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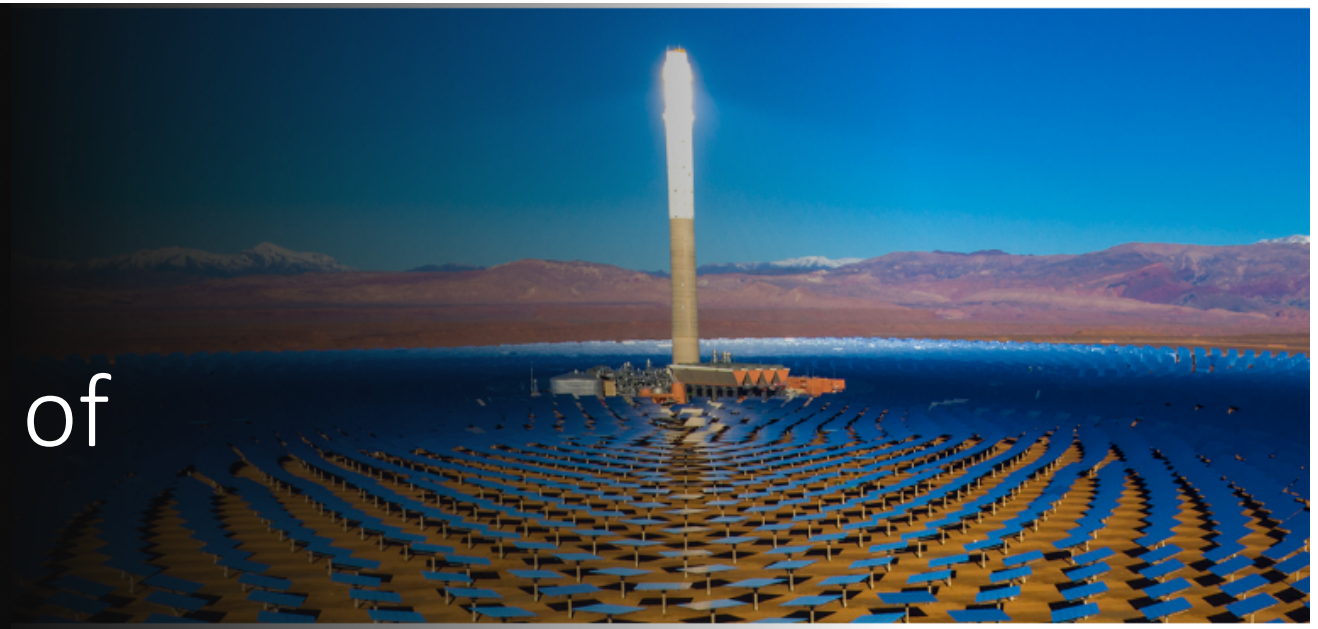
Dependability of CSP Plants



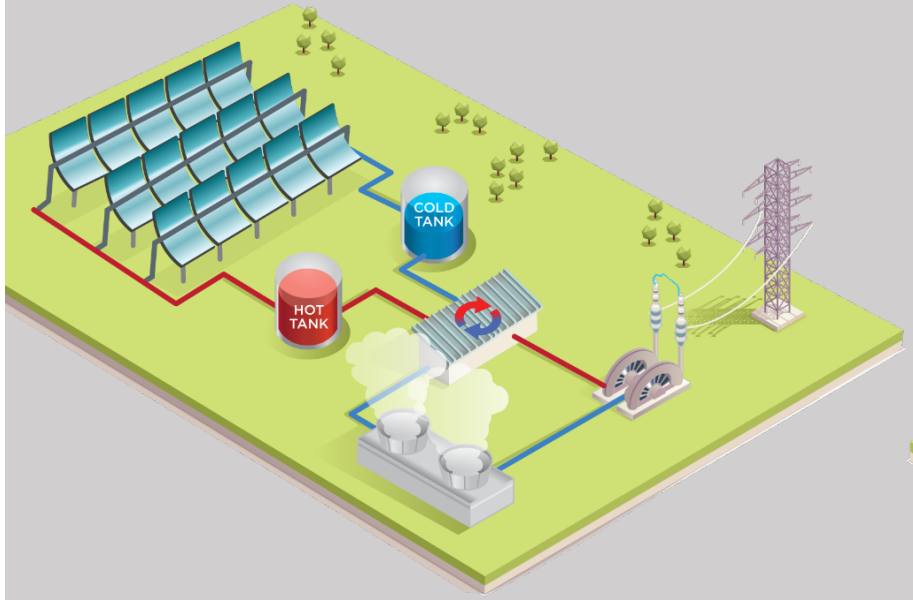
Dr. Fred Morse, Dr. Terry Peterson,
Dr. Luis Crespo, Dr. David Kearney

January 2021

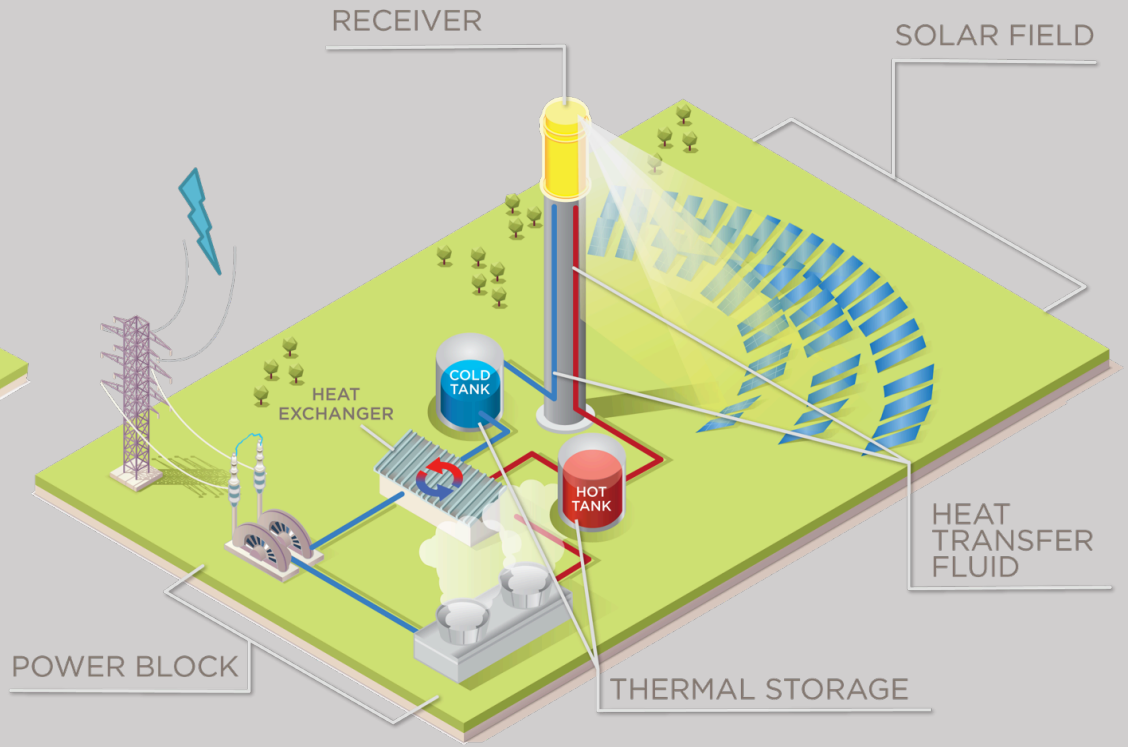
Are CSP plants dependable?

- In 2020, there were 99 CSP plants operating globally and a subset of those provided dependability data
- A “dependable” plant or fleet should have over 90% availability and less than 10% variation in annual output
- The Ivanpah and Crescent Dunes CSP plants in the U.S. had first-of-a-kind early operating issues and thus are not representative of CSP plants globally.

2020 Global CSP Fleet



83 **Parabolic Trough** plants are operating globally with a total capacity of 5.2 GW



16 **Power Tower** operating globally with a total capacity of 1.3 GW

Worldwide status of CSP plants*

- 99 in operation
  - Over 6 GW total
  - 83% are parabolic trough
- 47 include thermal energy storage (TES)
  - Totaling 3.3 GW of capacity and 25 GWh
  - Nearly 8 hours of energy storage on average
  - Largest is 17.5 hours of full-power TES
- 43 use molten-salt TES
  - First commercial plant came online in 2007
  - 3 of 19 US plants include TES
  - Most built in the last 7 years include TES

*NREL/SolarPACES database <https://solarpaces.nrel.gov/>

50-MW Termosol 1 Plant (Spain)
with 9 hours of molten-salt TES

Sources of CSP-plant dependability data

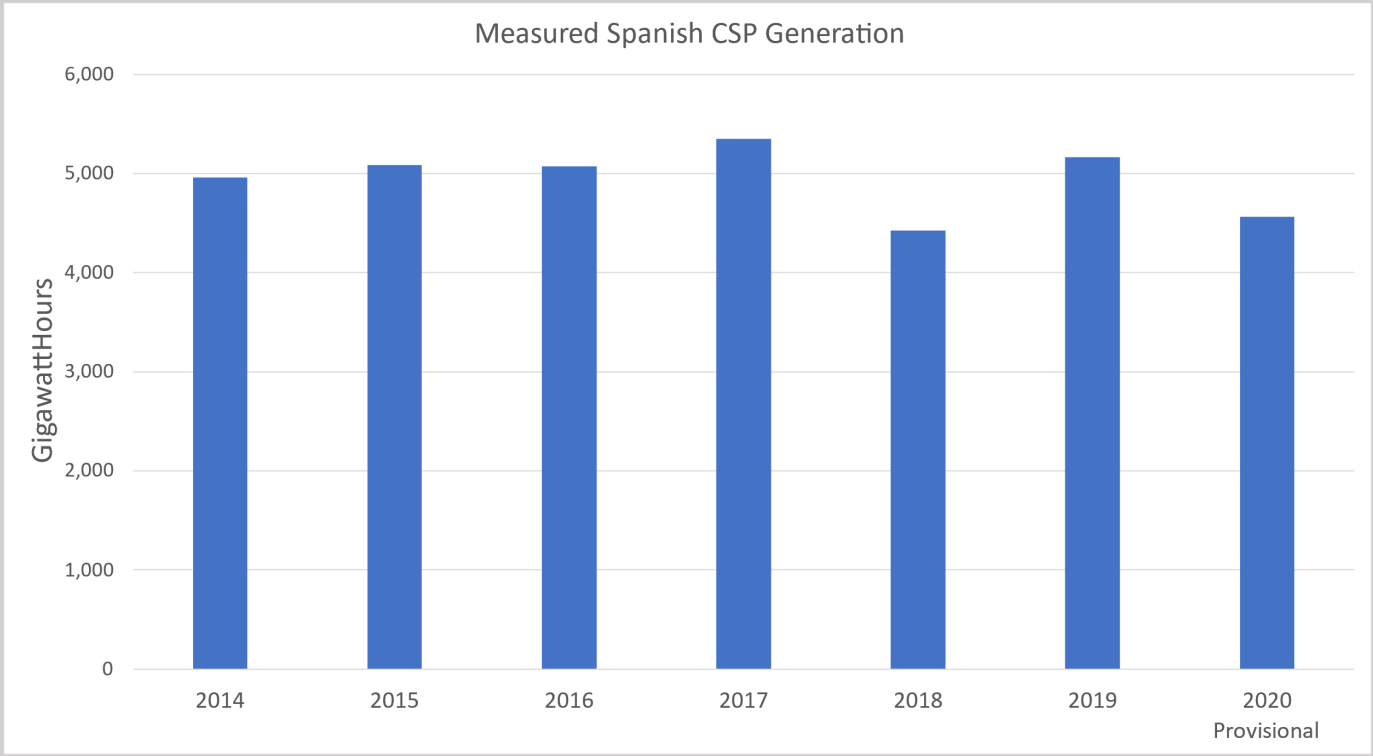
- Spain — 49 plants, 2.3 GW in commercial operation since 2013, 39 plants provided public individual-plant performance data
- U.S. —
  - 9 SEGS plants, totaling 354 MW, completed long-term PPA contracts
  - 64-MW Nevada Solar One plant in commercial operation since 2007
  - 5 CSP plants, 2 with TES, were funded under the DOE Loan Guarantee Program, and were constructed between 2010–2014
  - All provided dependability data via DOE Energy Information Agency

Spain has a mature 2.3–GW fleet of CSP plants

- 49 operating CSP plants
- 44 parabolic-trough (PT) plants, each limited to 50 MW by Spanish regulations
- 17 PT plants include 7 to 9 hours of full-power TES
- First plants began operation in 2007, all have operated since 2013
- Operation since 2014 has been without natural gas auxiliary heating
- January 2020 Spanish Ministry national energy and climate plan* sees fleet expansion to 7 GW by 2030

*https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en#final-necps

The Spanish 2.3-GW CSP fleet has demonstrated dependability



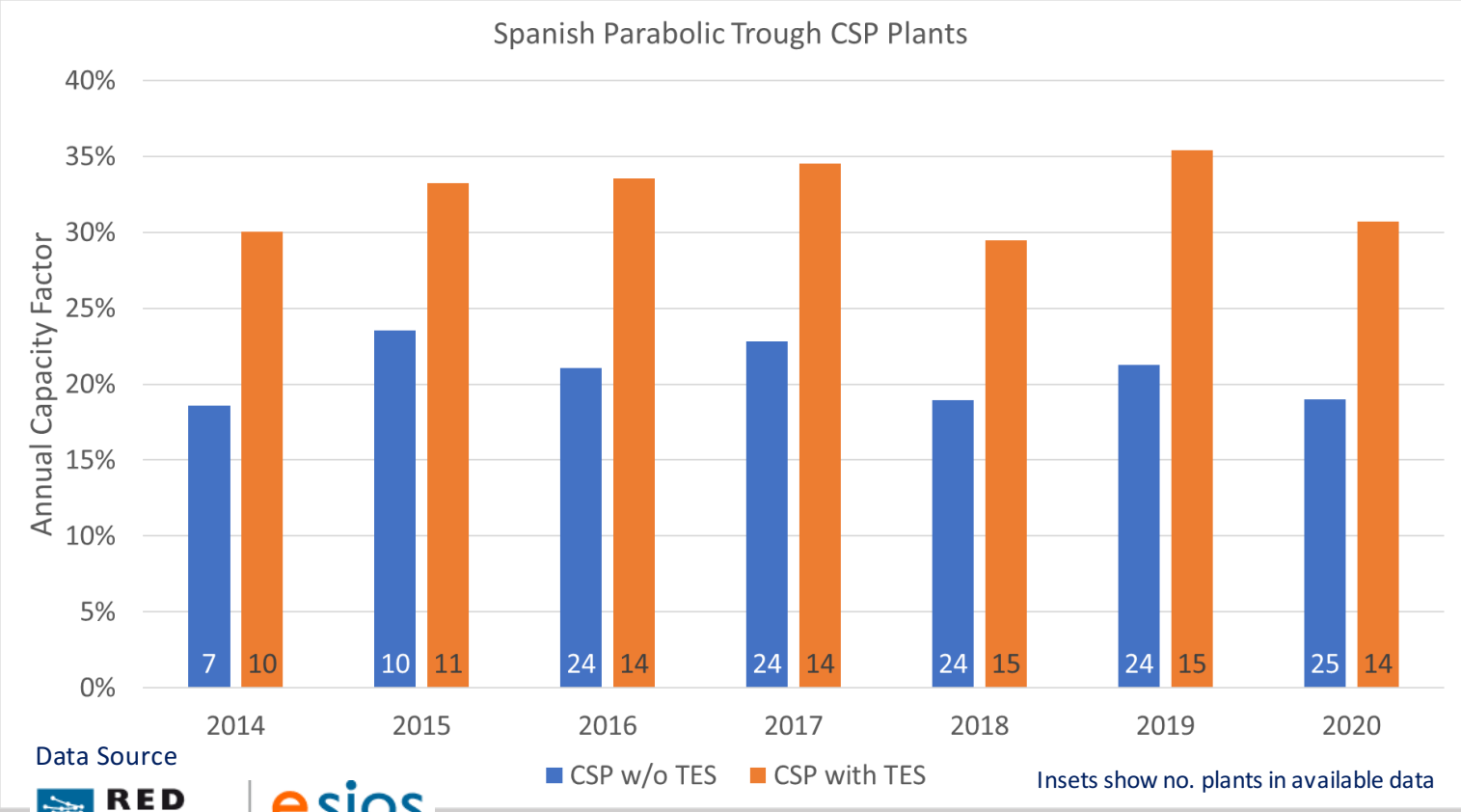
Data Source: https://www.ree.es/en/datos/generation/generation-structure

Since 2014, the Spanish CSP plants have operated fully on solar energy with no natural gas contribution.

Annual production has generally tracked available sunlight. 2018 insolation was 8% below average and 2020 preliminary data indicate that it was also well below average.

In the summer months, these CSP plants often meet 8% of Spain's hourly demand.

Spanish parabolic trough plants have been dependable with or without thermal energy storage



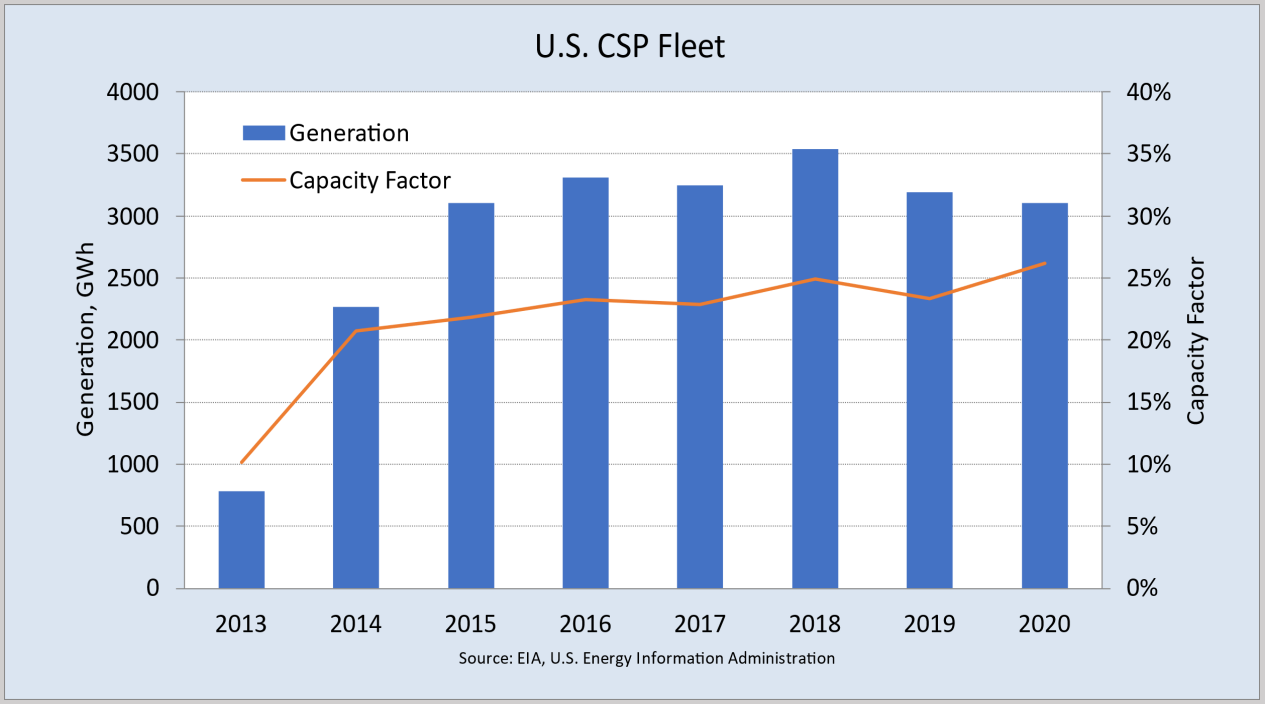
Data Source

RED ELÉCTRICA DE ESPAÑA | esios SISTEMA DE INFORMACIÓN DEL OPERADOR DEL SISTEMA

In the Spanish market and climate, trough plants with no TES are typically designed for about 20% annual capacity factor, while 30% to 35% is the corresponding target capacity factor for plants with 7 to 9 hours of TES.

The available ESIOS data indicate over 96% availability for trough plants, both with and without TES.

The current U.S. CSP fleet has shown dependable performance for the past 6 years

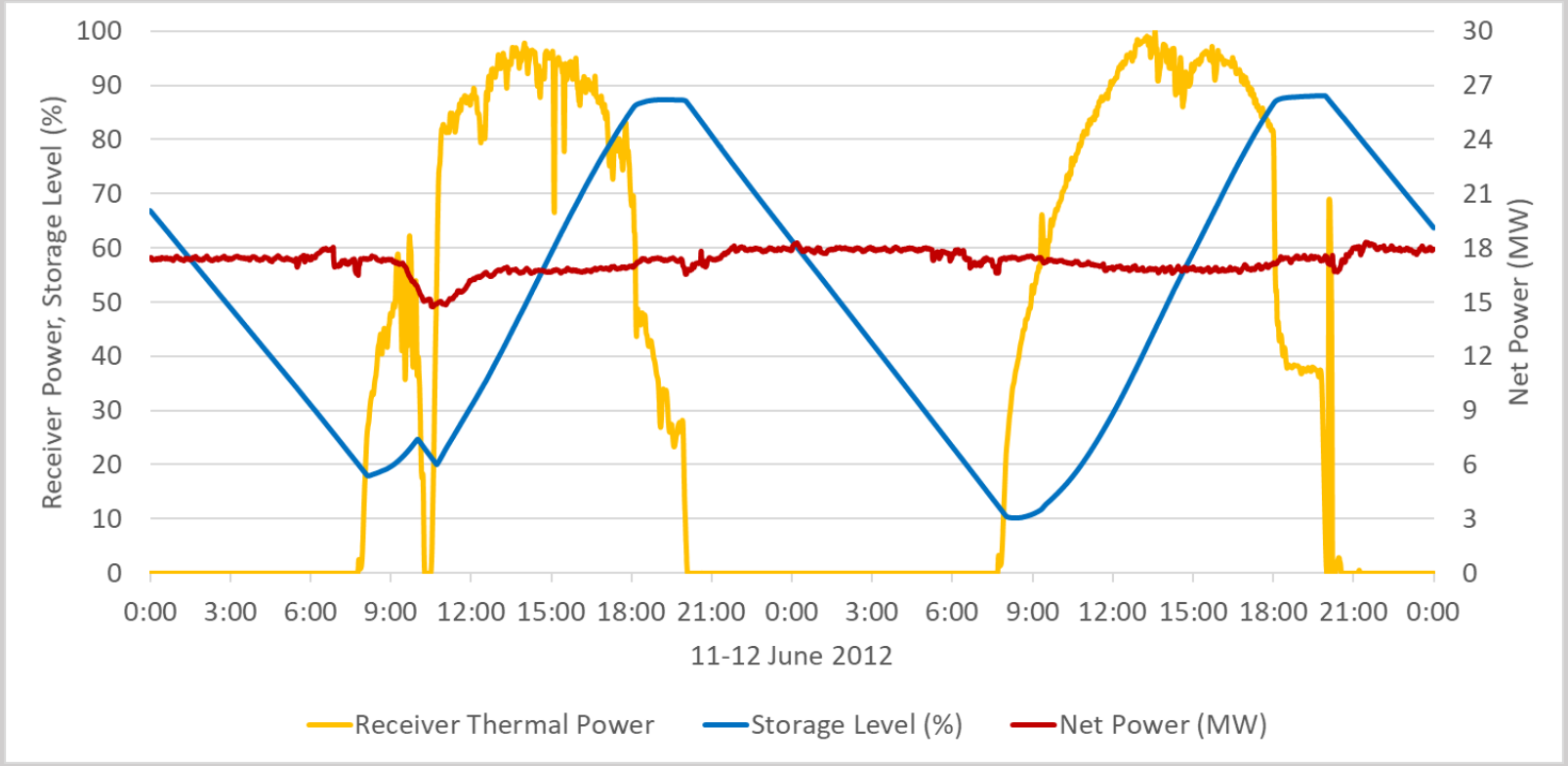


- Current fleet reached 1.6 GW in 2015
- It included 11 PT plants and 2 central-receiver plants that total 4 towers
- The final SEGS plants retired in 2019 and 2020 reducing total capacity to 1.4 GW
- Ongoing learning is evident in the increasing capacity factor

Gemasolar (Spain)

- 17-MW power tower CSP plant with 15 hours of full-power TES
- Many novel aspects made it a “first of a kind” plant and therefore not “typical”
- Despite its novelty, the plant has achieved over 92% availability in 3 of the last 6 years
- It has run up to 36 days non-stop at nominal power

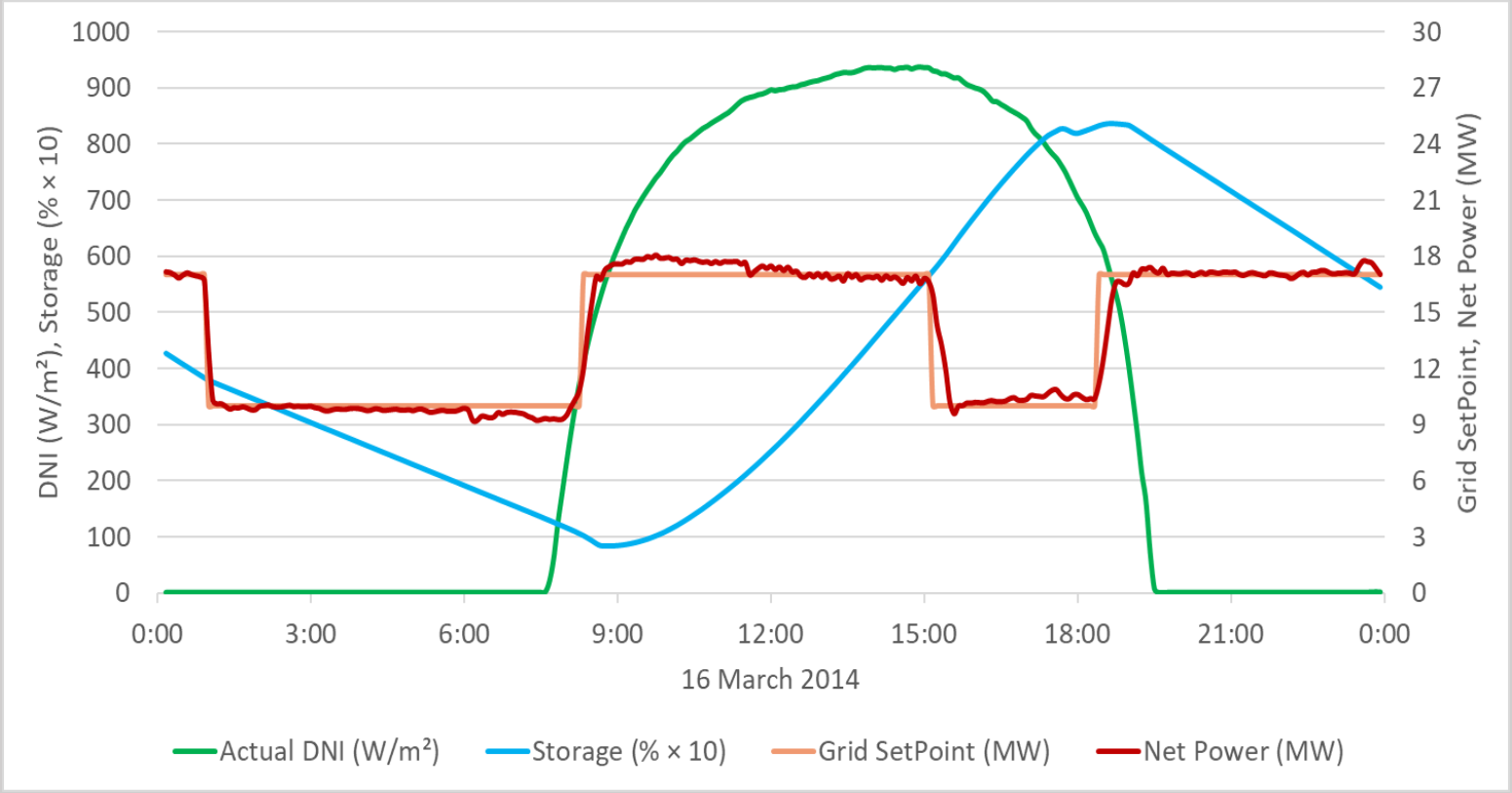
Gemasolar stable production through cloud transients



- Continuous output (—) despite intermittent cloudiness (—)

Torresol Energy
reinventing solar power

Gemasolar production following grid operator requirements



- Output matches grid operator setpoints (—), not irradiance (—)
- Curtailed output in early morning and afternoon, but energy not lost

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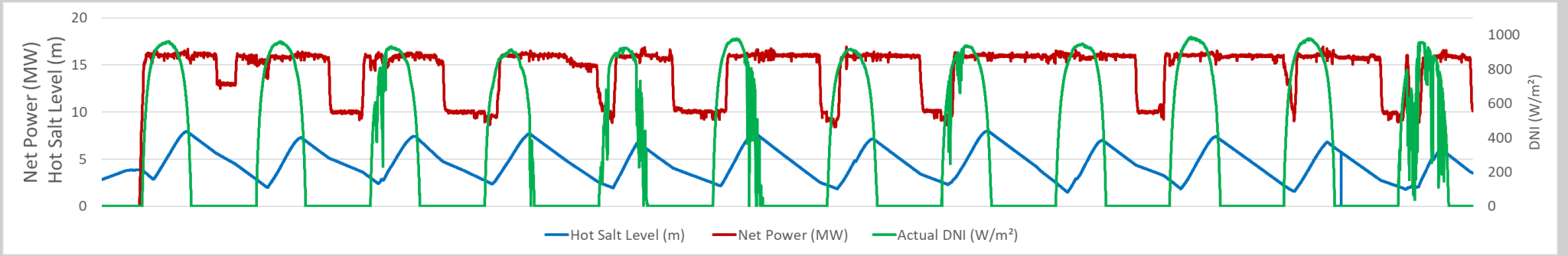
Gemasolar 24/7 production over many winter days



12 days of continuous production in February

- Continuous output despite intermittent cloudiness
- Generation (—) decoupled from irradiance (—)
- In sunnier times of the year, Gemasolar has run up to 36 days non-stop at full nominal power

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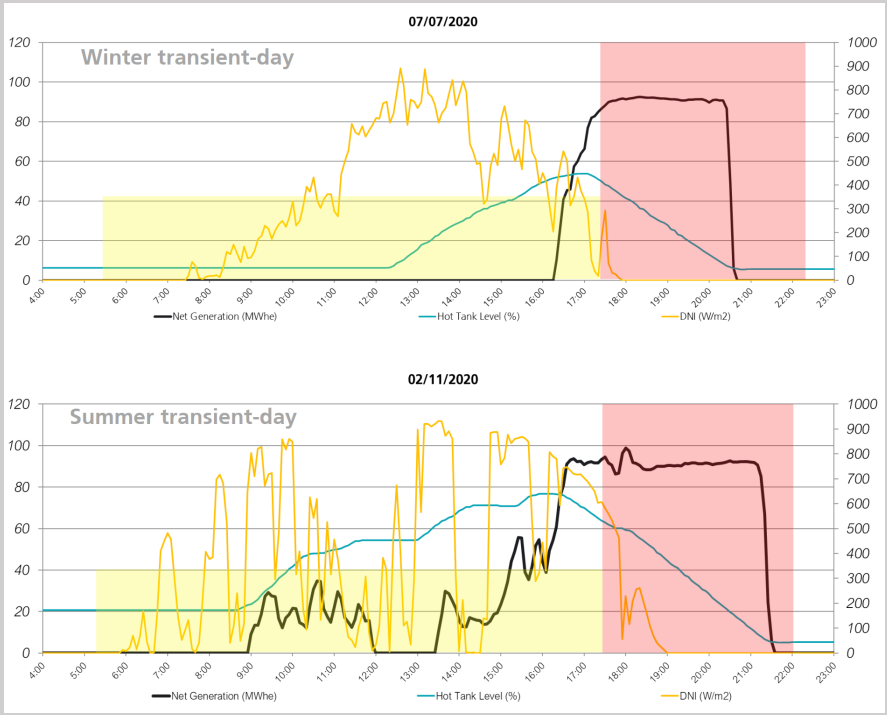
Xina (South Africa) – 100 MW with 5.5 hours full load thermal energy storage

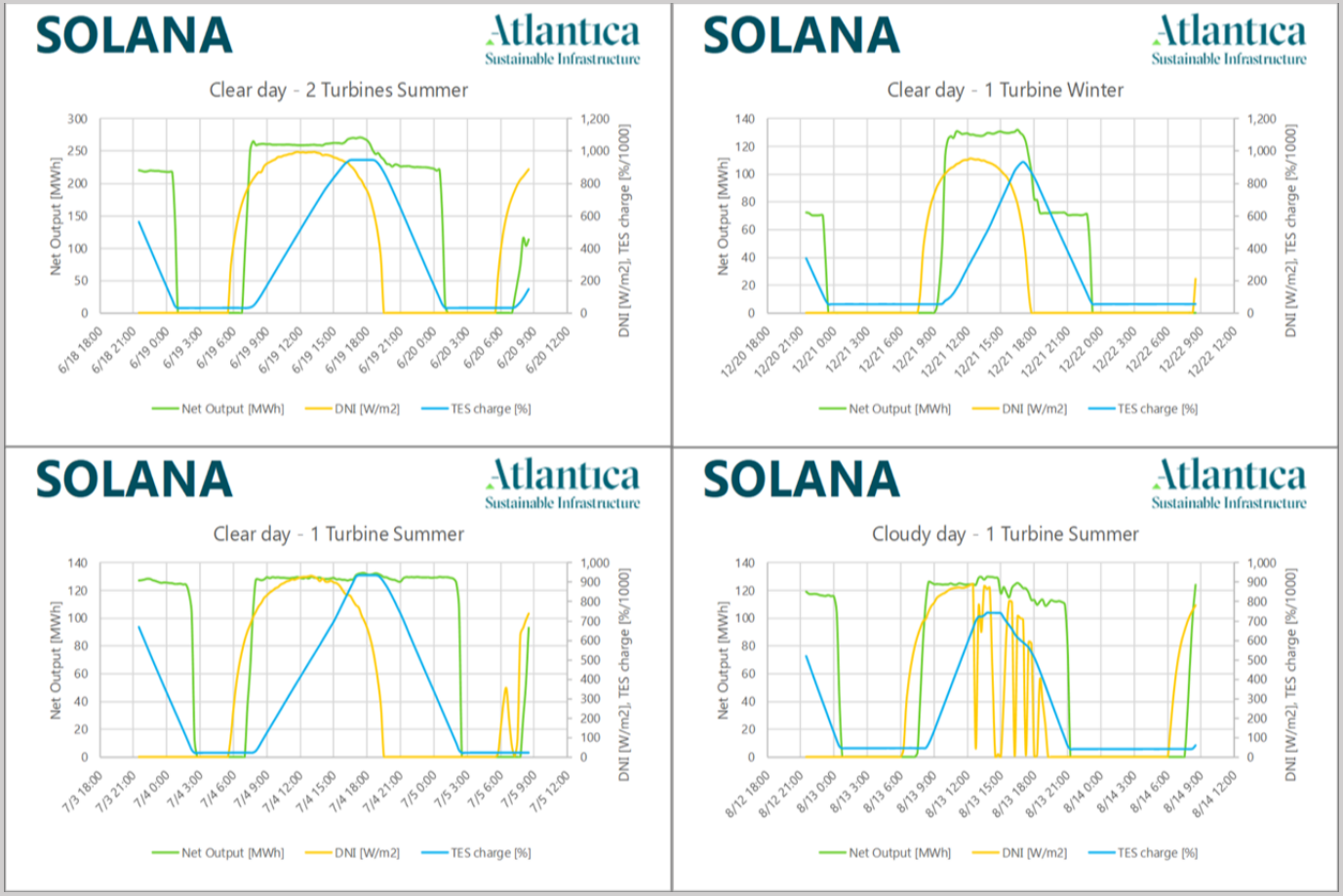
Xina Solar One meeting evening peaks



- Xina is only paid for production between 06:00 and 22:00 daily (yellow- and pink-shaded areas) with substantially more paid after 17:00 (pink-shaded area)
- The plant was designed to maximize post-17:00 “peak” production
- In its first 3 years of operation, it averaged over 93% availability total and over 91% during the “peak” times

Solana (Arizona) – 250 MW with 6 hours full-load thermal energy storage

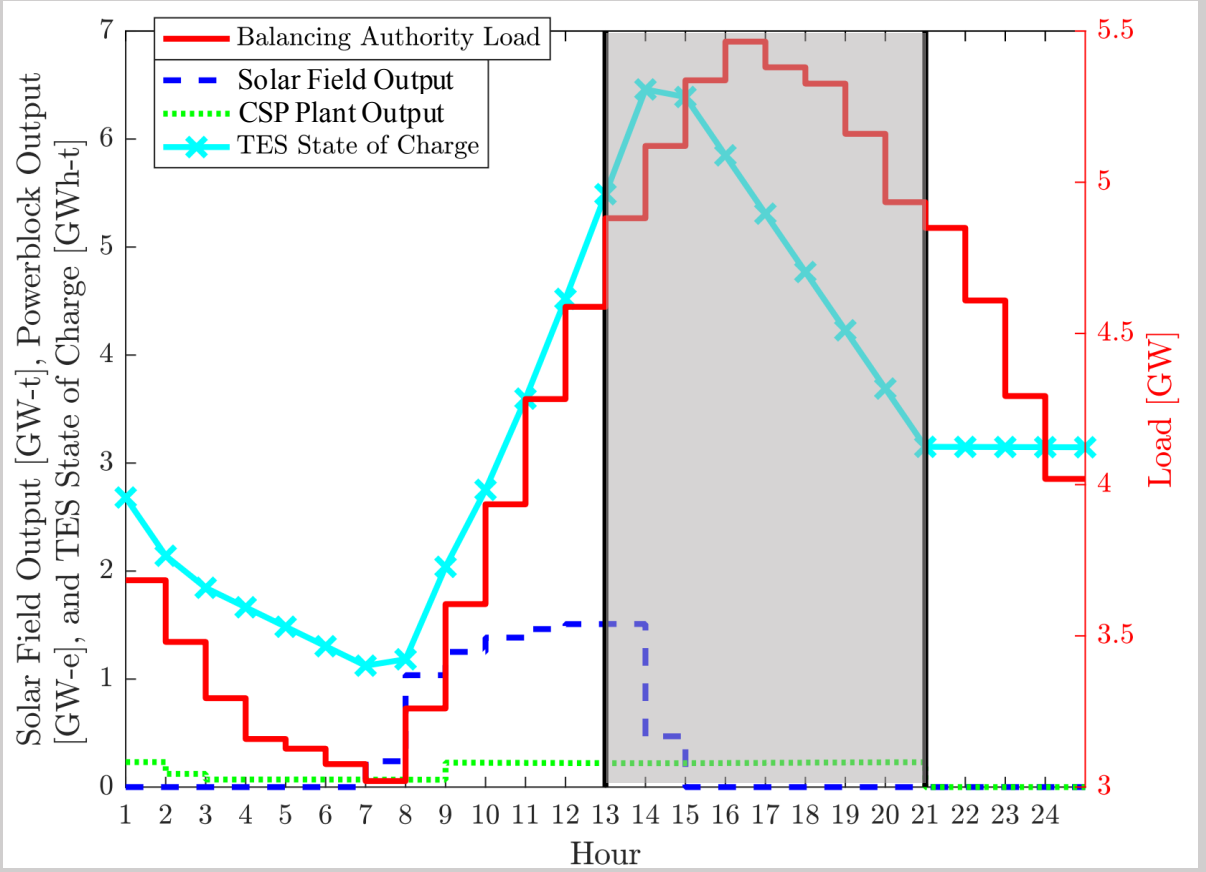
Solana Generating Station meeting the evening peaks



CSP+TES and Resource Adequacy

- Yagi et al.* modeled CSP towers with 12 hours TES producing 8 hours of nameplate power during peak system loads in 28 SW U.S. locations over 18 years using actual weather and load data
- Example partially sunny day at right: Boulder City, NV on August 1, 2014
- Modeling required 8-hour output 13:00 to 21:00 (shaded area) to bracket balancing authority (—) peak-load period
- Solar energy input (- - -) spanned only 08:00–14:00, missing most of the load peak
- TES (–X–) charged during morning solar input
- Plant output (▪▪▪) began at 09:00 and lasted 12 hours

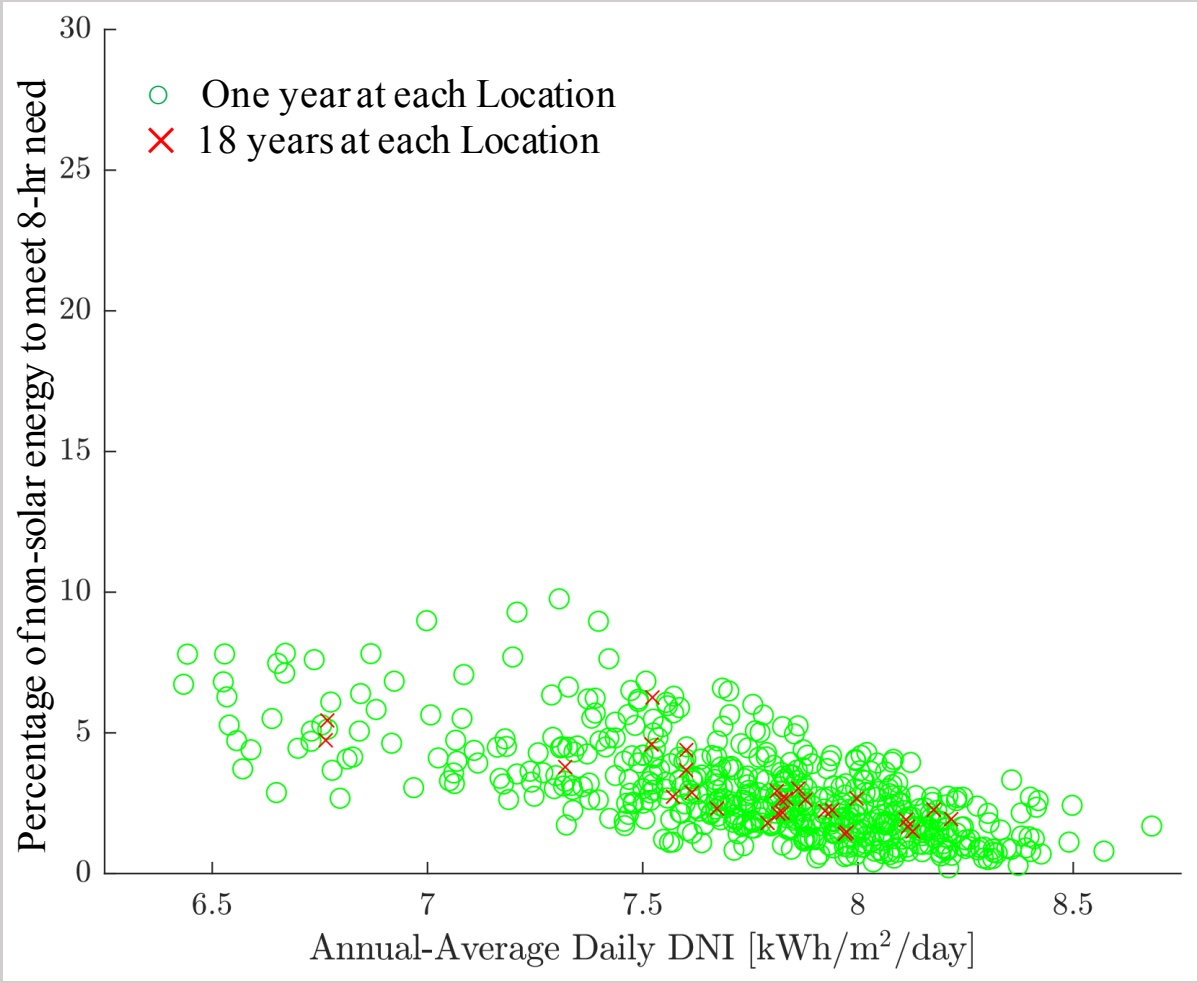
*Yagi, Sioshansi, Denholm. *Solar Energy, 191*, **2019**, 686



CSP+TES and Resource Adequacy

- At right: Percentage of supplemental non-solar energy needed in individual years (○) and 18-yr totals (×) for modeled CSP towers with 12 hours TES to produce 8 hr of nameplate power during peak system loads 365 days/yr in 28 SW U.S. locations over 18 years using actual weather and load data*
- The majority of the 18-yr totals range between 2% and 5% with none over 7%
- Most locations on most years needed less than 3% additional energy with none needing more than 10% non-solar energy in a single year

*Yagi, Sioshansi, Denholm. *Solar Energy, 191*, **2019**, 686

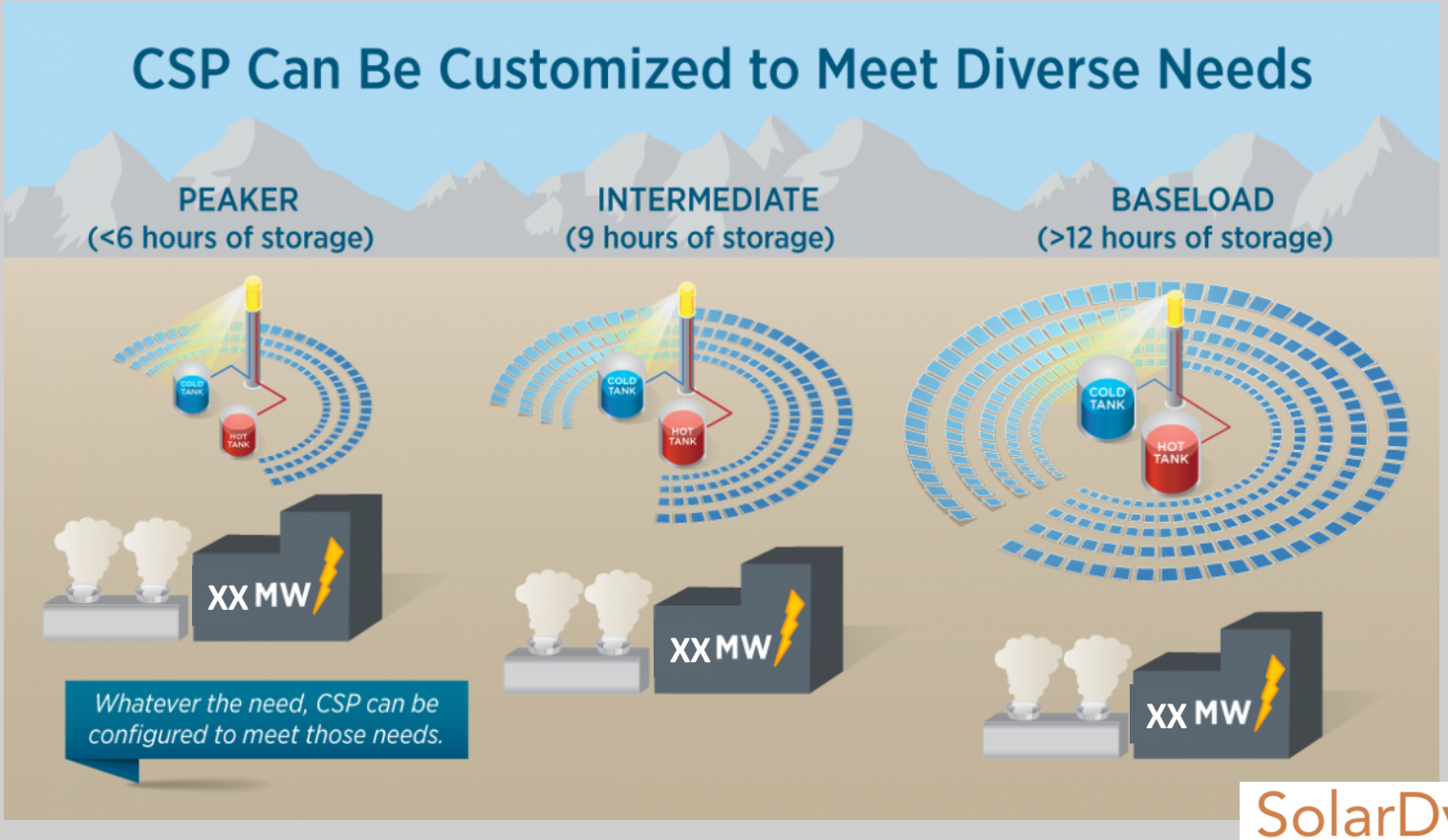


Capabilities of dependable CSP + TES

- Long Duration Storage — plants can operate 24 hours a day when needed
- Can be hybridized — with PV, Natural Gas, or Biogas
  - e.g., a hybrid CSP plant with 12 hours TES can provide full-year capacity with 2%–5% of the fuel consumption of a natural gas plant*
- Synchronous Generation with wide range of grid reliability services
  - e.g., stability and inertia
- Flexible — in design and output to meet any demand profile
- Dispatchable — separates energy collection from electricity generation
- Costs continue to decrease — still high on the learning curve (6 GW globally) — lowest currently 8.2¢/kWh in relatively low DNI

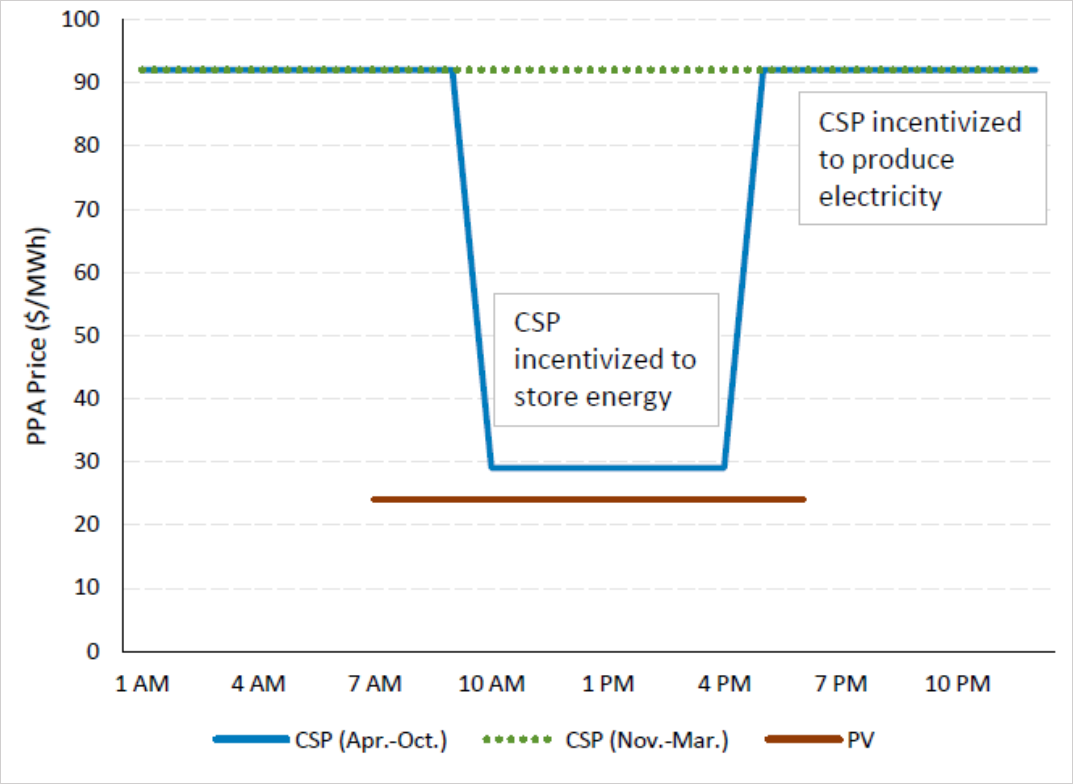
*Yagi, Sioshansi, Denholm. *Solar Energy, 191*, **2019**, 686

Flexible Designs for an Evolving Grid



SolarDynamics

Commercial Developers are Optimizing CSP/PV Hybridization



DEWA IV – Dubai – PV co-located

- Developer: ACWA Power
- PPA signed at $0.073/kWh
- 950 MW total capacity
  - 200 MW x3 Troughs with 10 hours TES
  - 100 MW Tower with 15 hours TES
  - 250 MW PV

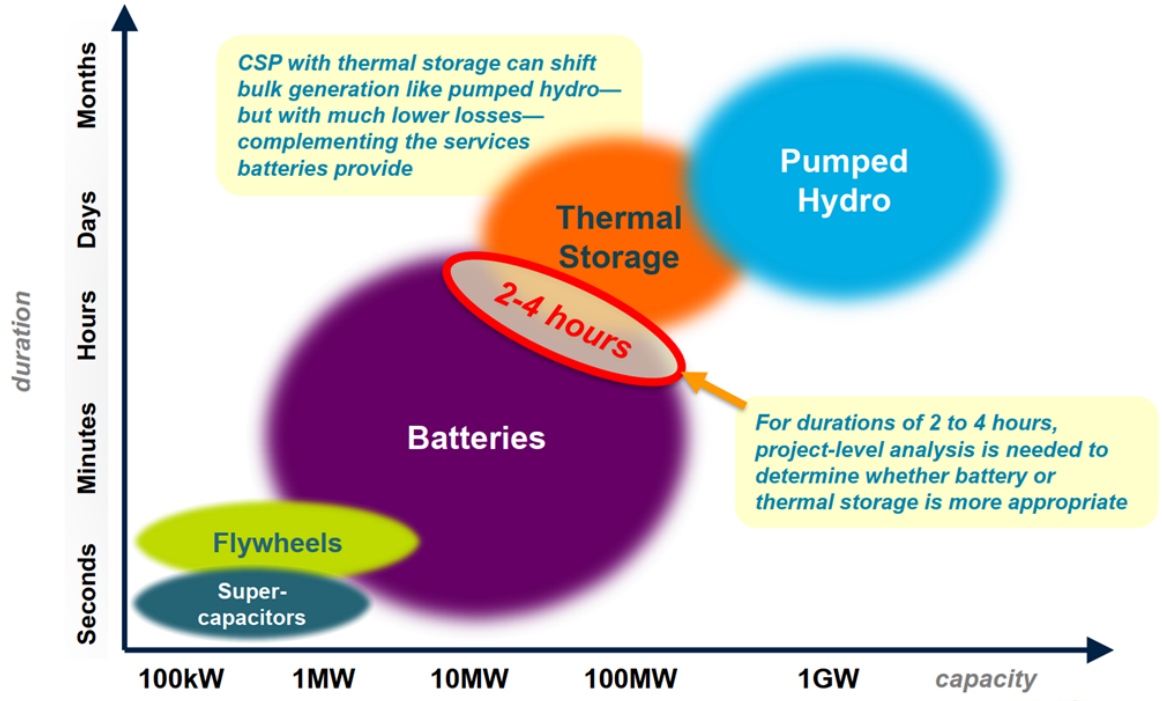
Midelt 1 – Morocco- PV hybrid

- Developer: EDF/MASDAR/Green of Africa
- PPA signed at $0.071/kWh
- 400 MW PV (per press release)
- 400 MW Trough with 5 hours TES
- Excess PV electricity will be stored in molten salt TES

Many CSP roles in the future energy grid

- As grids move to 100% carbon-free generation, they need to maintain system inertia and balance, fast ramping capabilities, and adequate resources for contingency reserves
- CSP + TES plants are the least costly renewable choice for complementing PV all night long
- CSP + TES plants can be designed to meet multi-hour evening peaks with minimal non-solar energy
- CSP + TES plants—with zero or little investment—can provide additional services to the grid such as firm strategic reserve for demand peaks whether the previous days were sunny or not
- CSP + TES could also collect curtailed generation from PV and wind for generation when needed.
- With demonstrated dependability, CSP + TES plants could support the ongoing energy transition process

…but there is no silver-bullet energy storage technology that fulfills all power system needs



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