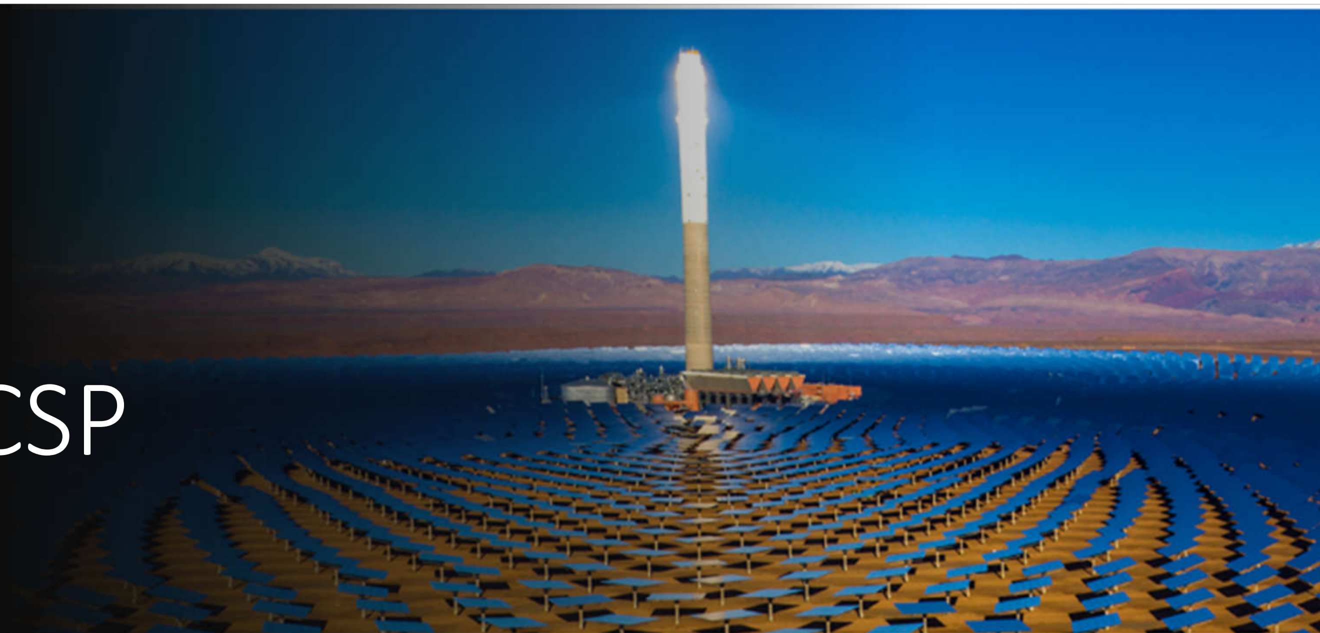
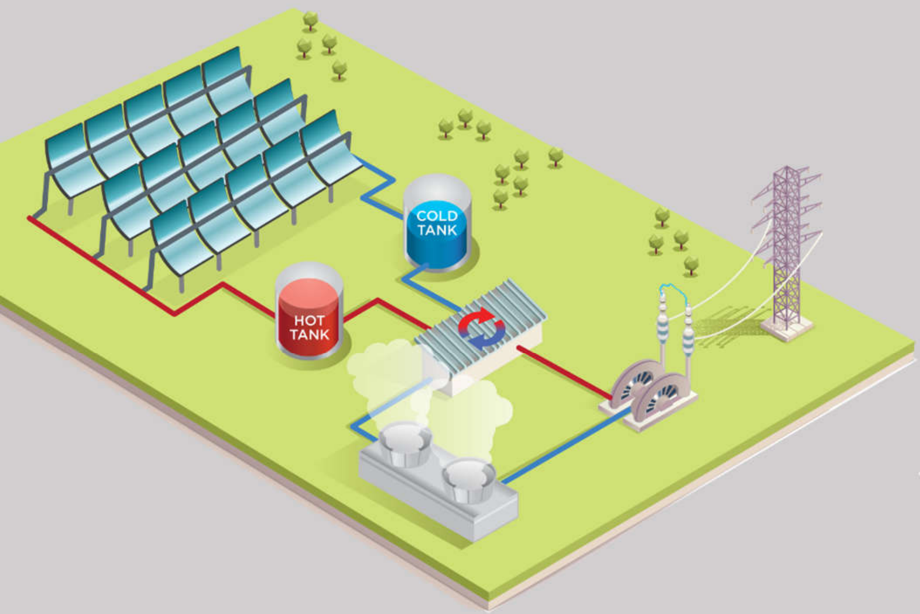
Overview of CSP Plants

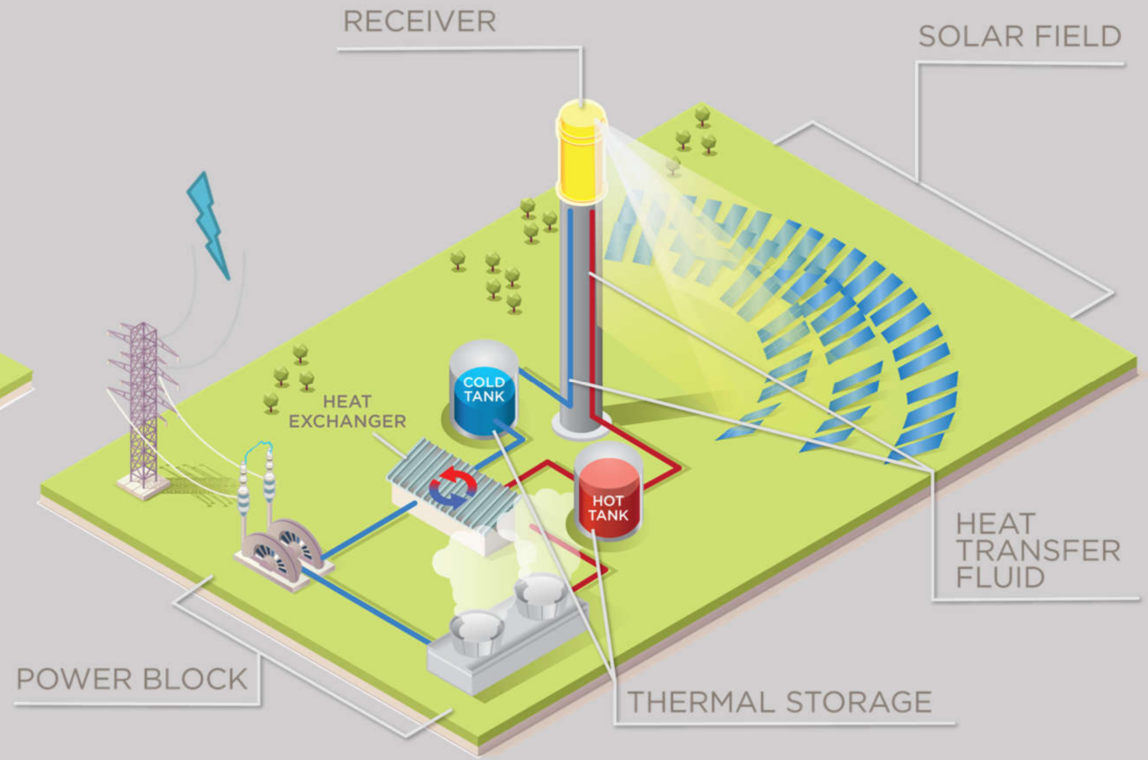


Dr. Fred Morse, Dr. Terry Peterson,
Dr. Luis Crespo, Dr. David Kearney

5 April 2021

2020 Global CSP Fleet

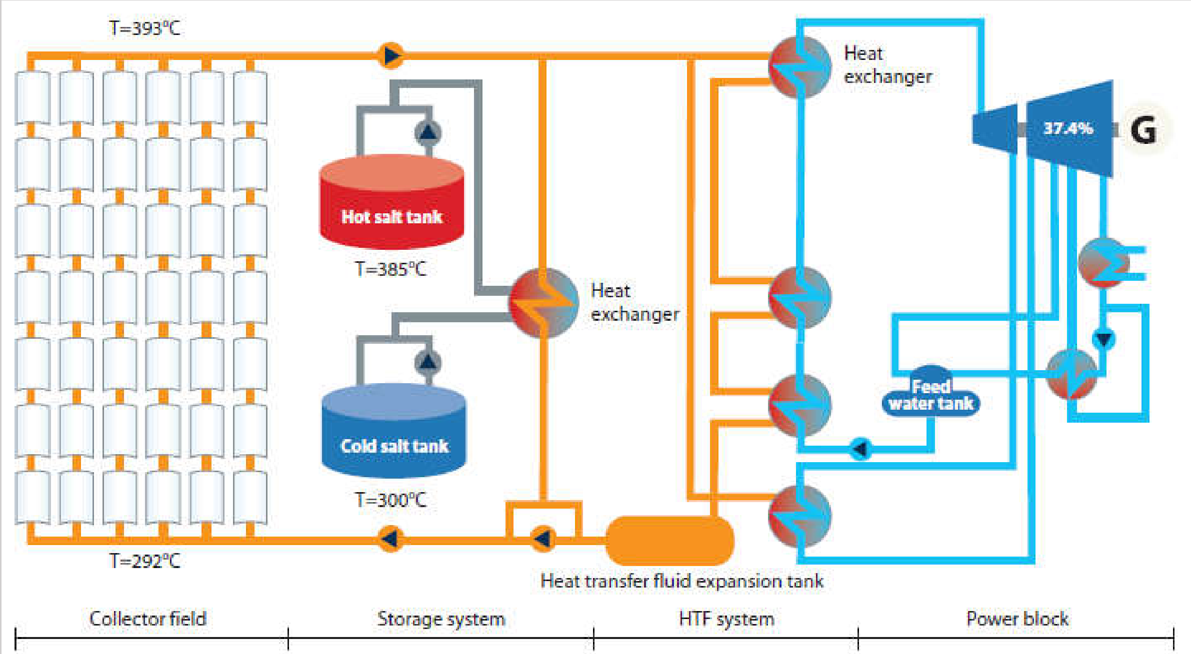




83 **Parabolic Trough** plants are operating globally with a total capacity of 5.2 GW

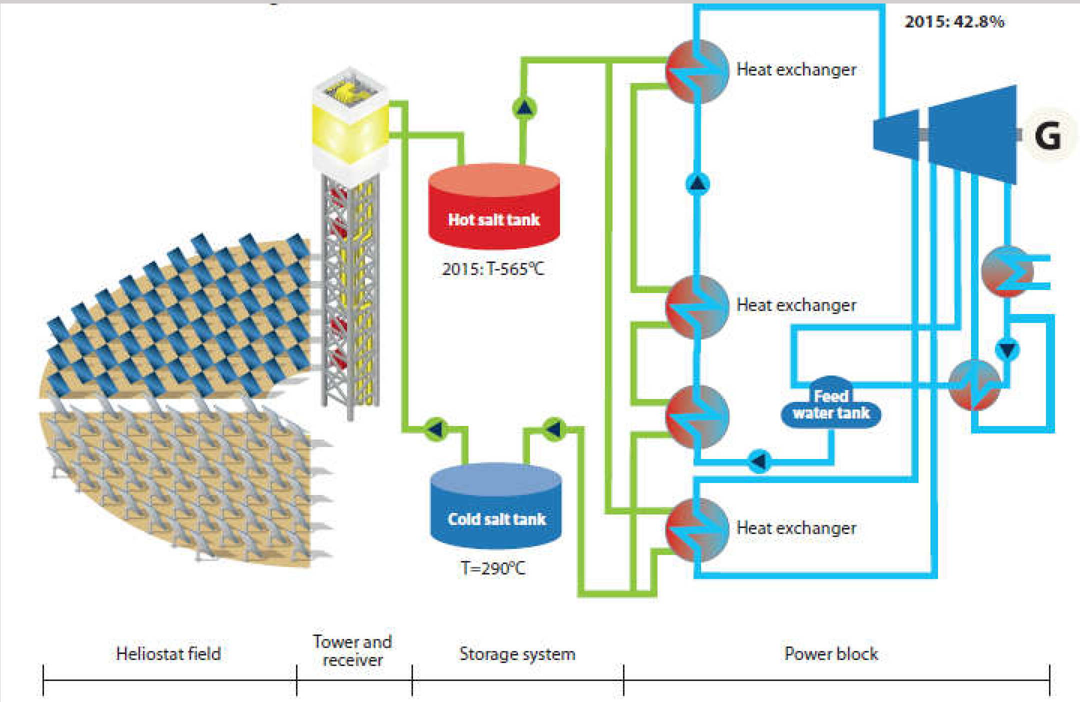
16 **Power Tower** operating globally with a total capacity of 1.3 GW

Parabolic Trough CSP+TES system



Source: Adapted from IRENA (2016).
Note: The heat transfer fluid, shown in orange, is thermal oil; the storage medium, shown in gray, is molten salt. The water/steam circuit is in blue. HTF = heat transfer fluid. G = Generator.

Central Receiver CSP+TES system



Source: Adapted from IRENA (2016).
Note: Molten salts, shown in green, serve as the heat transfer fluid and storage medium. The water/steam circuit is in blue. G = generator

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

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

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

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.

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

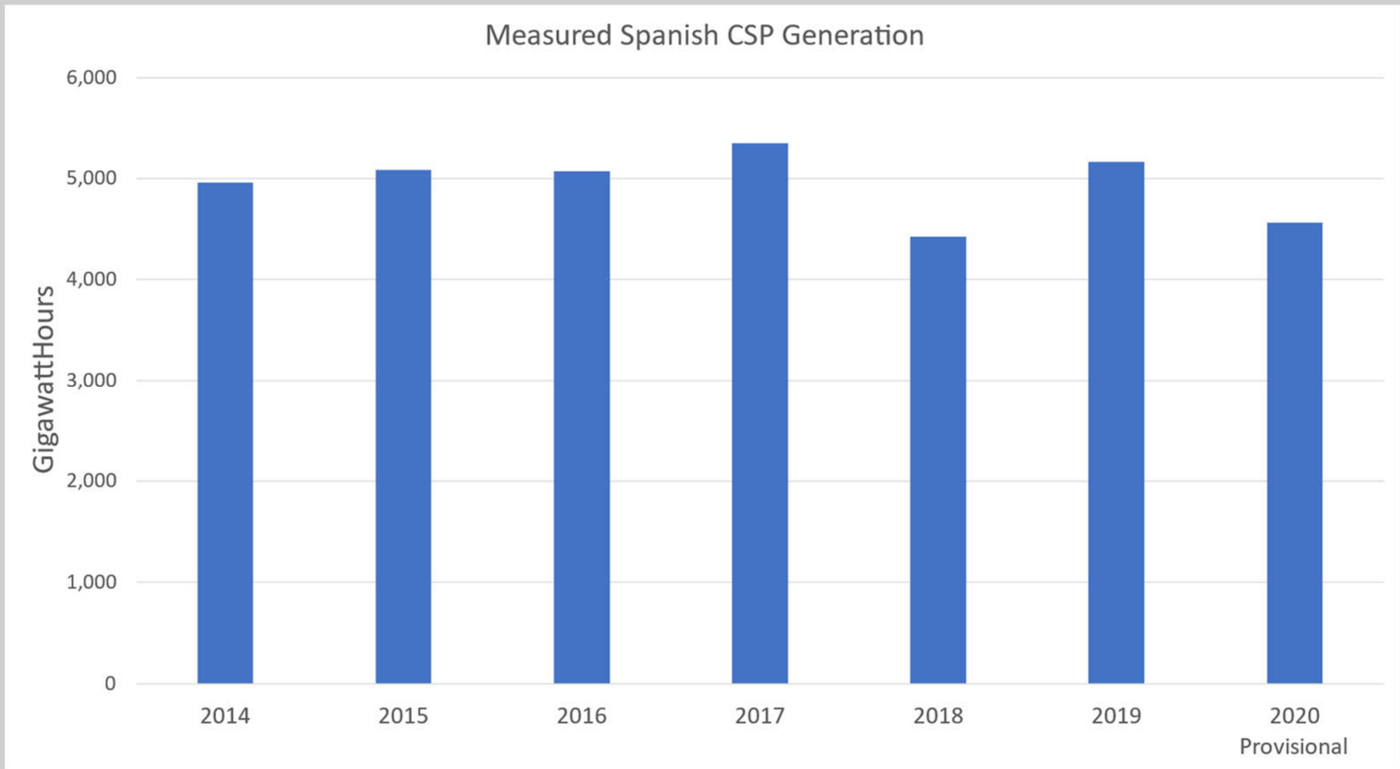
Spain has a mature 2.3–GW fleet of CSP plants

- 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

PROTERMO SOLAR



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

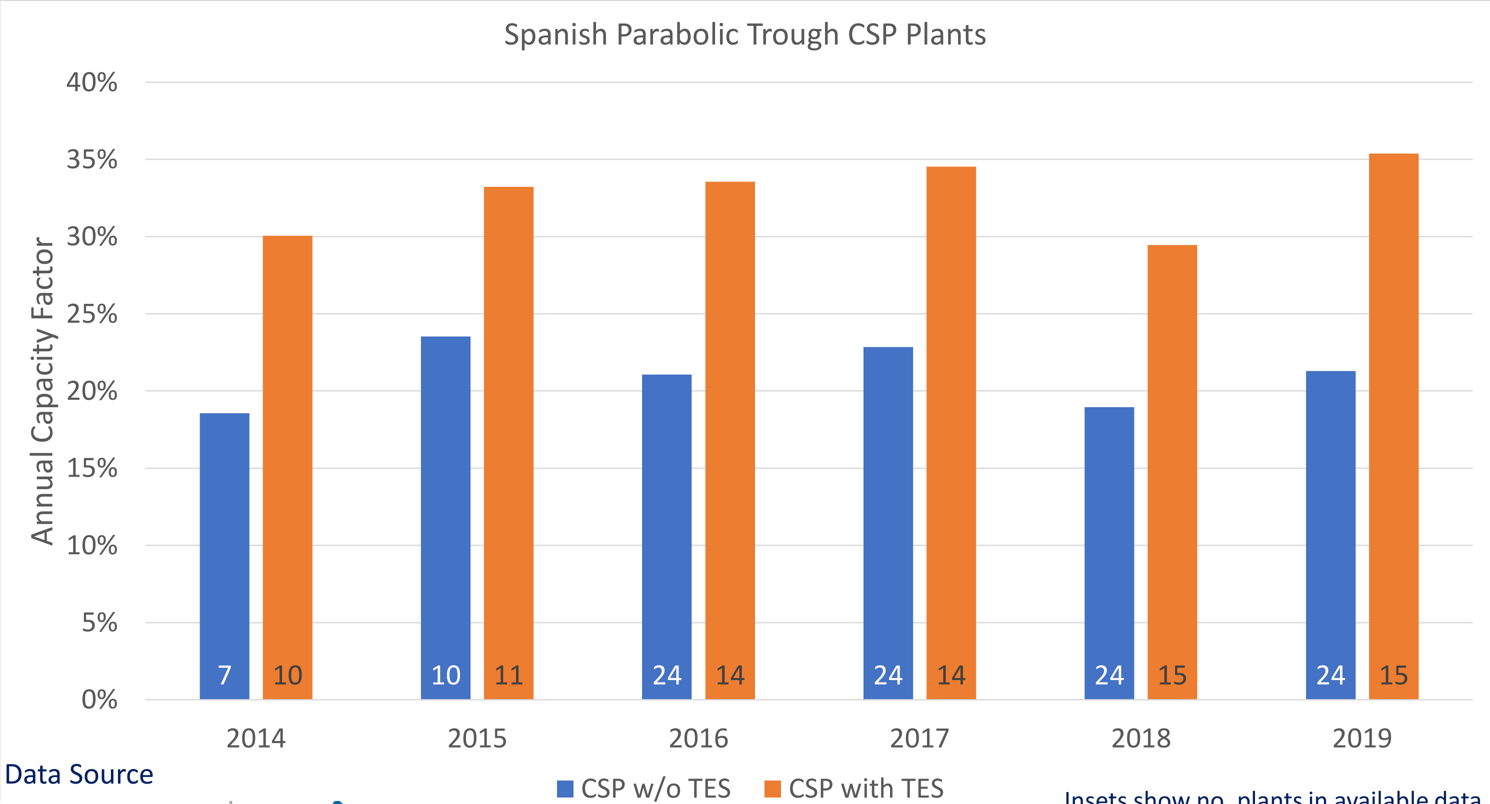
RED ELÉCTRICA DE ESPAÑA | esios SISTEMA DE INFORMACIÓN DEL OPERADOR DEL SISTEMA

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



Insets show no. plants in available data

Data Source

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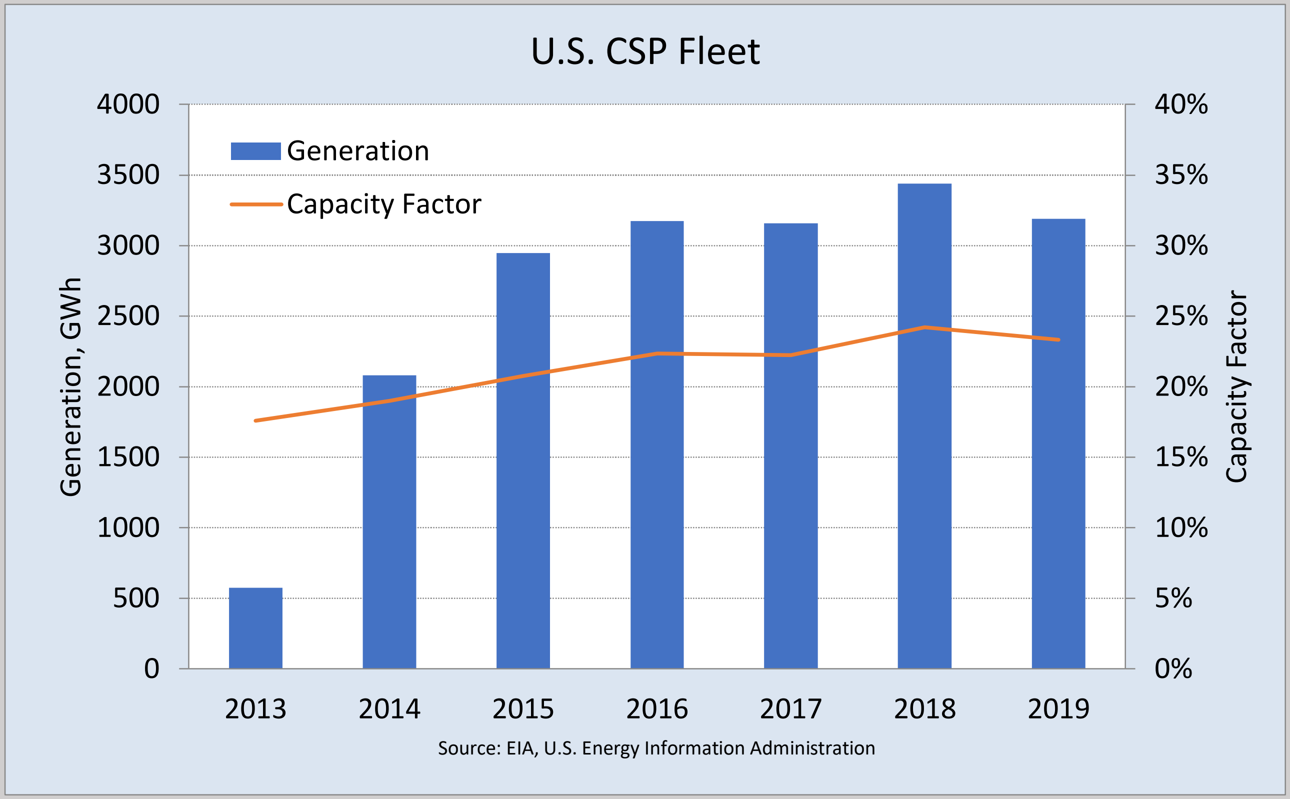
In the Spanish market and climate, trough plants with no TES are typically designed for about 20% annual capacity factor, while 30% to 35% is the corresponding target capacity factor for plants with 7 to 9 hours of TES.

The available ESIOS data for 2016-2019 indicate over 96% availability for trough plants, both with and without TES.

The current U.S. 1.6-GW CSP fleet has shown dependable performance for the past 5 years



- Current fleet was completed in 2015
- It includes 11 PT plants and 2 central-receiver plants that total 4 towers
- Ongoing learning is evident in the increasing capacity factor

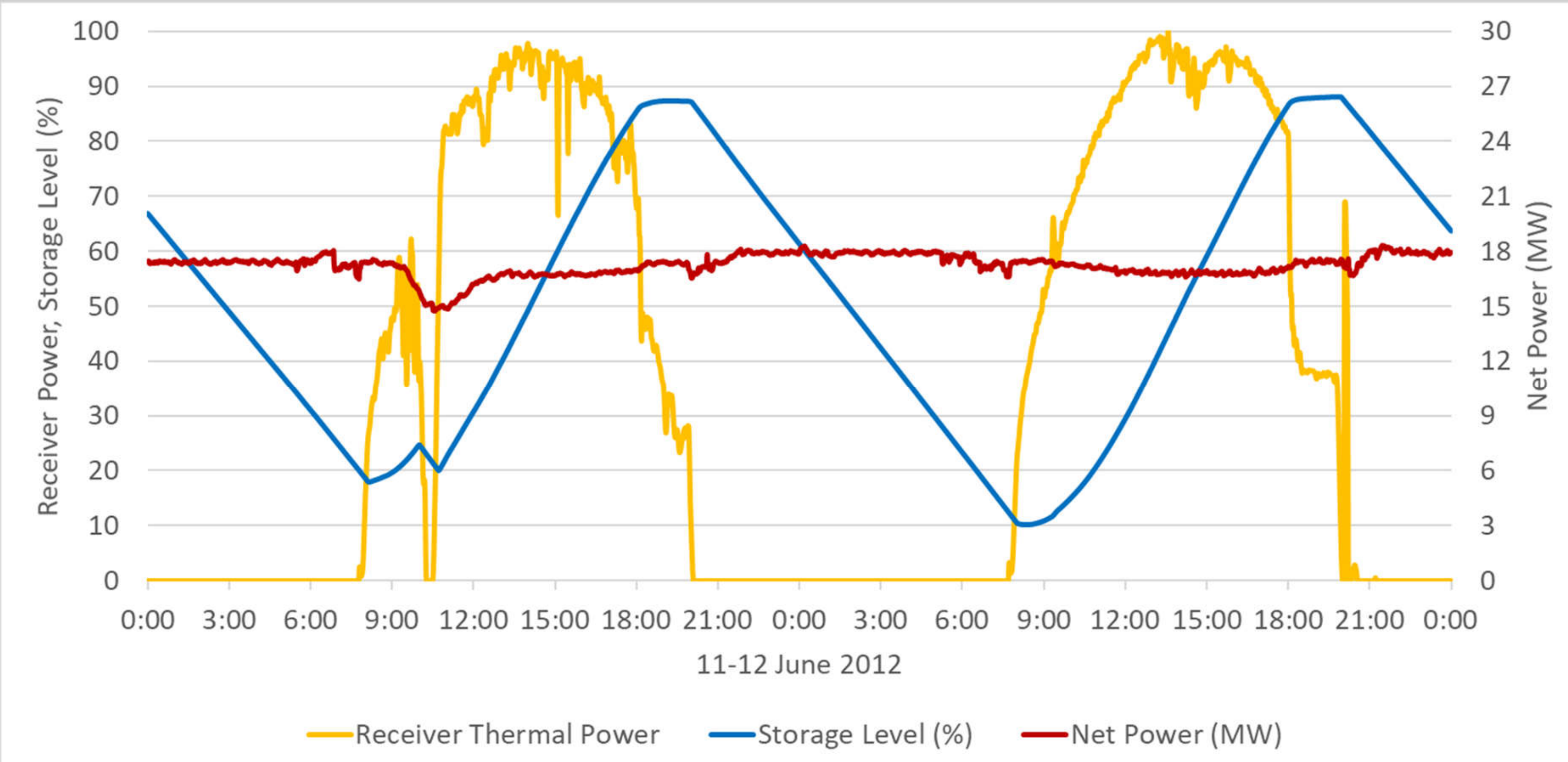
Can they meet the evening peak and operate 24/7?

- Gemasolar in Spain
- Xina in South Africa
- Solana in Arizona

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

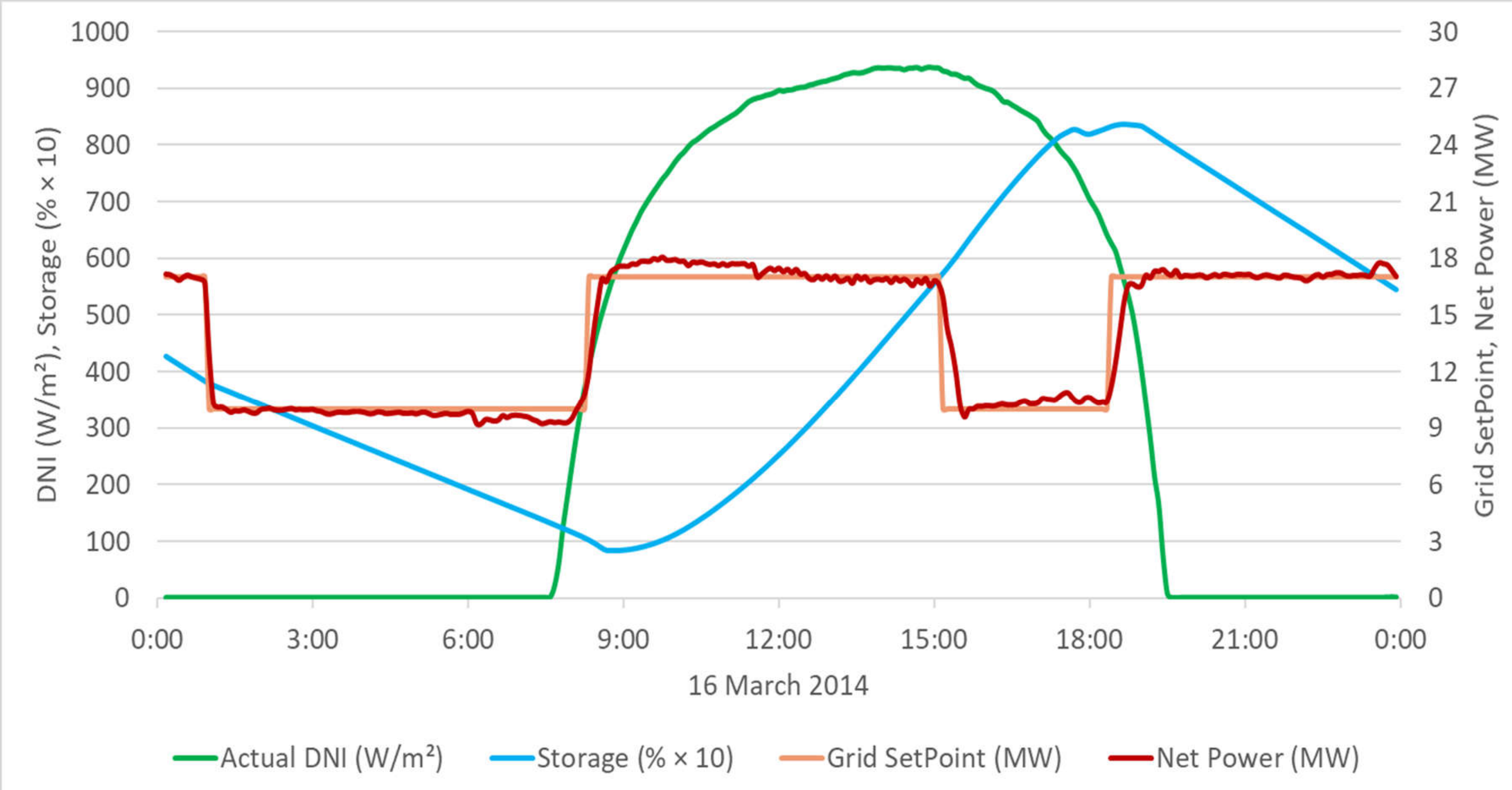
Gemasolar stable production through cloud transients



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

Torresol Energy
reinventing solar power

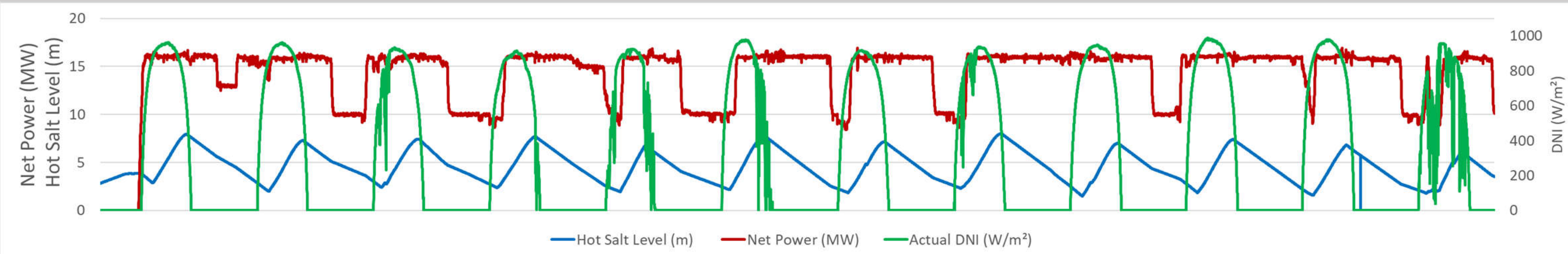
Gemasolar production following grid operator requirements



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

Torresol Energy
reinventing solar power

Gemasolar 24/7 production over many winter days



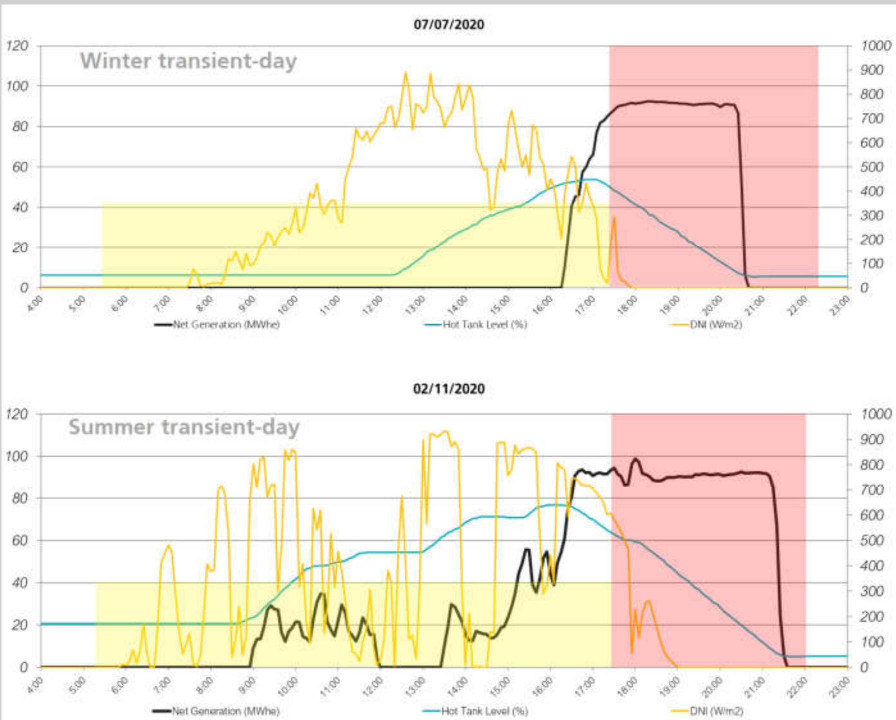
12 days of continuous production in February

- 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

Torresol Energy
reinventing solar power

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

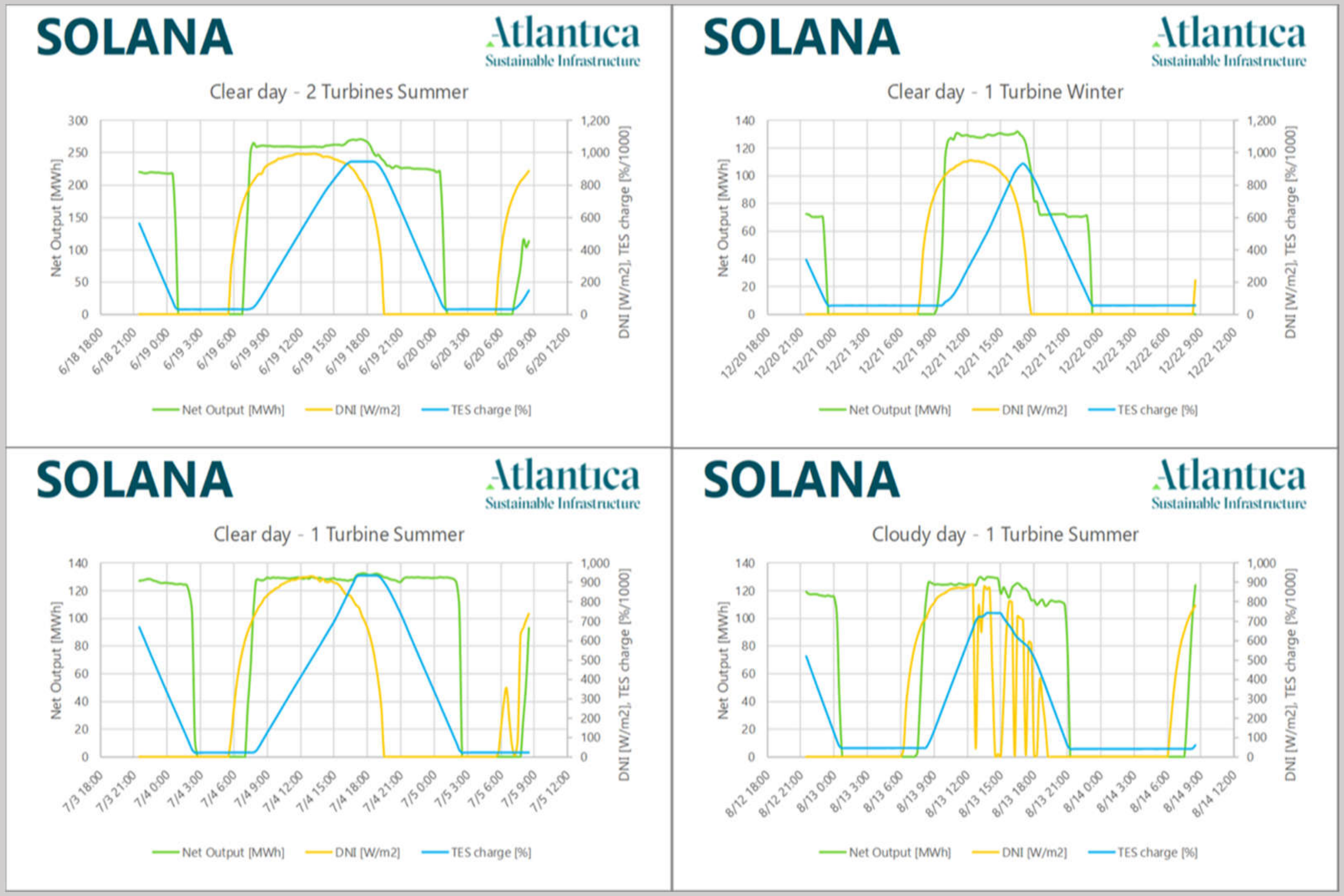
Xina Solar One meeting evening peaks



- 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



SolarDynamics

CSP Best Practices Study

- Best practices and issues with molten-salt TES in CSP plants
  - Trough plants
    - Generally a good operational track record reported.
    - Some issues with heat exchangers used to charge and discharge TES
  - Tower plants
    - Some issues scaling up the hot salt tanks to commercial sizes.
    - Some issues with salt to steam heat exchangers.
  - Lessons learned from initial plants should allow future plants to be constructed with reliable TES.

250-MW Solana Generating Station (Arizona, USA) with 6 hours of molten-salt thermal energy storage

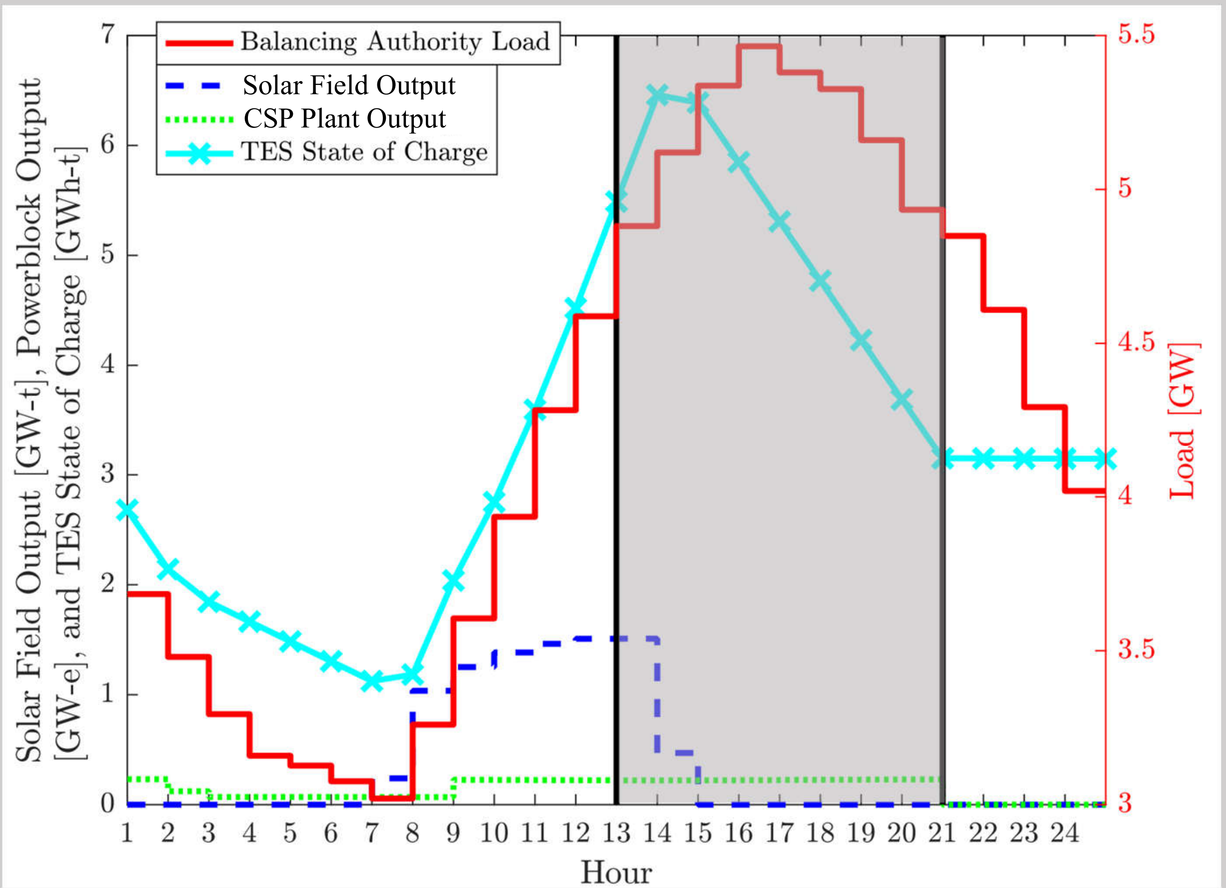
NREL Transforming ENERGY | SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy | World Bank | SolarPACES | ESTELA | EPRI | SolarDynamics

Can a CSP+TES plant run 365 days a year?

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

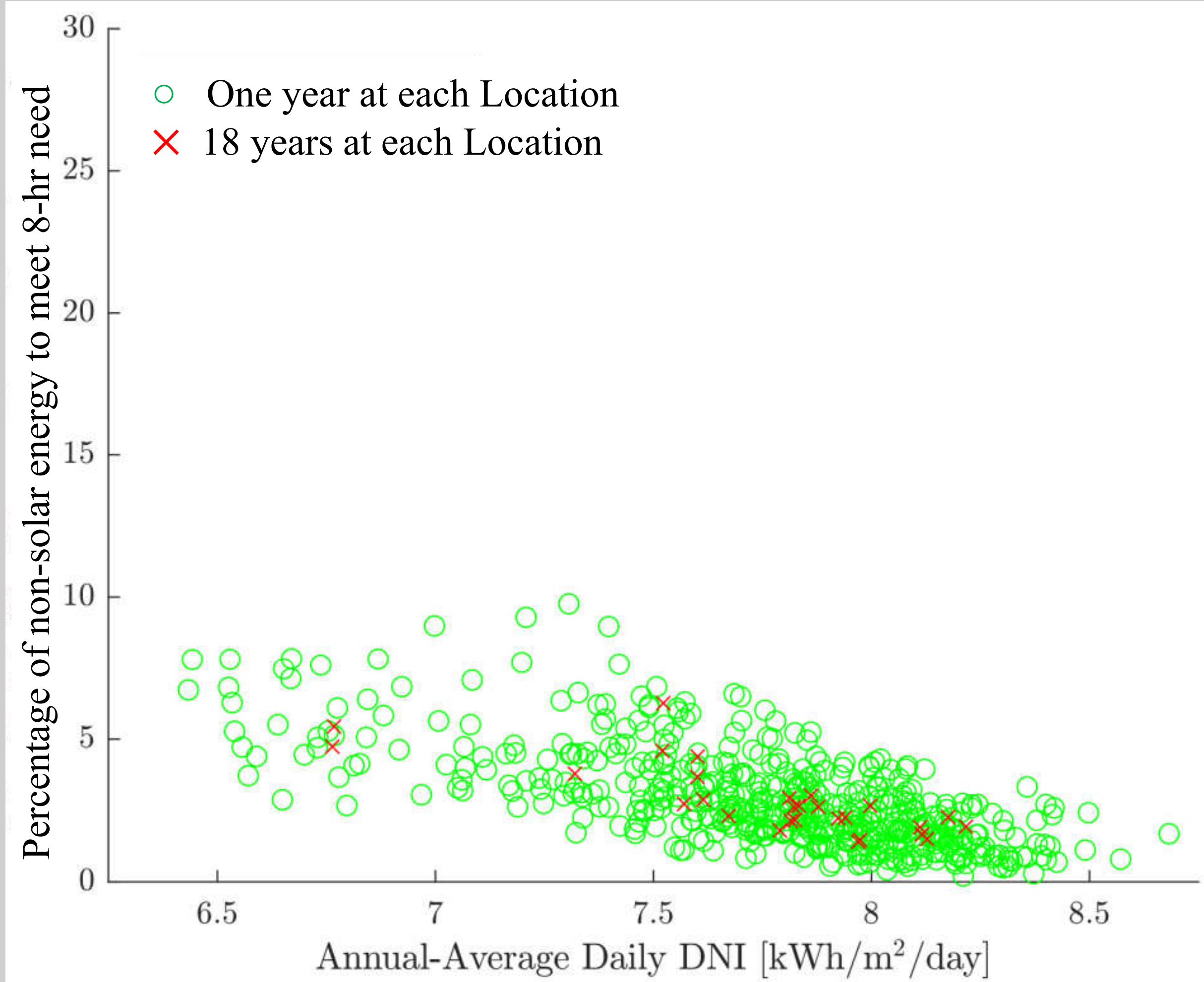
*Yagi, Sioshansi, Denholm. *Solar Energy, 191*, **2019**, 686



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

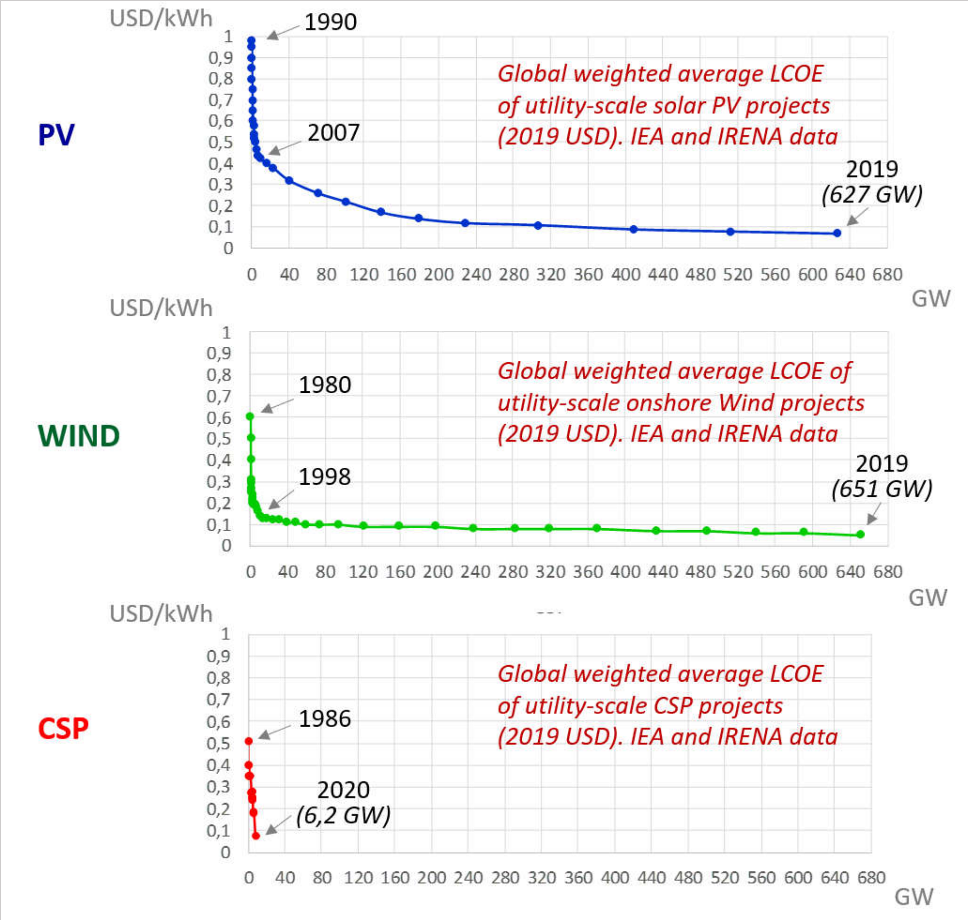
*Yagi, Sioshansi, Denholm. *Solar Energy, 191*, **2019**, 686



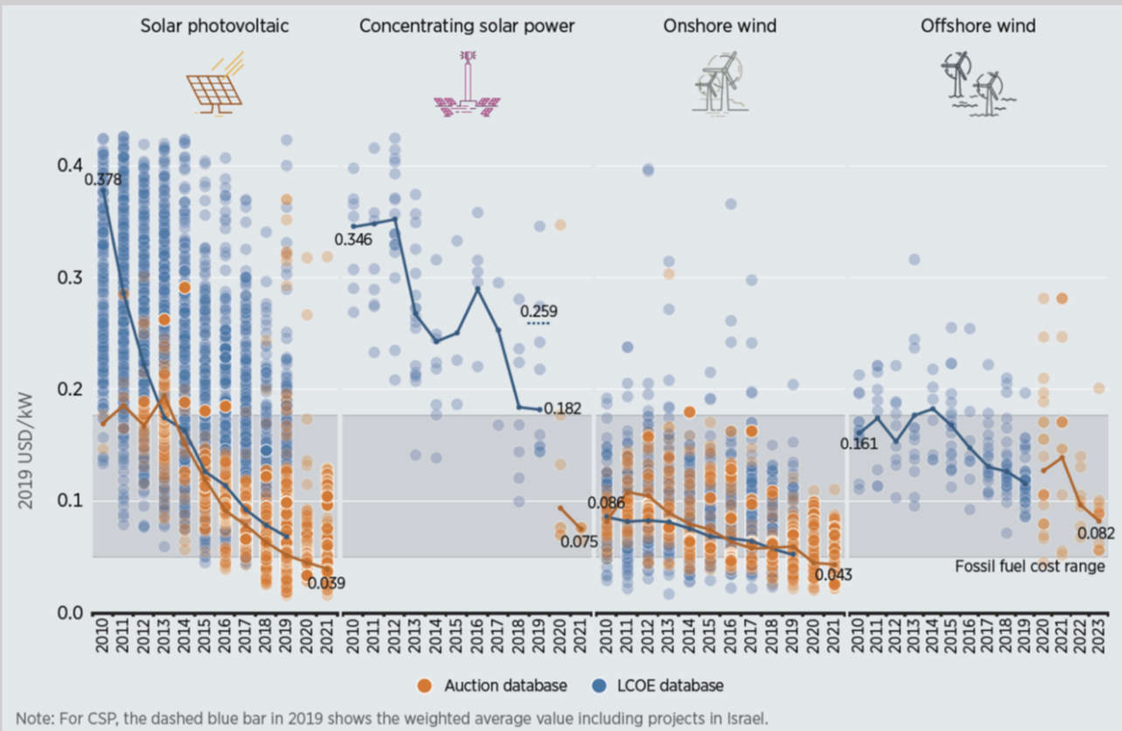
Are CSP plants affordable?

Costs have decreased rapidly and further reductions are predicted

Solar and wind cost reduction learning curves



Auction and PPA results: 2010-2021/23



Source: IRENA Renewable Cost Database.

Note: Each circle represents an individual project LCOE (blue dots), or an auction result (orange dots), where there was a single clearing price at auction, for the actual or estimated year of commissioning respectively. The centre of the circle is the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE, or auction values, by year. For the LCOE data, the real WACC is 7.5% for OECD countries and China, and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

- Cost reductions continue to 2021/23
- Utility-scale solar PV and onshore wind undercut cheapest new fossil fuel (75%-80% of projects)
- Offshore wind and CSP see step change in costs
- Offshore wind to USD 50-100/MWh
- CSP, with an even lower deployment, could fall to USD 70-80/MWh

Factors bringing CSP costs down

- Shift to higher DNI areas
- Lower cost of capital
- More experienced project developers
- Competitive procurements
- More competitive supply chains
- Technology improvements

Capabilities of CSP+TES plants

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 resource year around
- 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

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

Commercial Developers are Optimizing CSP/PV Hybridization

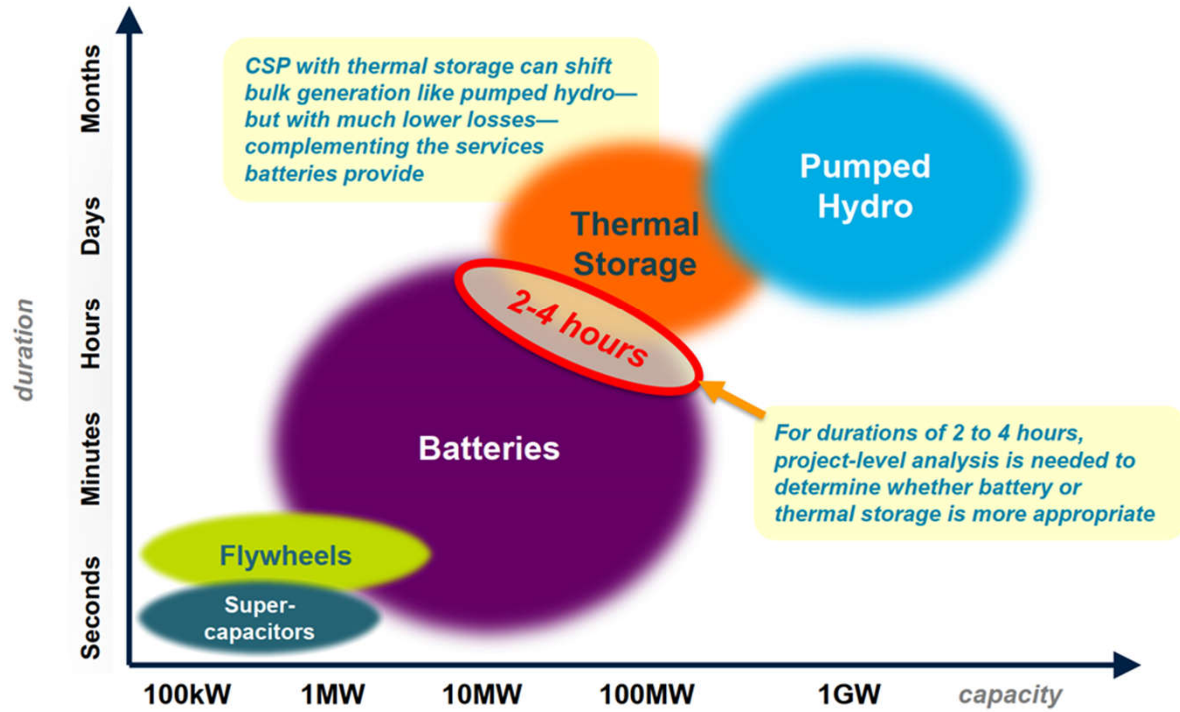
DEWA IV – Dubai – PV co-located

- 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

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



WORLD BANK GROUP Energy & Extractives | IRENA International Renewable Energy Agency | CIF Climate Investment Funds

CSP Storage cost

CSP+TES is and remains cheapest for more than 4 hours storage

A very recent paper (2021) contrasted the cost of:

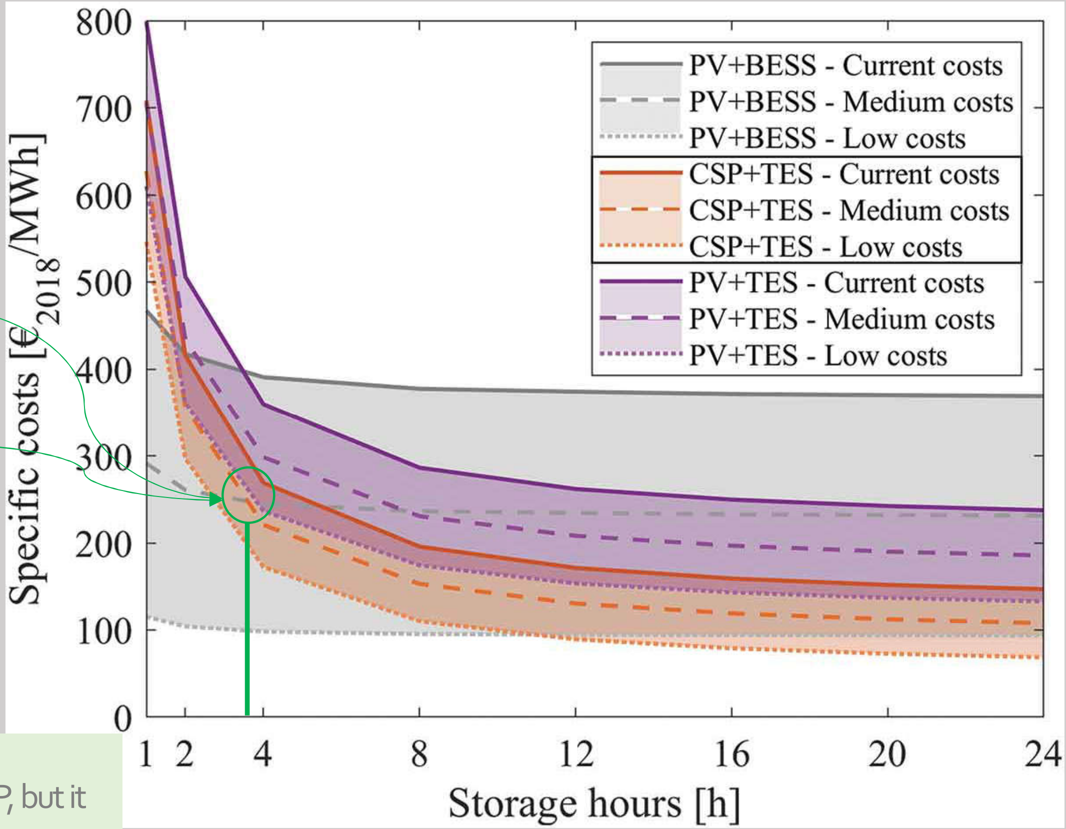
- PV + utility-scale Li-Ion batteries (PV+BESS)
- CSP + two-tank molten-salt (CSP+TES)
- TES using electric heater (PV+TES)

The reference case is a continuous load of 100MW during the pre-specified period (from 1 to 24h after sunset).

Results:

1. PV+BESS is cheaper than CSP+TES for short storage durations up to 2–3 hours.

2. CSP+TES is and remains cheapest for more than 4 hours storage except in the low-cost PV+BESS case where very strong PV+BESS learning is assumed, and the tipping point moves to 10 storage hours.

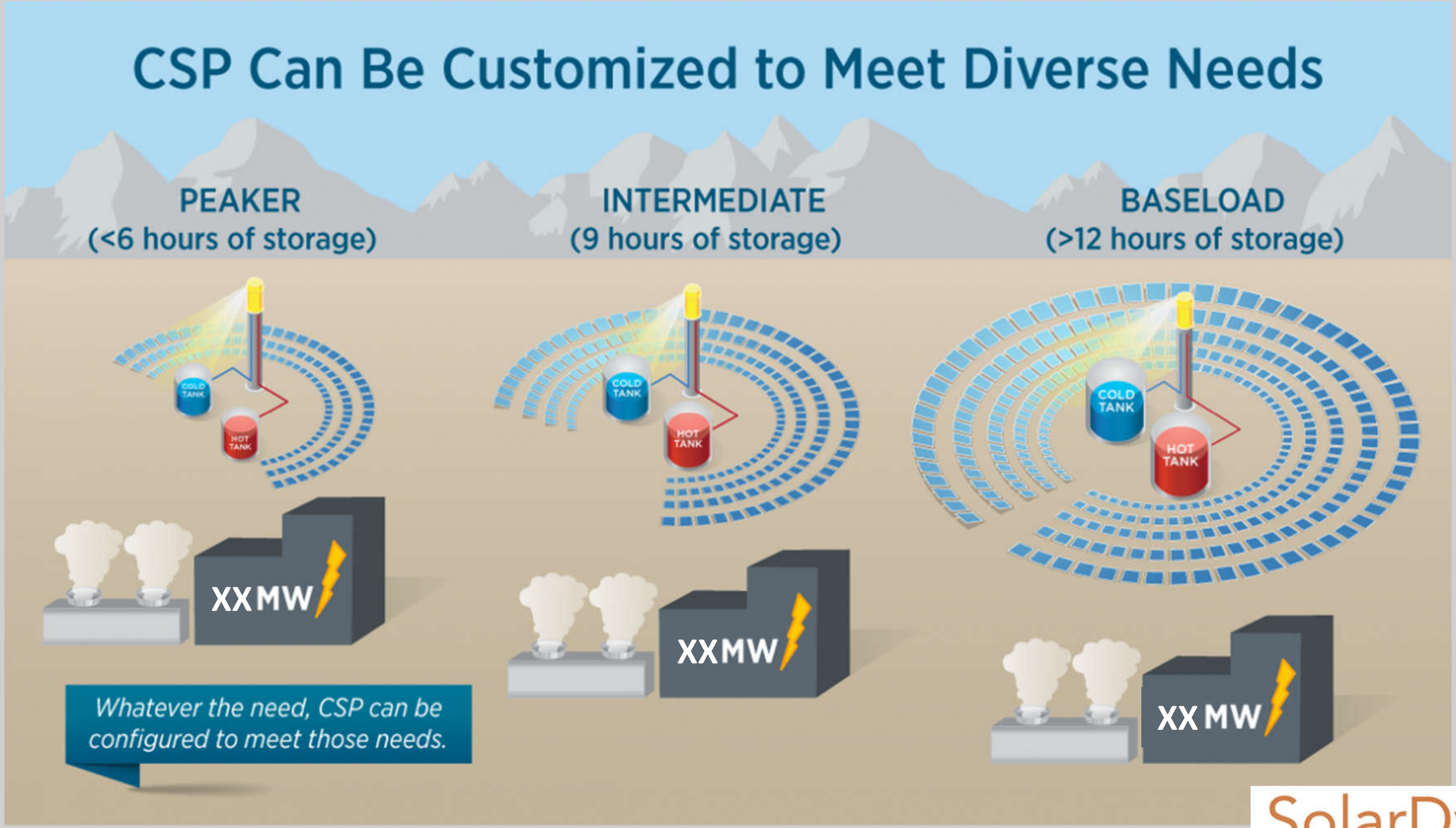


What time of the day?

- The general conception assumes PV is cheaper than CSP, but it is forgotten to include "***while the Sun is shinning***"
- At night, CSP is much cheaper than PV with batteries

Franziska Schöniger, Richard Thonig, Gustav Resch & Johan Lilliestam (2021) Making the sun shine at night: comparing the cost of dispatchable concentrating solar power and photovoltaics with storage, Energy Sources, Part B: Economics, Planning, and Policy, DOI: 10.1080/15567249.2020.1843565
https://www.tandfonline.com/doi/full/10.1080/15567249.2020.1843565

Flexible Designs for an Evolving Grid



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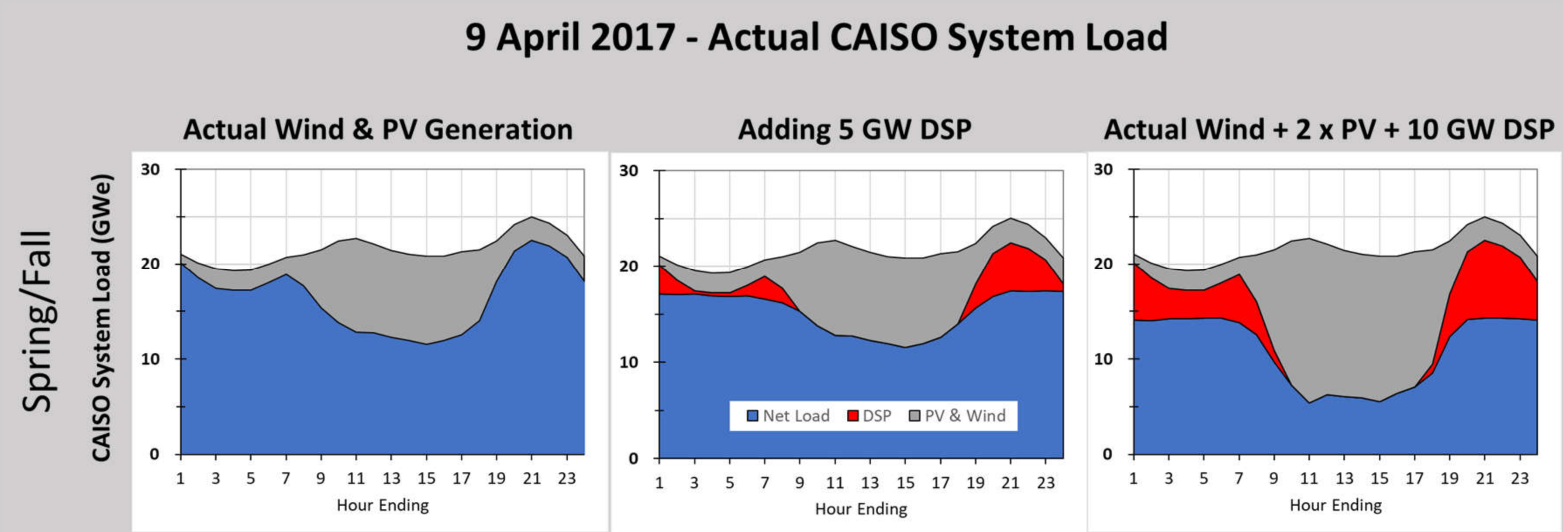
SolarDynamics

CAISO Spring System Load

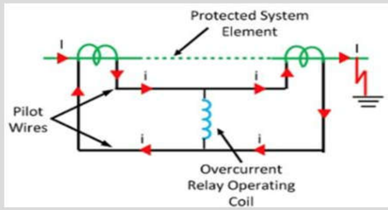


Existing:
- Wind 3,373 MW
- Solar 7,438 MW

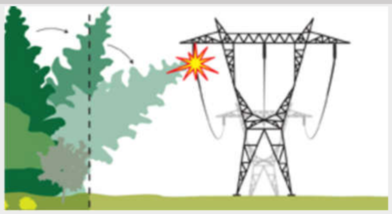
Existing:
- Wind 3,373 MW
- Solar 7,438 MW

Assumed:
- Wind 3,373 MW
- Solar 14,876 MW

Dispatchable CSP Provides Grid Strength

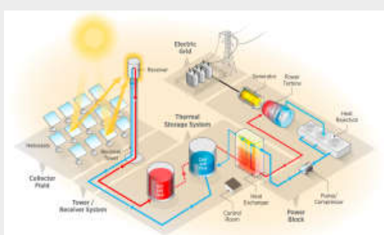


Transmission and distribution lines are protected from system disturbances by a network of relays and disconnect devices called Protective Relay Schemes.



When a fault occurs on a power line, the energized conductors become grounded. Line voltage plummets toward zero, causing the current to spike to very high levels.

Protective relay schemes are designed to “trip” in response to high levels of short circuit current, to open and isolate faults.

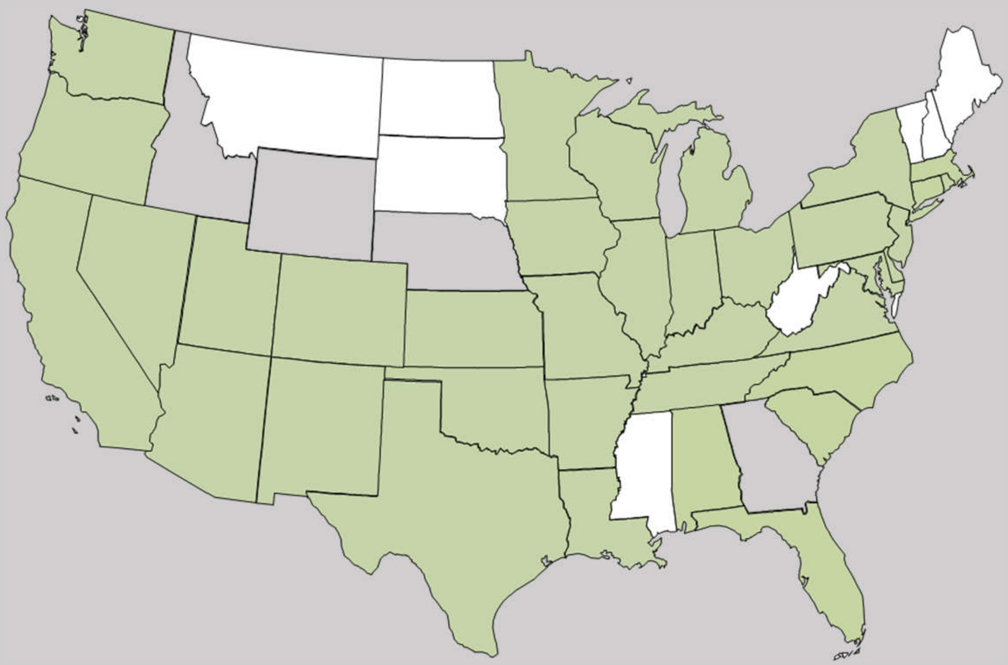


High levels of short circuit current can only be supplied by synchronous generation such as dispatchable CSP.

Dispatchable CSP enables greater penetration of inverter-based generation.

Job creation and local economic development

A significant amount of the goods and services for CSP plants can be locally sourced supporting jobs and economic development



For example, in the United States, more than 250 companies in 36 states provided goods and services for Mojave, Solana, Crescent Dunes, and Ivanpah CSP projects

CSP requires large construction teams

Is CSP+TES part of SMUD's future?

Fred Morse

President, Morse Associates, Inc.

202-276-0518

fredmorse@MAIenergy.com

Terry Peterson

Solar Power Consulting

650-394-5212

terry.peterson@solarpowerconsulting.com