ECE 333 – GREEN ELECTRIC ENERGY

17. Concentrated Solar Power Plants

George Gross

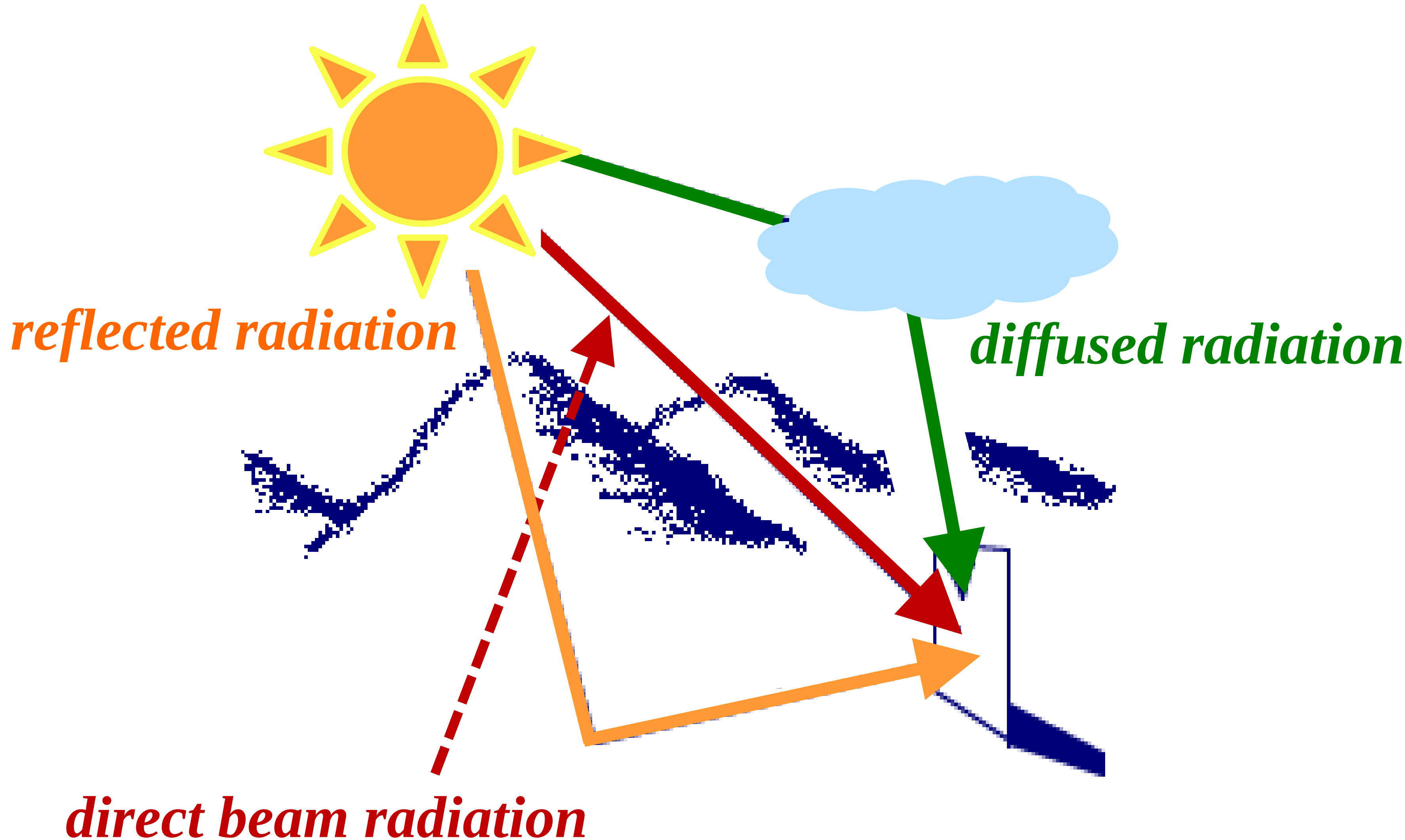
Department of Electrical and Computer Engineering

University of Illinois at Urbana-Champaign

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 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*

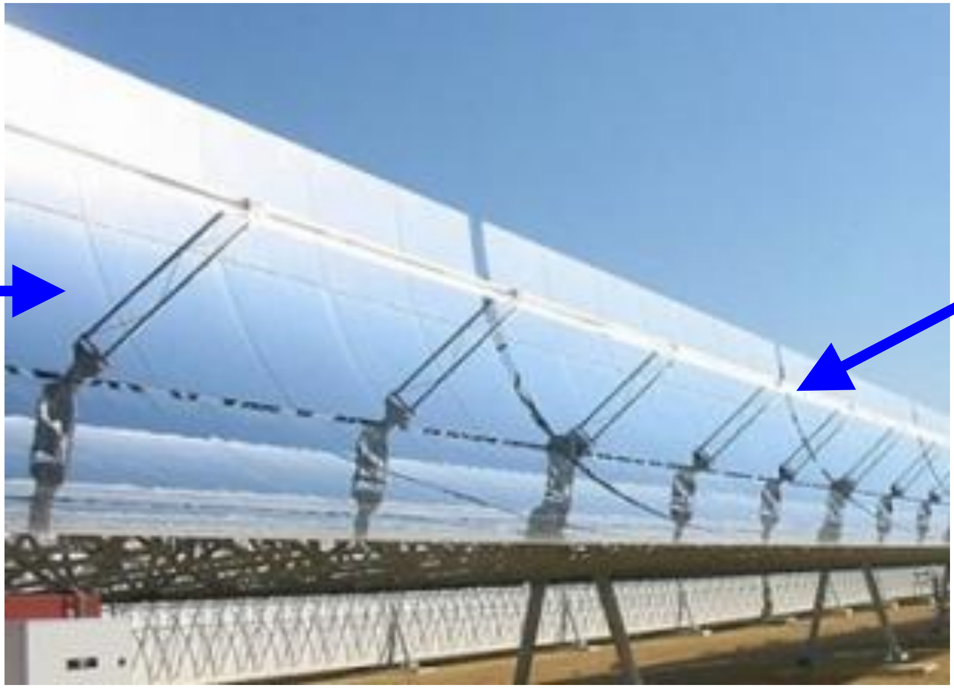
KEY COMPONENTS OF A *CSP* PLANT

- **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***
  - ***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

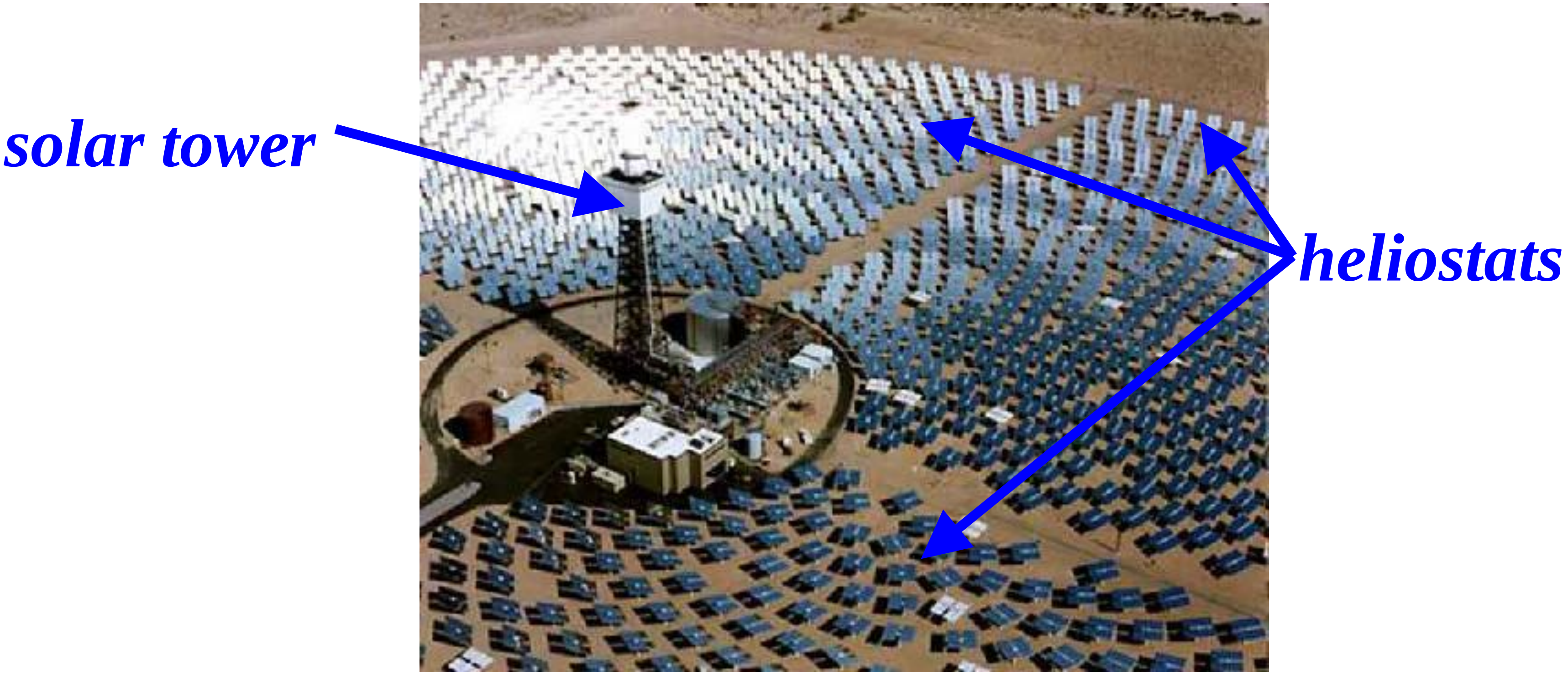
Source: http://www.abengoa.com

CALIFORNIA 354 – *MW* SOLAR ELECTRIC GENERATION SYSTEM

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*

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

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

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

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

TES

- 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

TES

- **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***

TES CAPABILITY

- 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

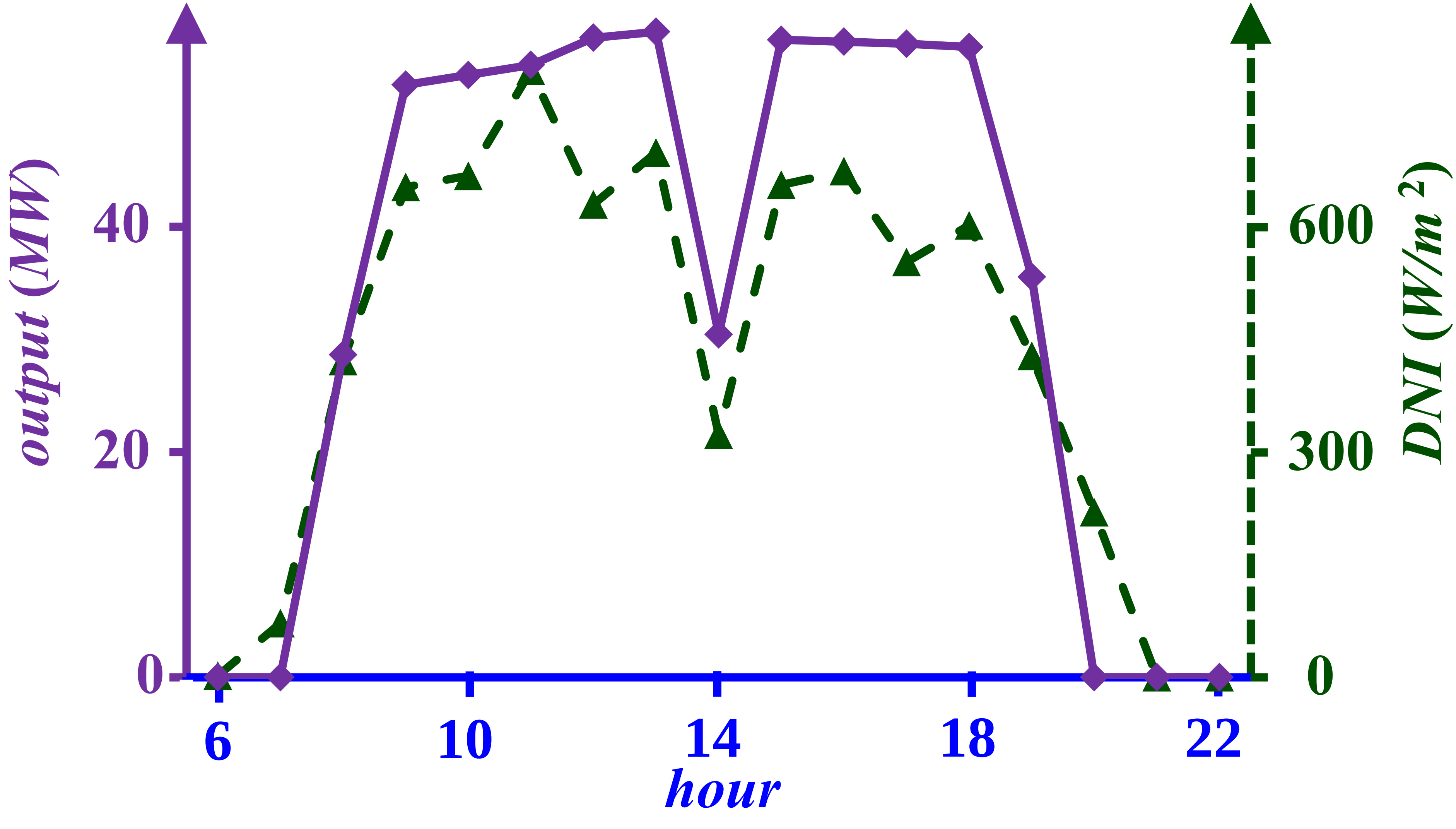
EXAMPLE: *TES* IMPACTS FOR *CSP*

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

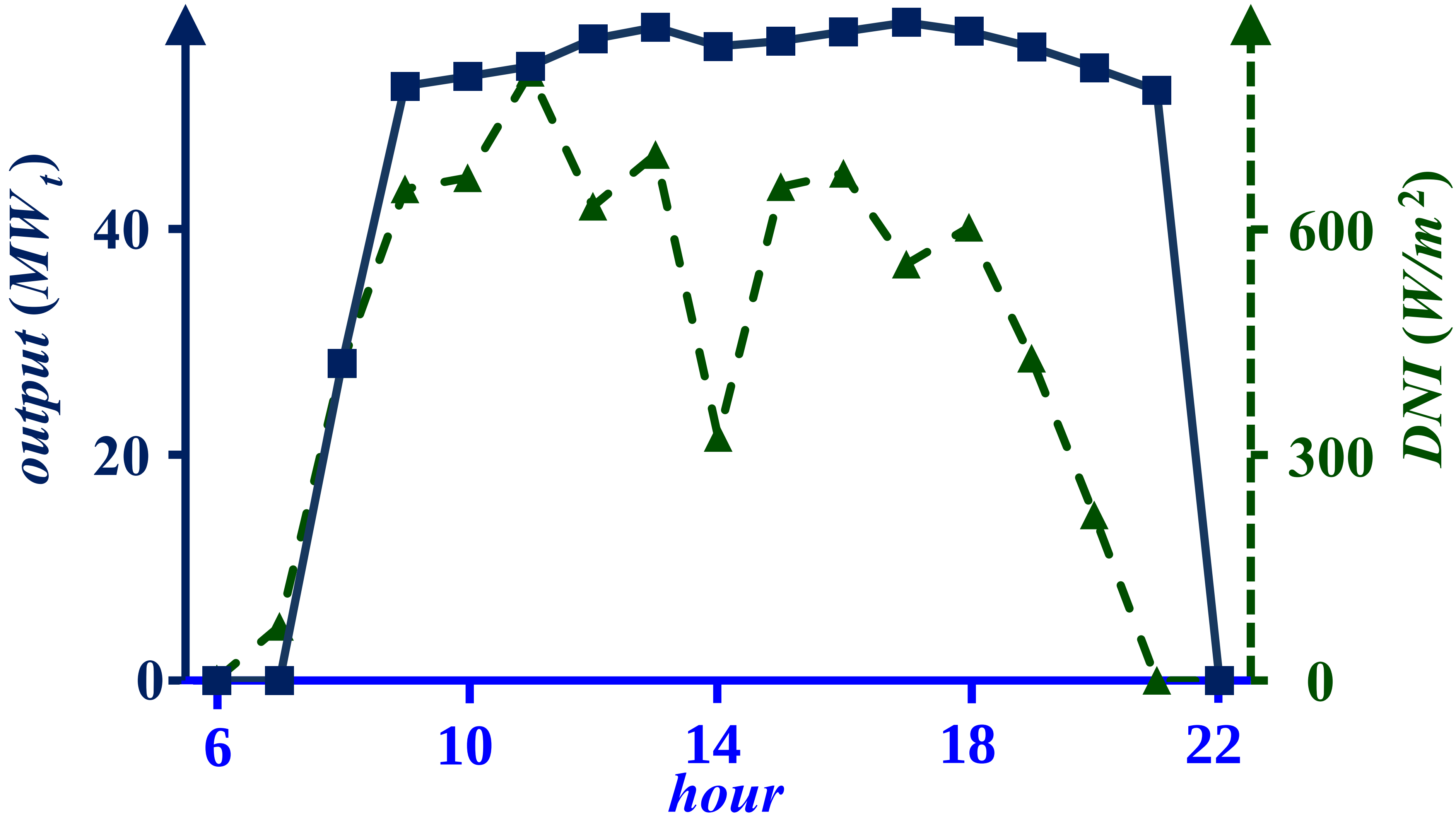
TES SCHEDULER

- To *optimize the contribution* 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

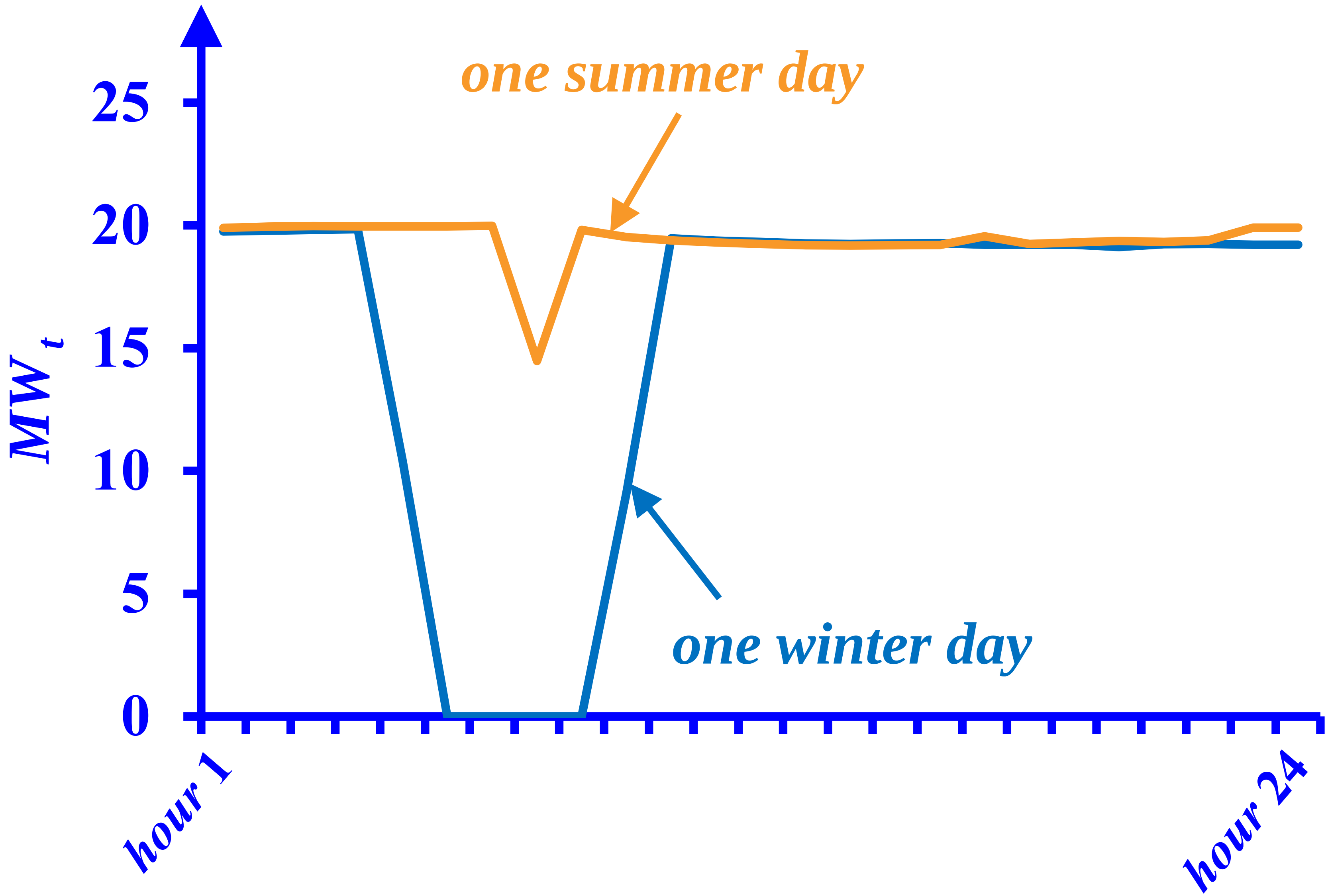
DAILY *CSP* POWER OUTPUT WITHOUT *TES*



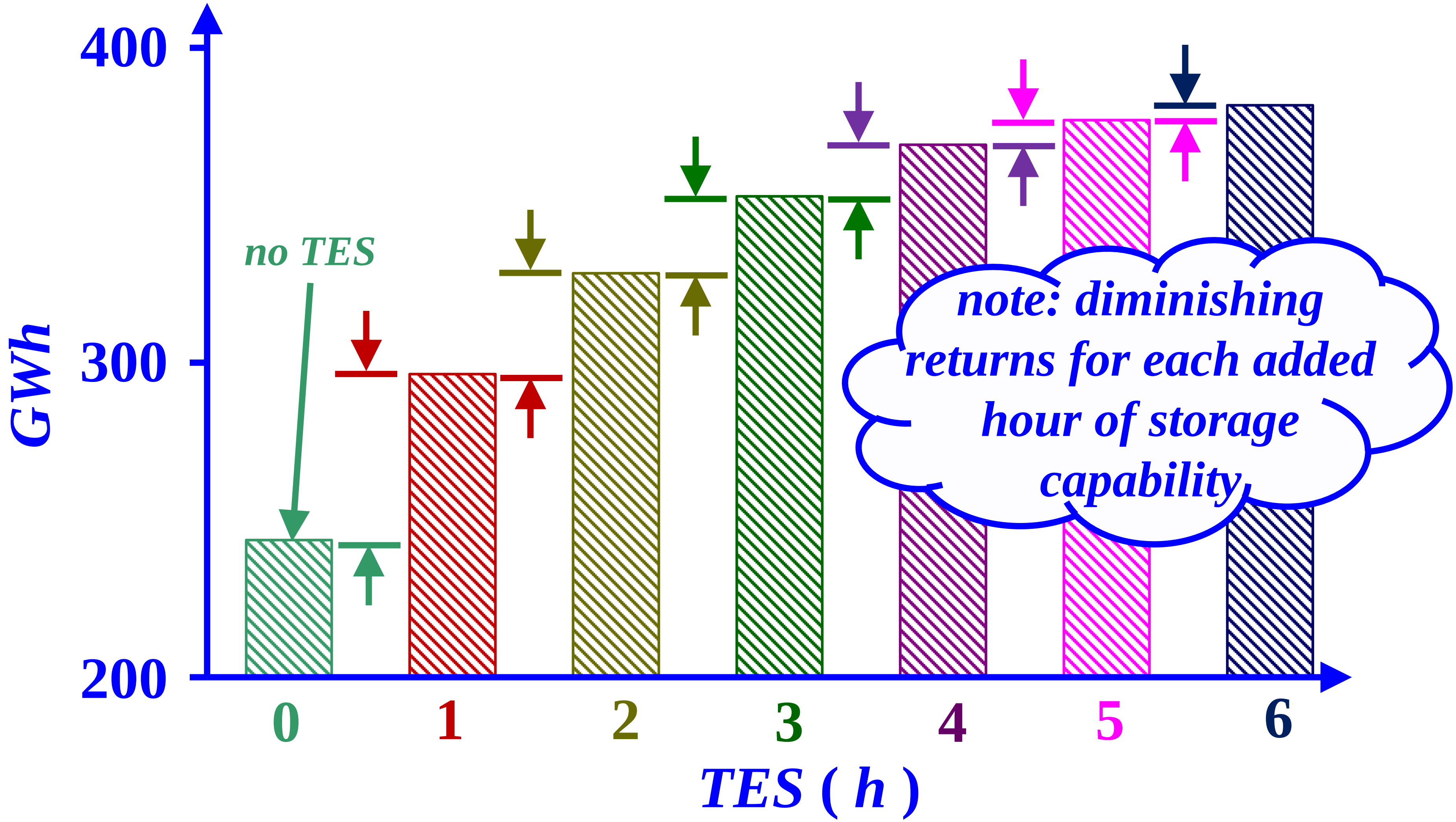
DAILY *CSP* POWER OUTPUT WITH *TES*



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



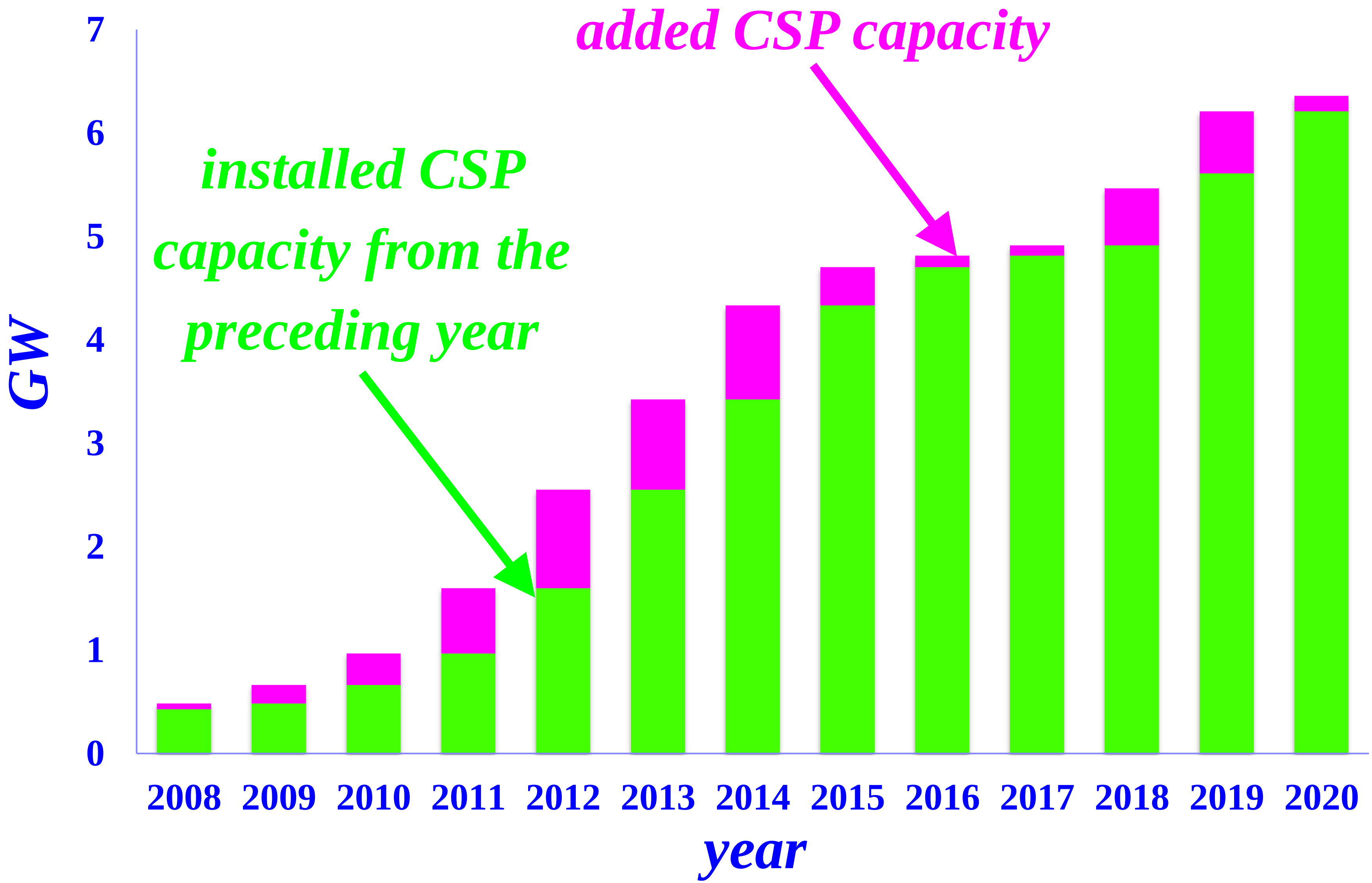
MEAN ANNUAL ENERGY GENERATION BY A 120 – *MW CSP* PLANT



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**

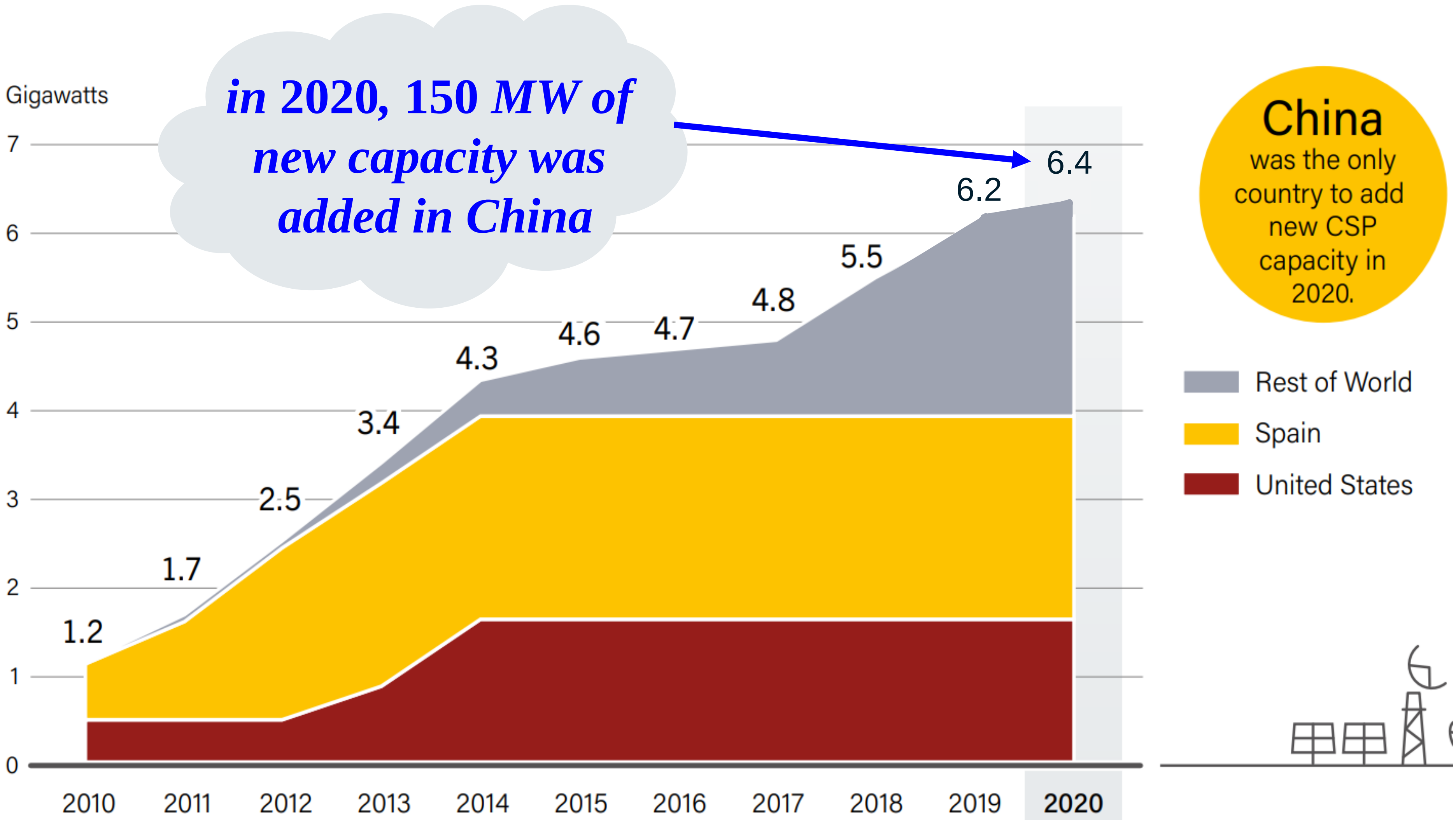
2006 – 2020 GLOBAL CUMULATIVE *CSP* CAPACITY



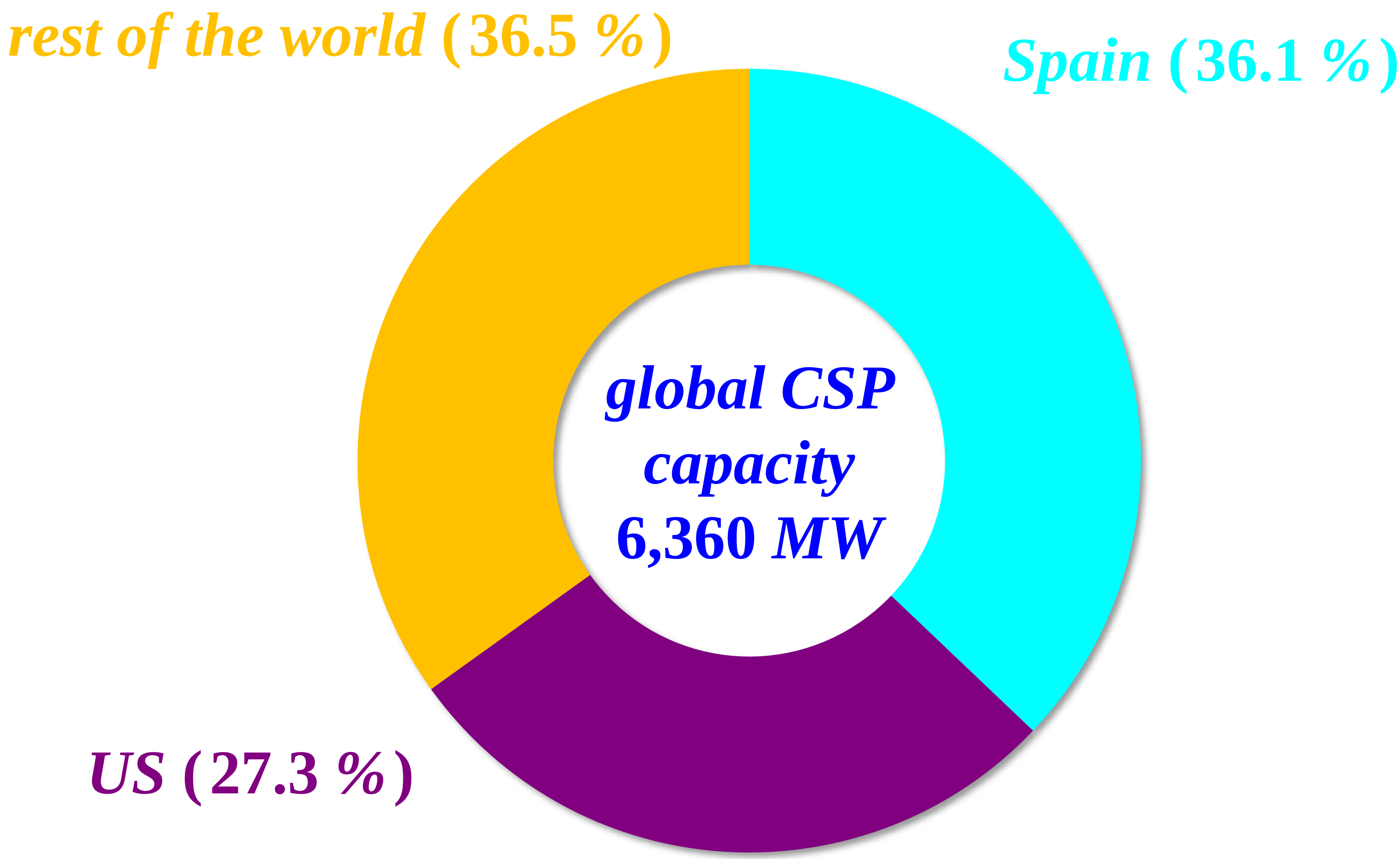
Source: REN 21, Renewables 2020 Global Status Report p. 238; available online at https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf

GLOBAL *CSP* CUMULATIVE CAPACITY 2009 – 2020

Source: REN 21, Renewables 2021 Global Status Report p. 134; available online at https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf



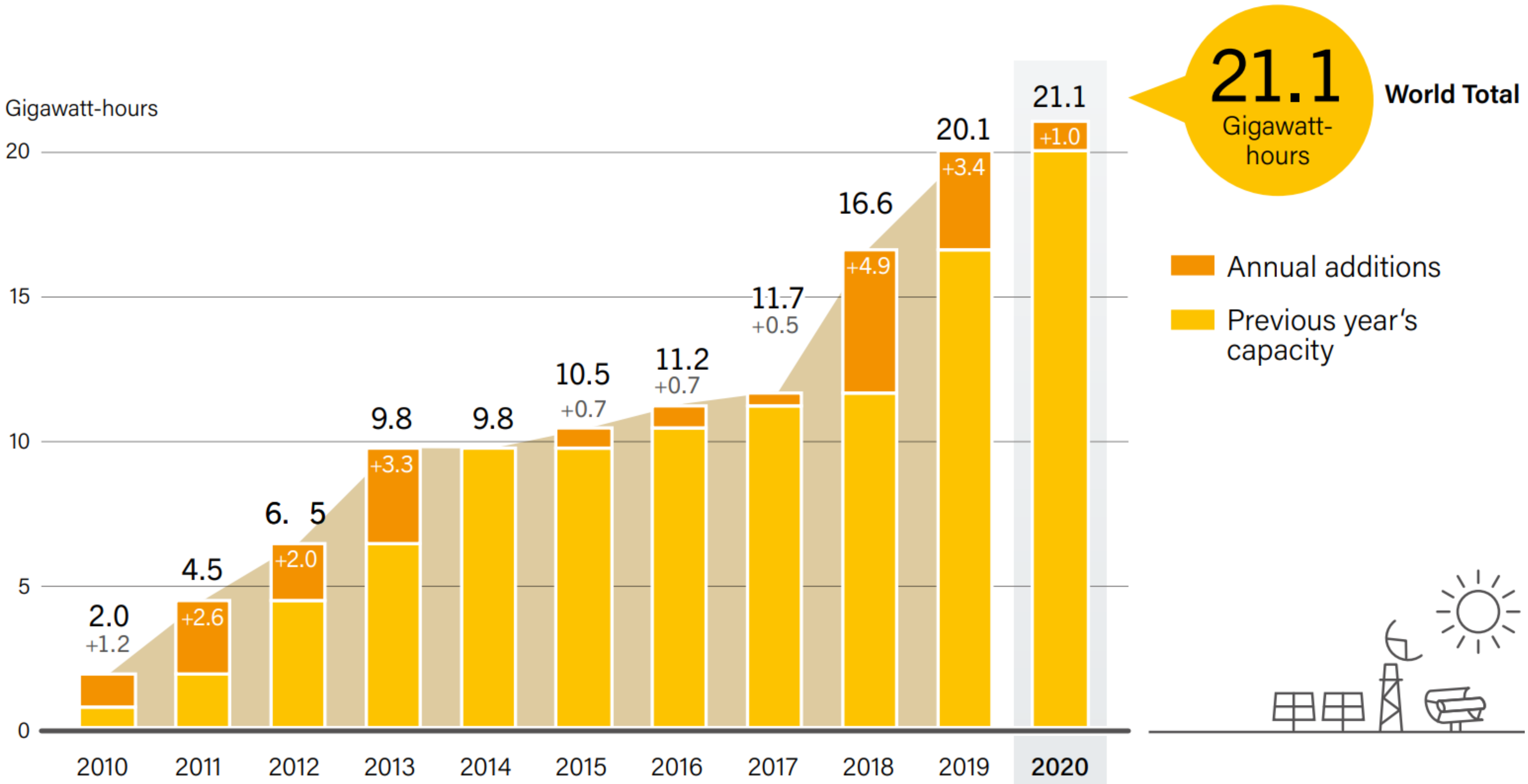
2020 *CSP* CAPACITY BY COUNTRY



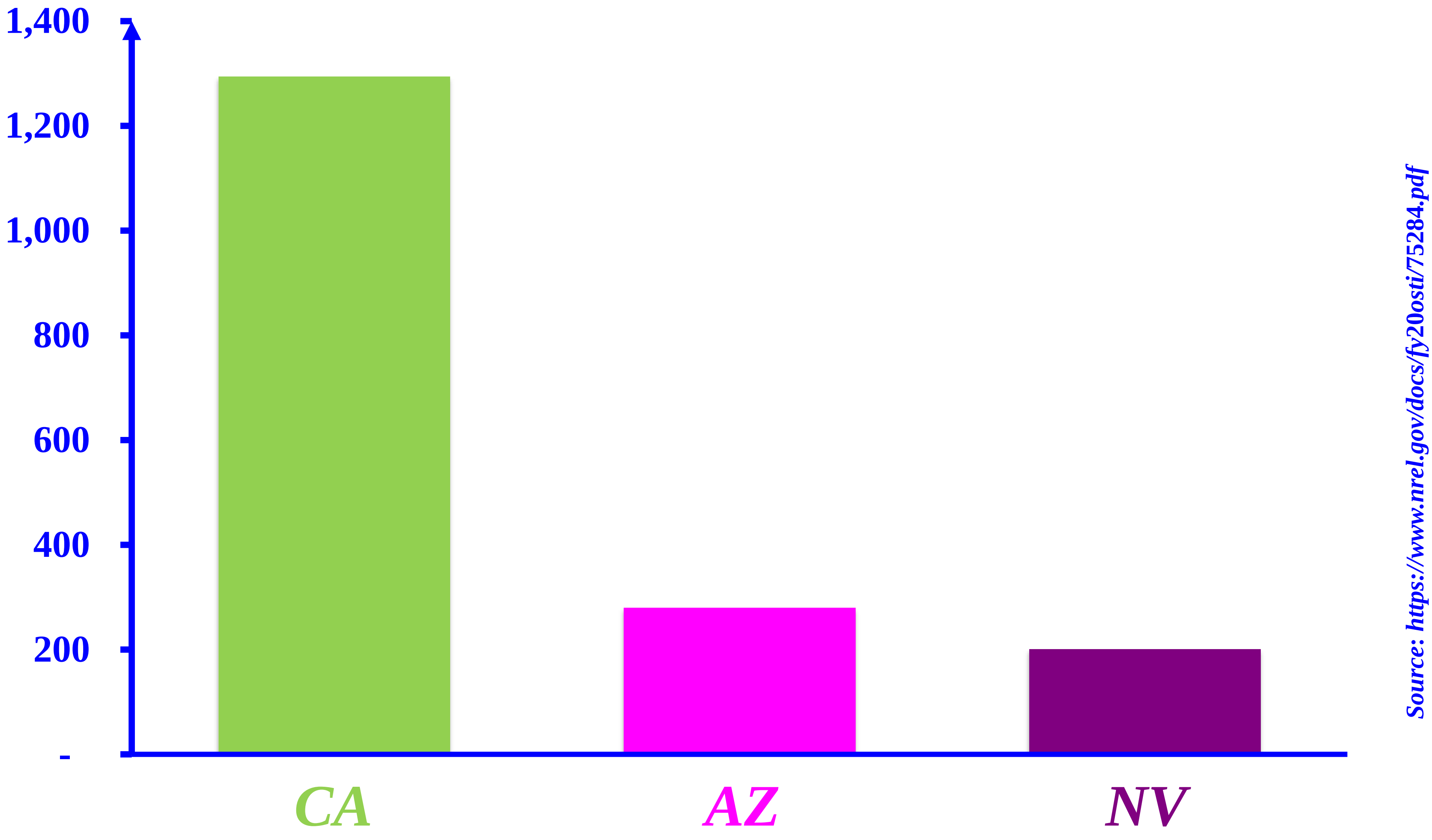
Source: REN 21, Renewables 2020 Global Status Report p. 238; available online at https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf

GLOBAL *CSP* THERMAL ENERGY STORAGE CAPABILITY 2009 – 2020

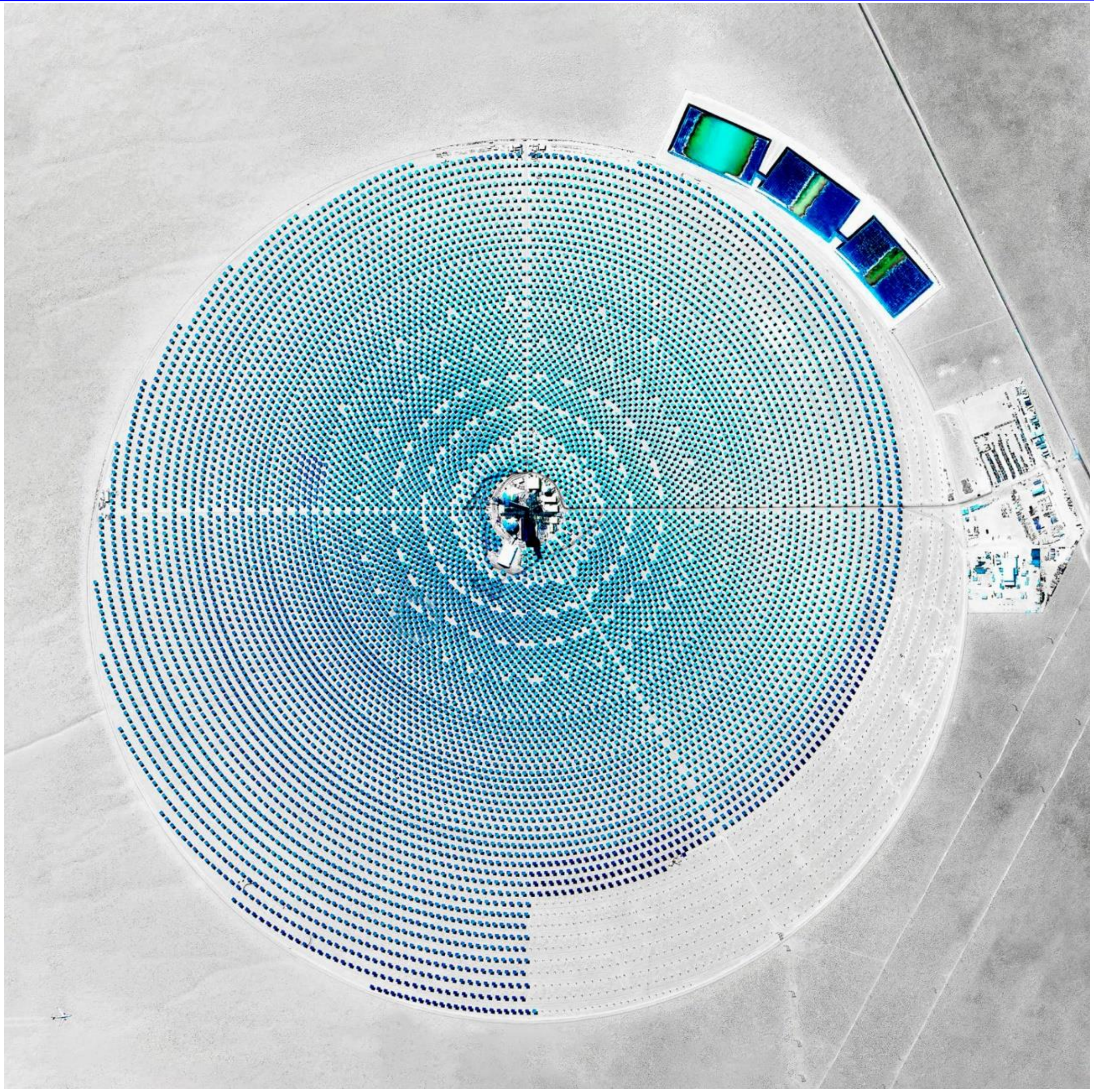
Source: REN 21, Renewables 2021 Global Status Report p. 135; available online at https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf



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

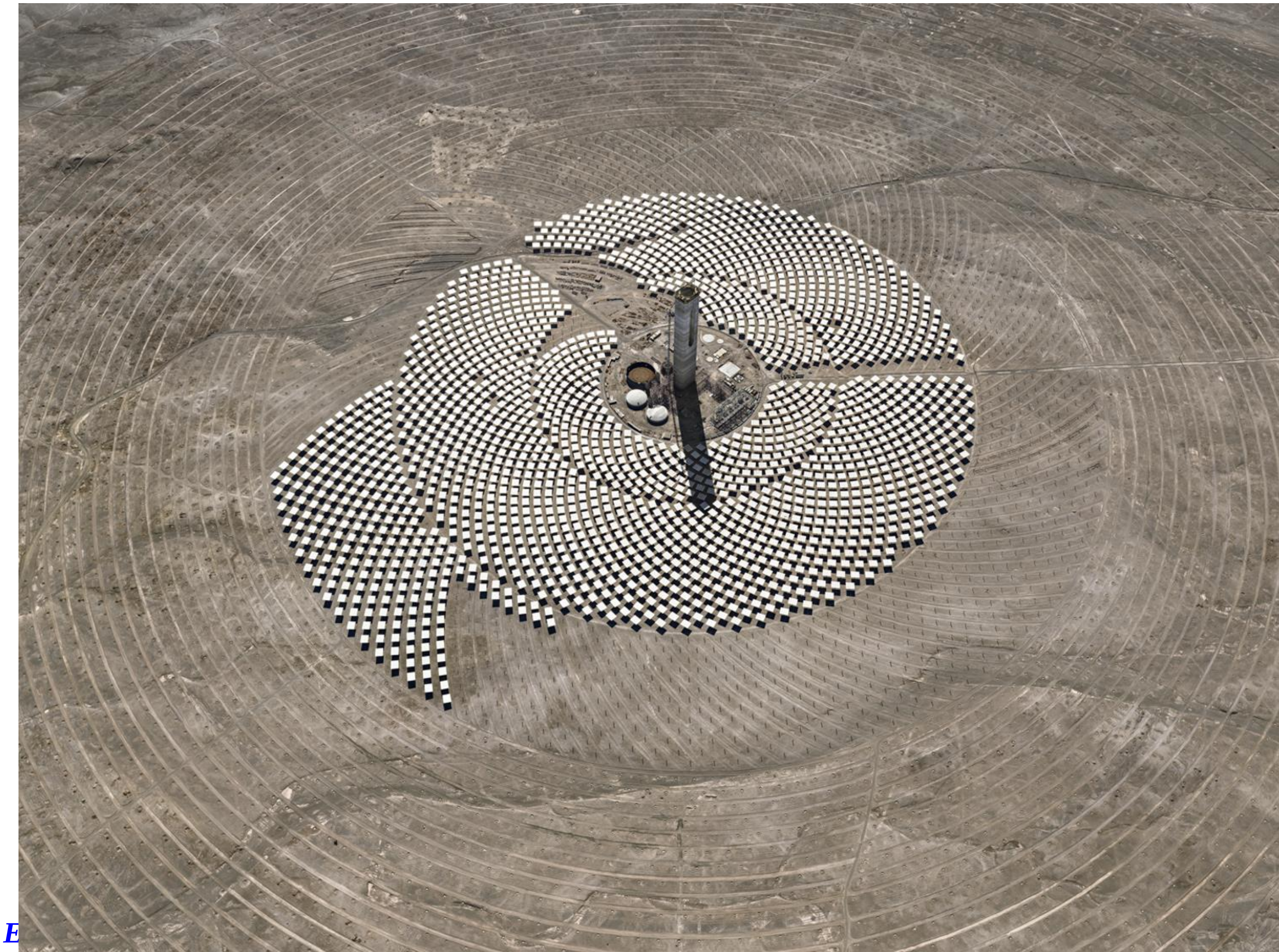


THE *CRESCENT DUNES* SOLAR PROJECT IN *NEVADA*



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

CERRO DOMINADOR SOLAR PROJECT



Source: photograph by Edward Burtynsky, courtesy of Bryce Wolkowitz Gallery

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 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

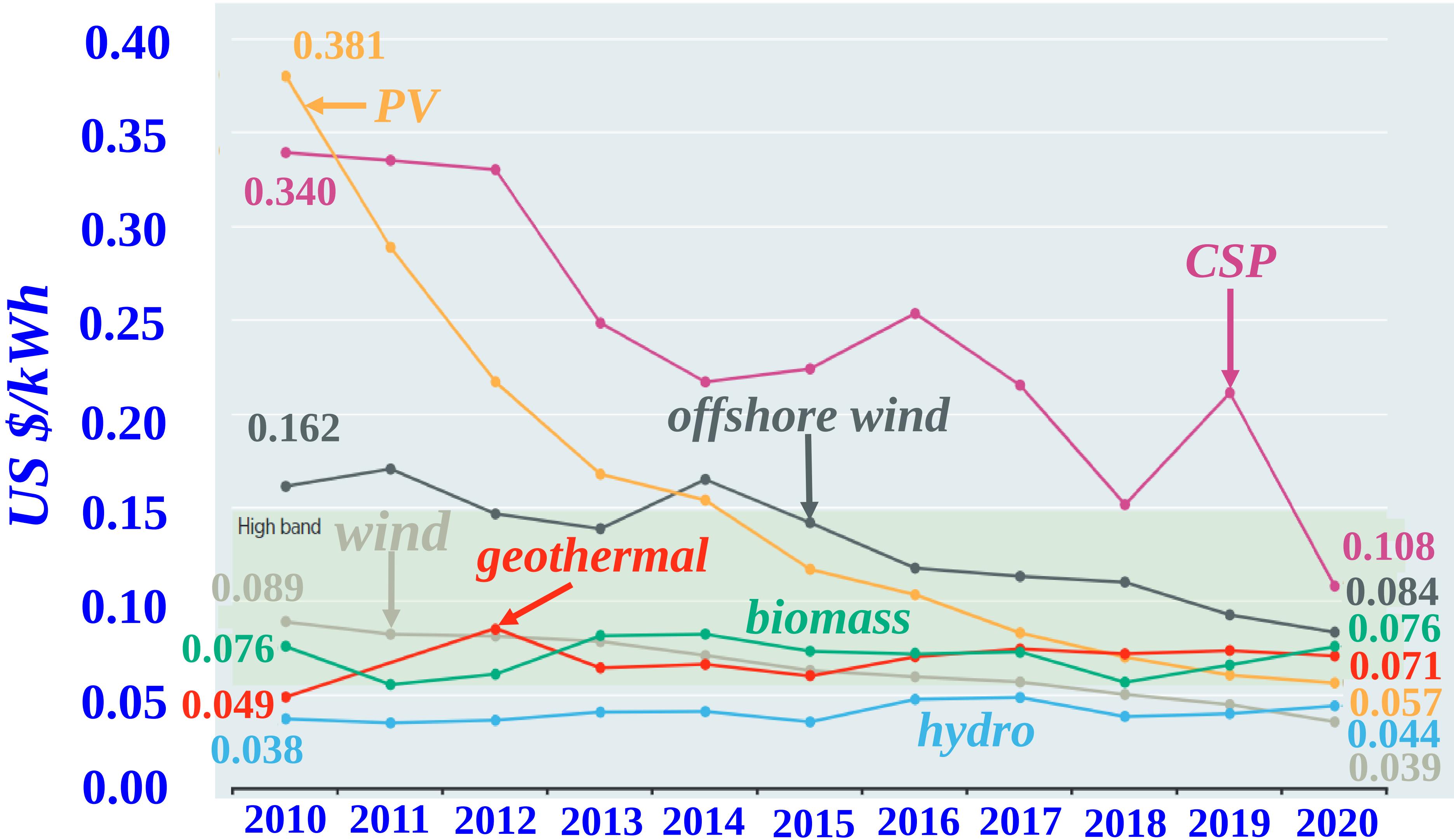
2020 *CSP* COST COMPONENTS

Source*: *IRENA Power Generation Costs 2020*, p. 108; *available online at https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

cost component	*share in % of the total costs of*	
	parabolic trough	*solar tower*
owner borne	8	9
indirect EPC cost	12	15
thermal storage	17	12
power block	18	16
tower	0	2
receiver	6	18
solar field	39	28

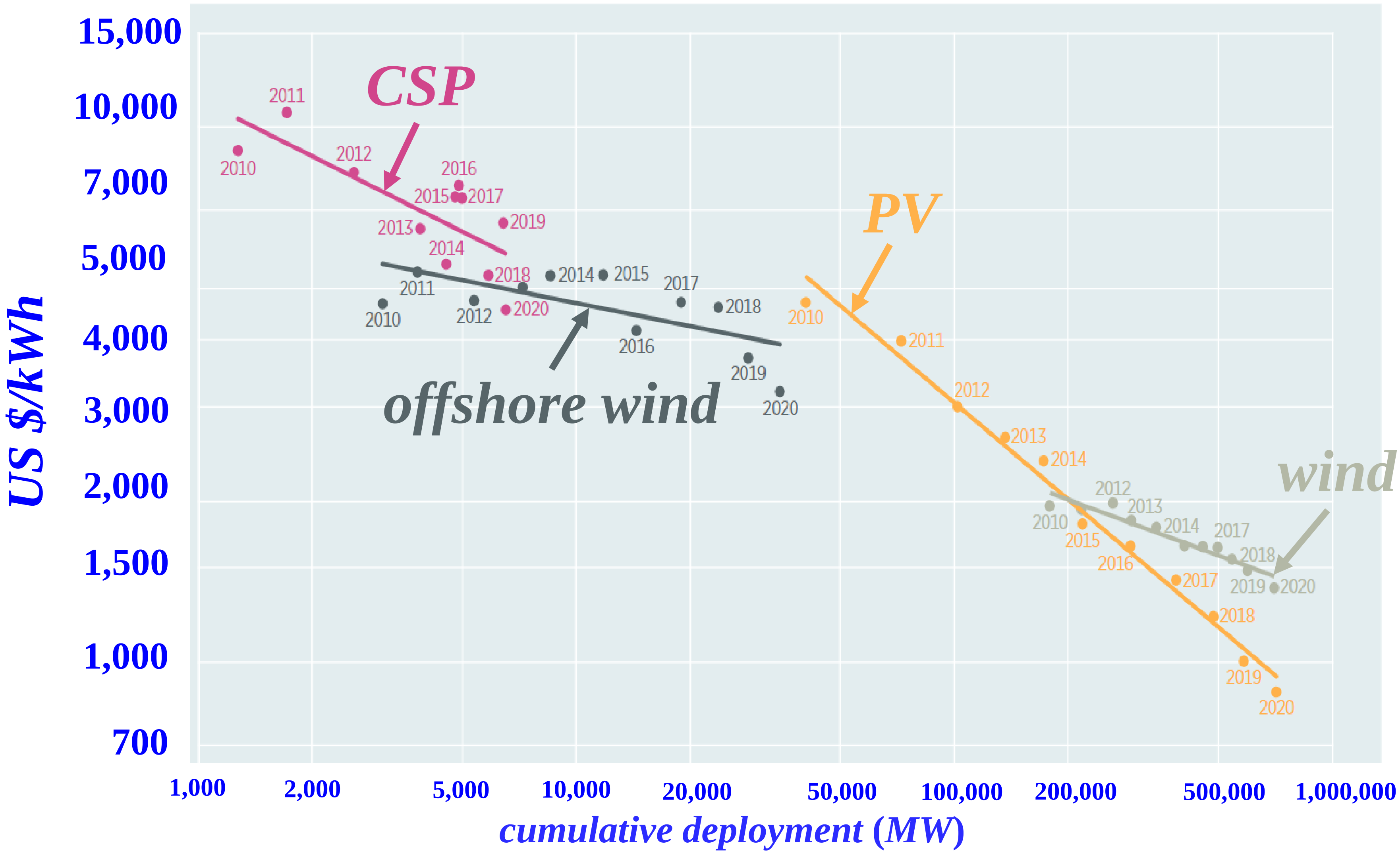
GLOBAL WEIGHTED – AVERAGE UTILITY–SCALE *LCOE*s: 2010 – 2020

Source: IRENA Power Generation Costs 2020, p. 33; available online at https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020



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

Source**:** *IRENA Power Generation Costs 2020, p. 38; available online at https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020*

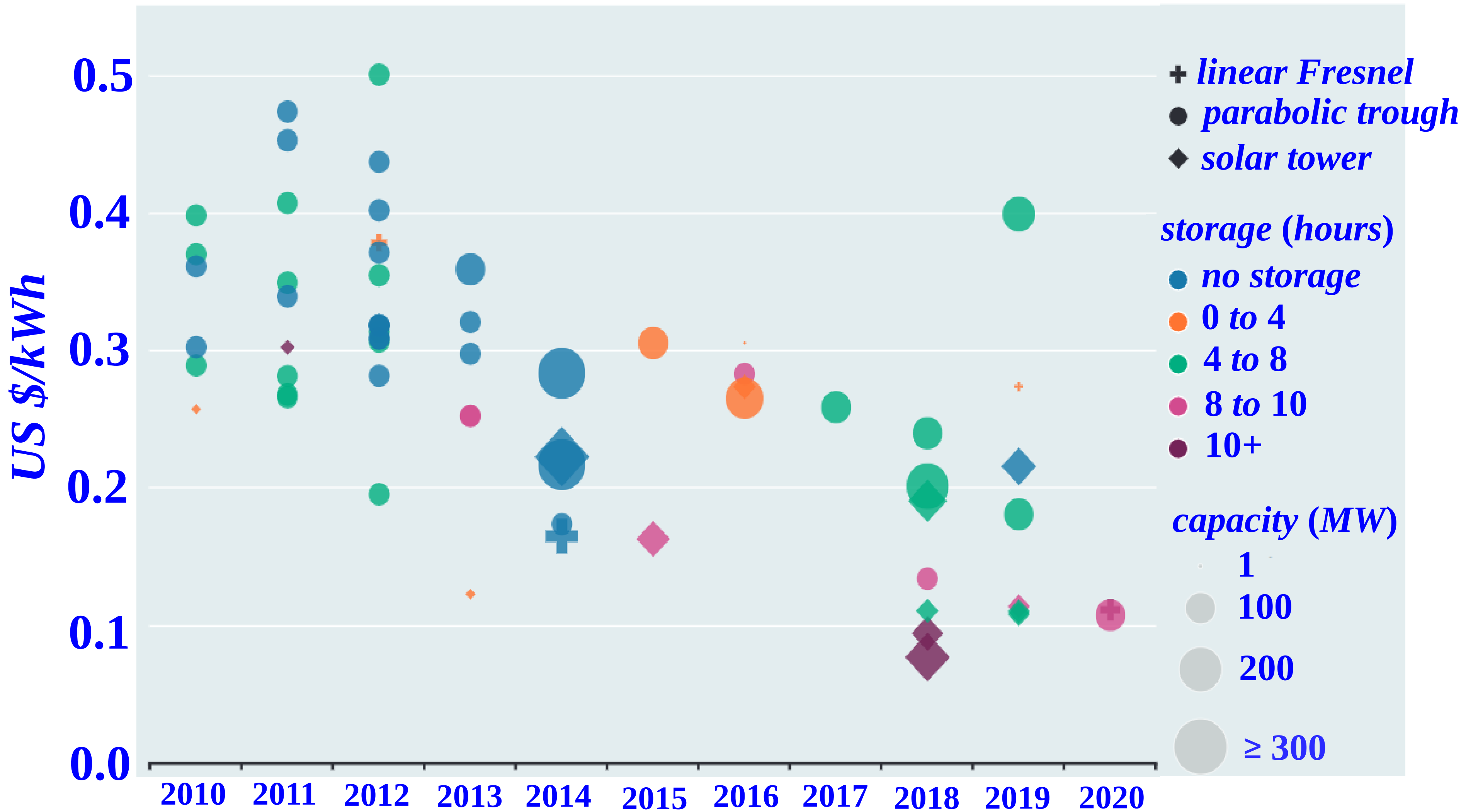


CSP LCOE

- **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***

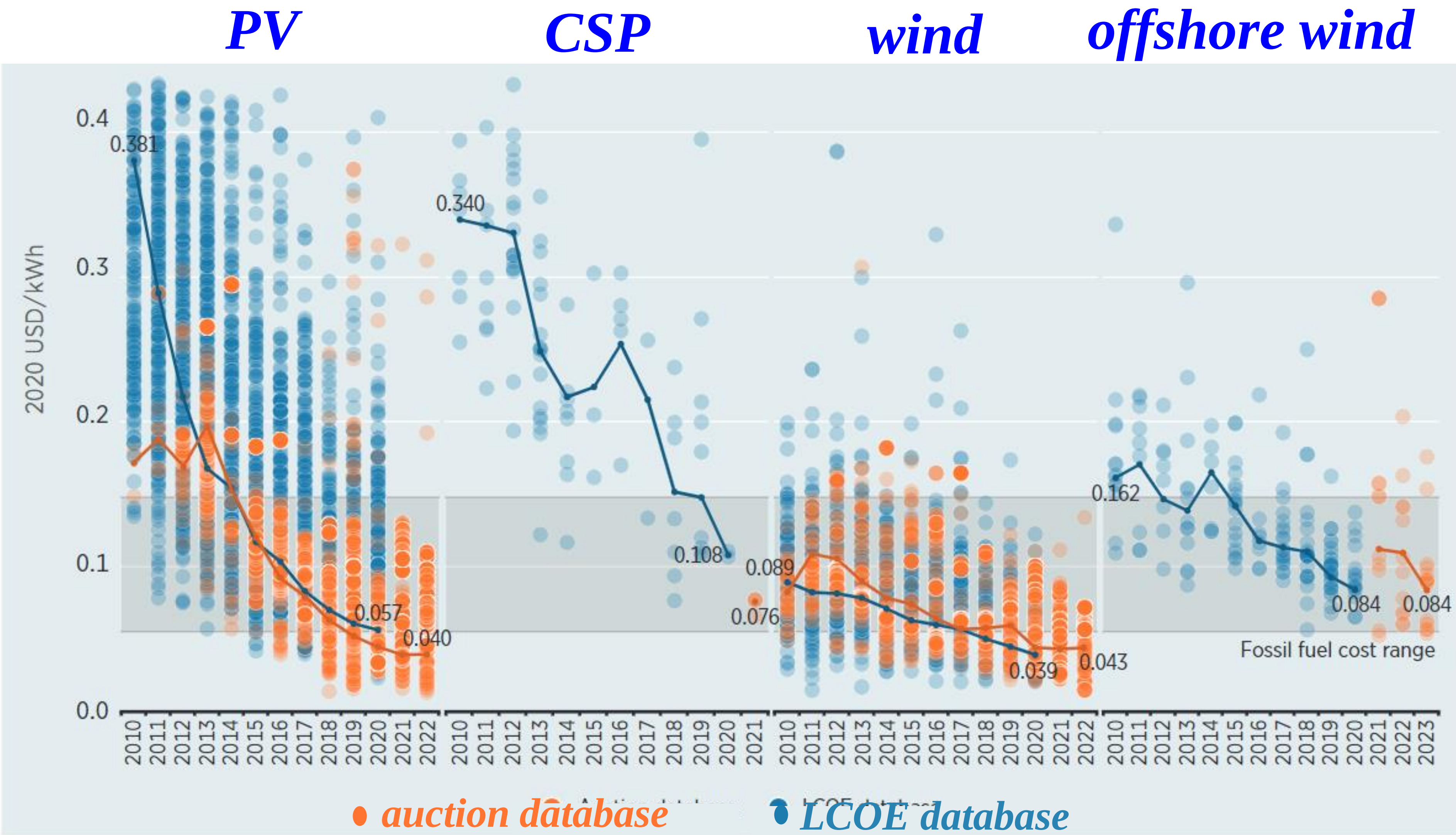
CSP LCOEs FOR 2010 – 2020

Source*: *IRENA Power Generation Costs 2020, p. 113; available online at https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020



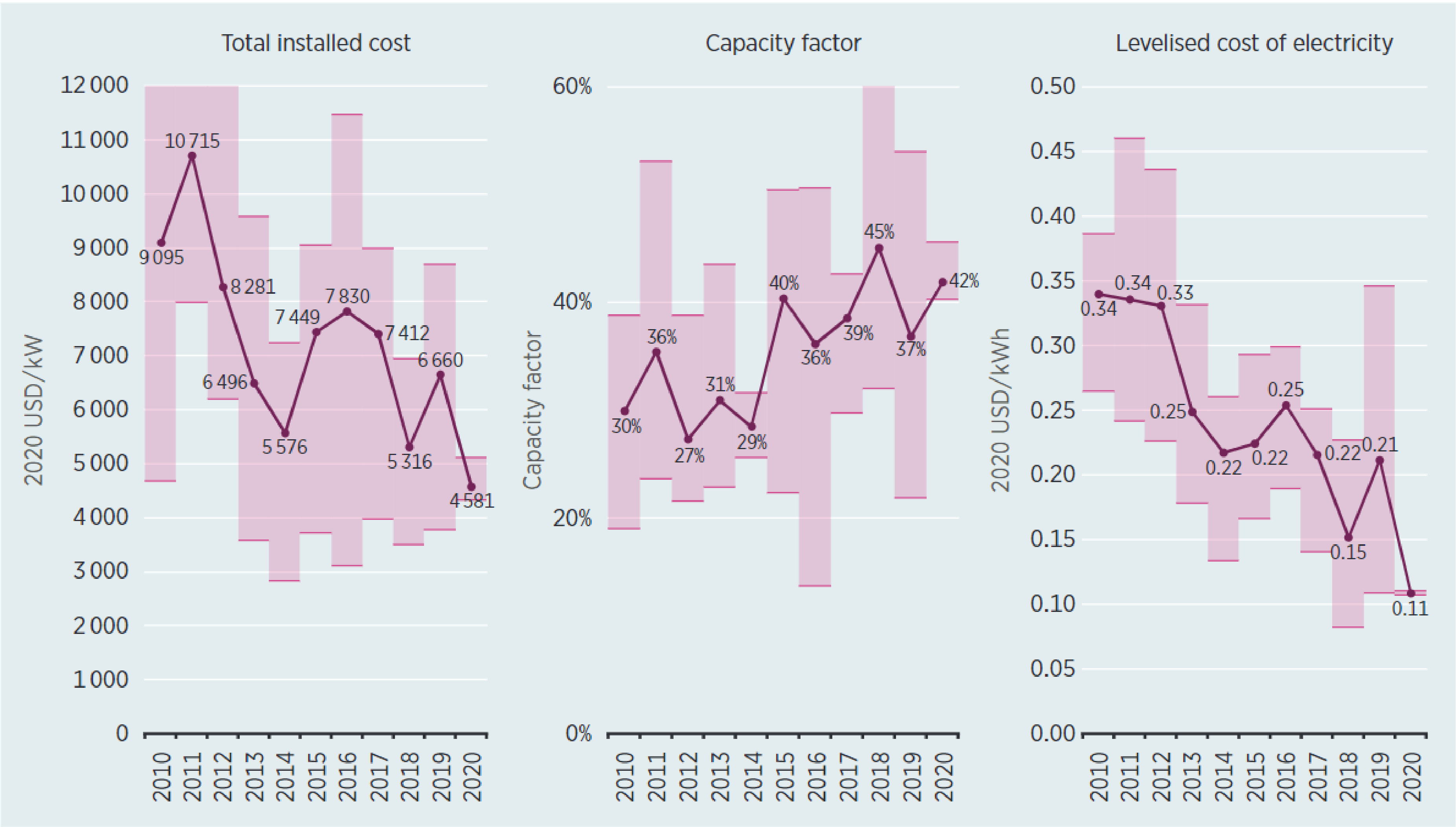
PROJECT AND GLOBAL WEIGHTED-AVERAGE *LCOE* AND *PPA/AUCTION* PRICES: 2010 – 2023

Source: IRENA Power Generation Costs 2020, p. 35; available online at https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020



CSP INSTALLED COSTS, *c.f.*s AND *LCOE*s: 2010 – 2120

Source*: *IRENA Power Generation Costs* 2020, *p.* 105; *available online at https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020



CSP COST REDUCTION POTENTIAL

- 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 *HTF*s 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

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	0.11 – 0.34

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