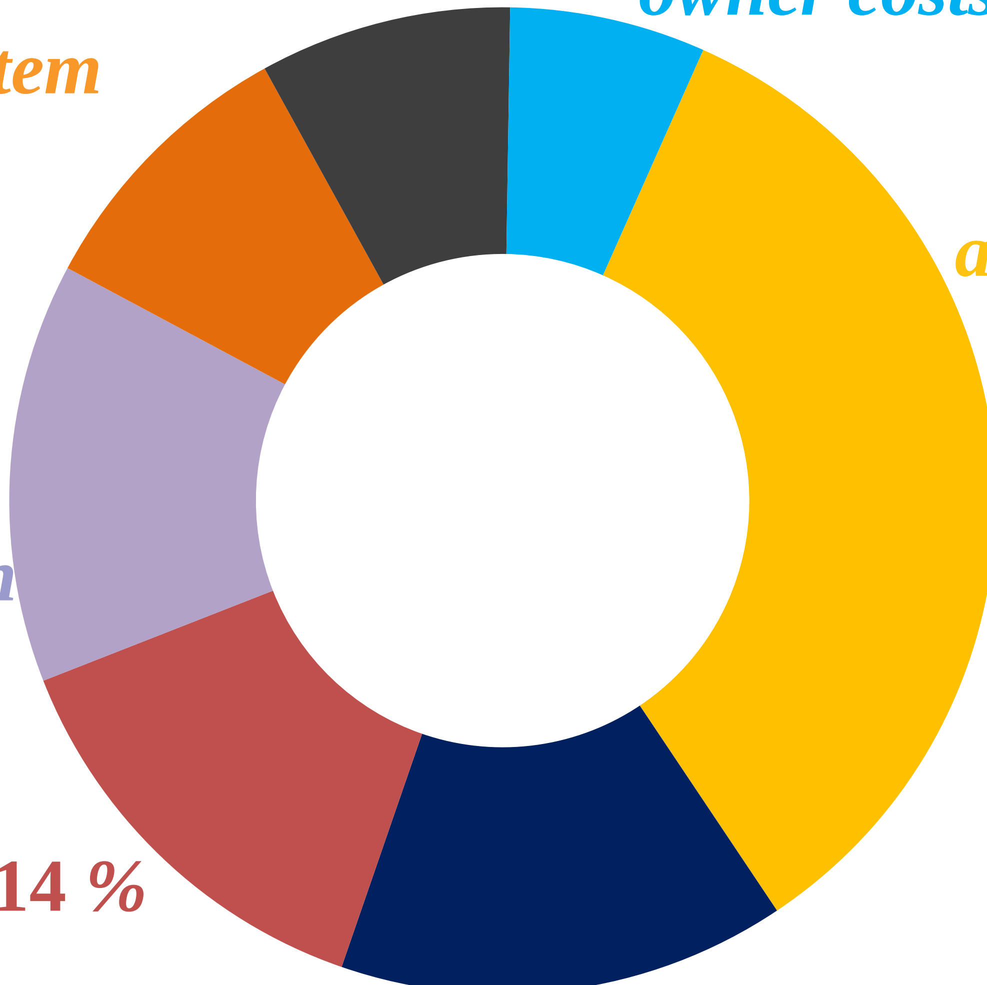
- The current investment costs for parabolic trough and solar tower *CSP* without *TES* range from 4.5 to 7.5 *$/kW*
- *CSP*s with *TES* tend to be more expensive with costs ranging from 5 to 10.5 *$/kW* and have higher *c.f.*s with the added ability to shift generation outside the sunrise–sunset periods

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



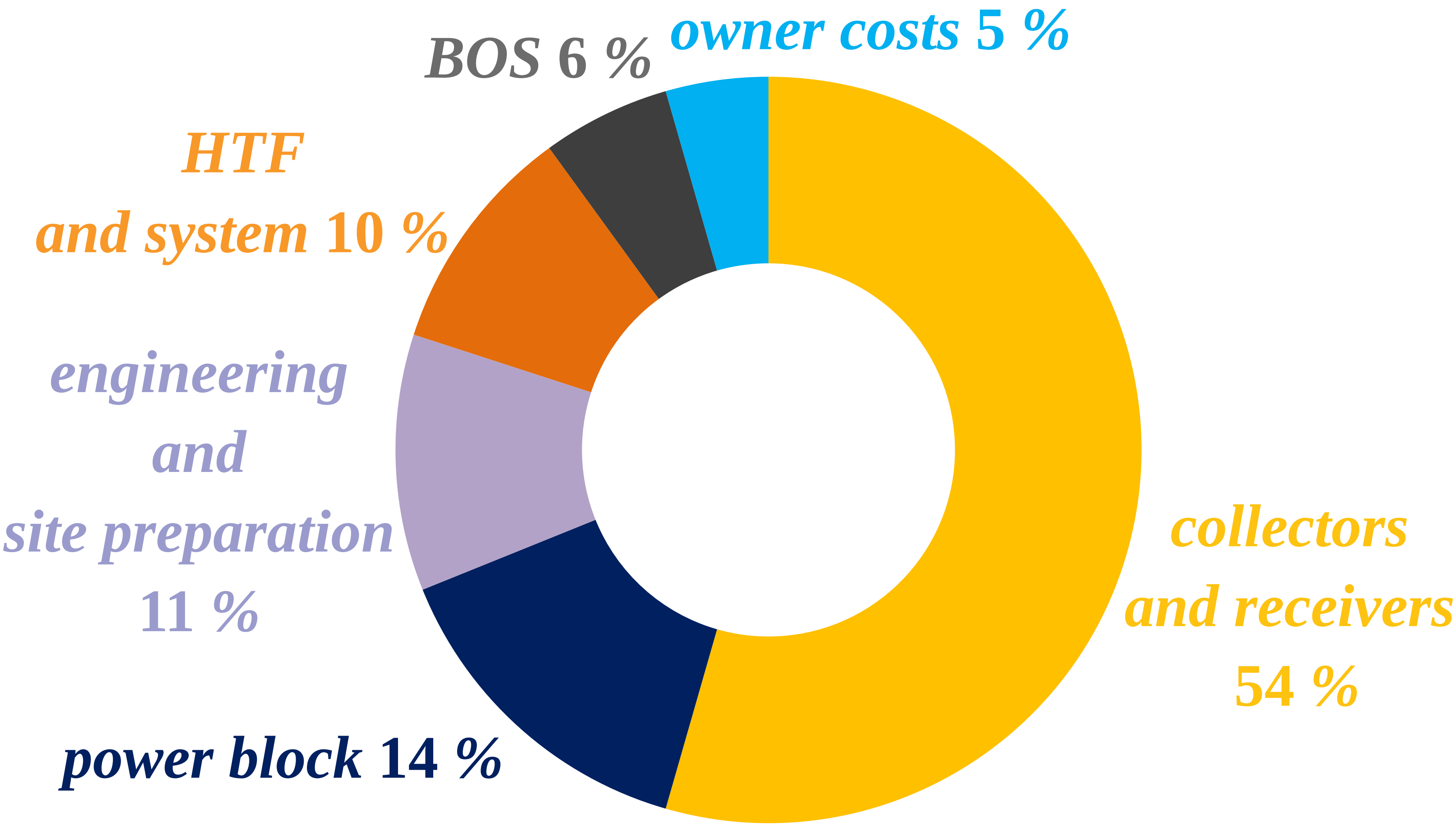
Source: http://www.nrel.gov/

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



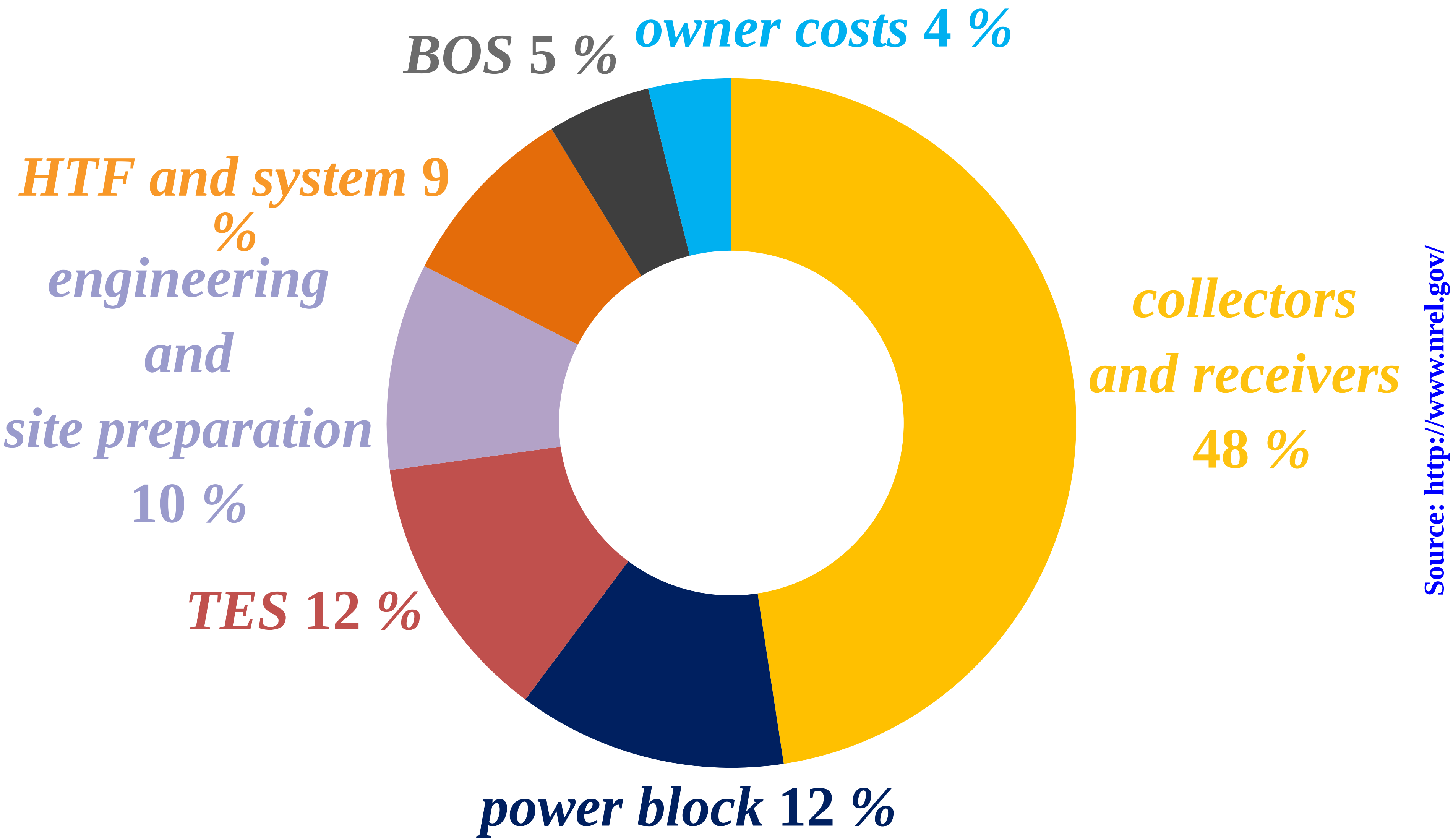
Source: http://www.nrel.gov/

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



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

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



CSP COST REDUCTION POTENTIAL

- There are multiple opportunities to reduce the costs of *CSP*
- 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 nature of technology deployed
- *CSP* with *TES* decreases the *CSP LCOE* with a range from 0.20 to 0.36 *$/kWh* for parabolic trough *CSP* and from 0.16 to *$* 0.30 *$/kWh* for solar tower *CSP*
- The *U.S*. Department of Energy *Sunshot Initiative* aims to reduce the *CSP LCOE* by 2020 to 0.06 *$/kWh*

PV AND *CSP*

- *PV* and *CSP* are the two most mature solar energy technologies for electricity generation
- Both represent commercialized technologies with rapid growth potential in the future
- By the close of June 2013, the *U.S*. total capacity of solar resources in operation is about 5,000 *MW*, with 89 % *PV* and 11 % *CSP*

PV AND *CSP*

- Unlike *PV* , *CSP* can only make use of the *direct* component of the insolation
- However, the utilization of *TES* , which allows *CSP* to produce electricity outside the sunrise-to-sunset periods, is a definite 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 drop drastically, its economic competitiveness becomes questionable**
- **Instead of direct *PV* and *CSP* competition, they may work symbiotically to deepen solar penetration in the future grid**