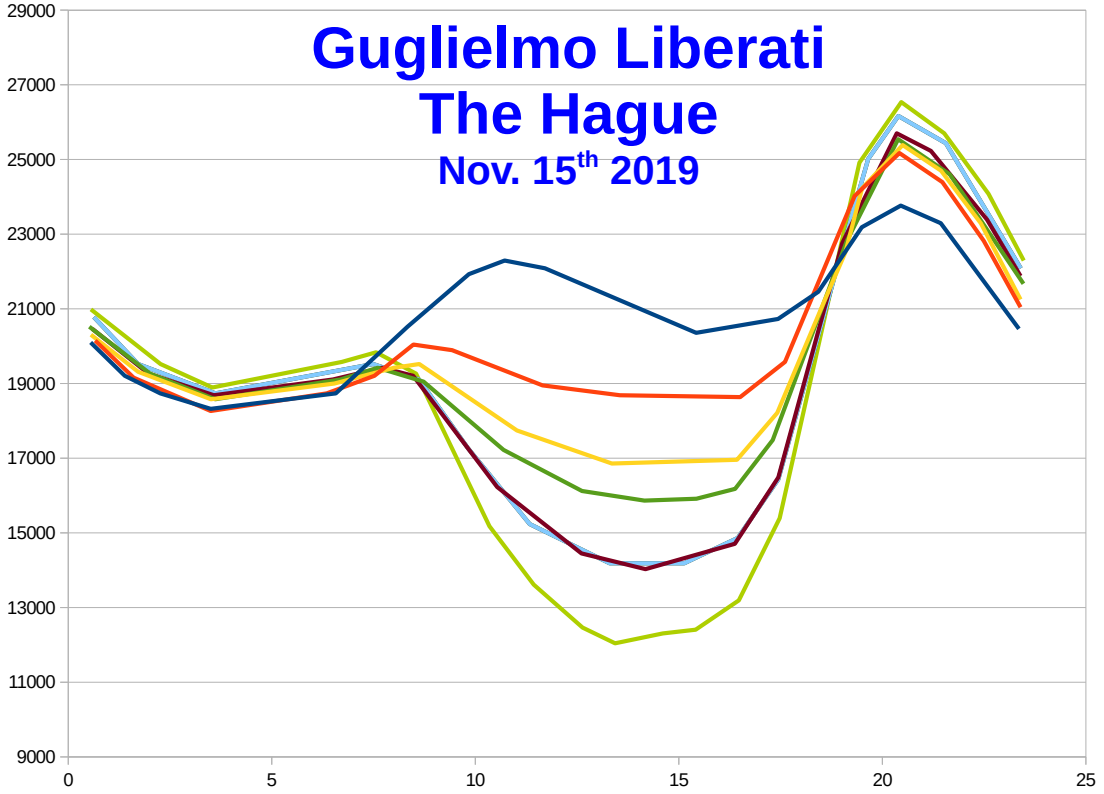
“Duck curve” sheds new light on CSP

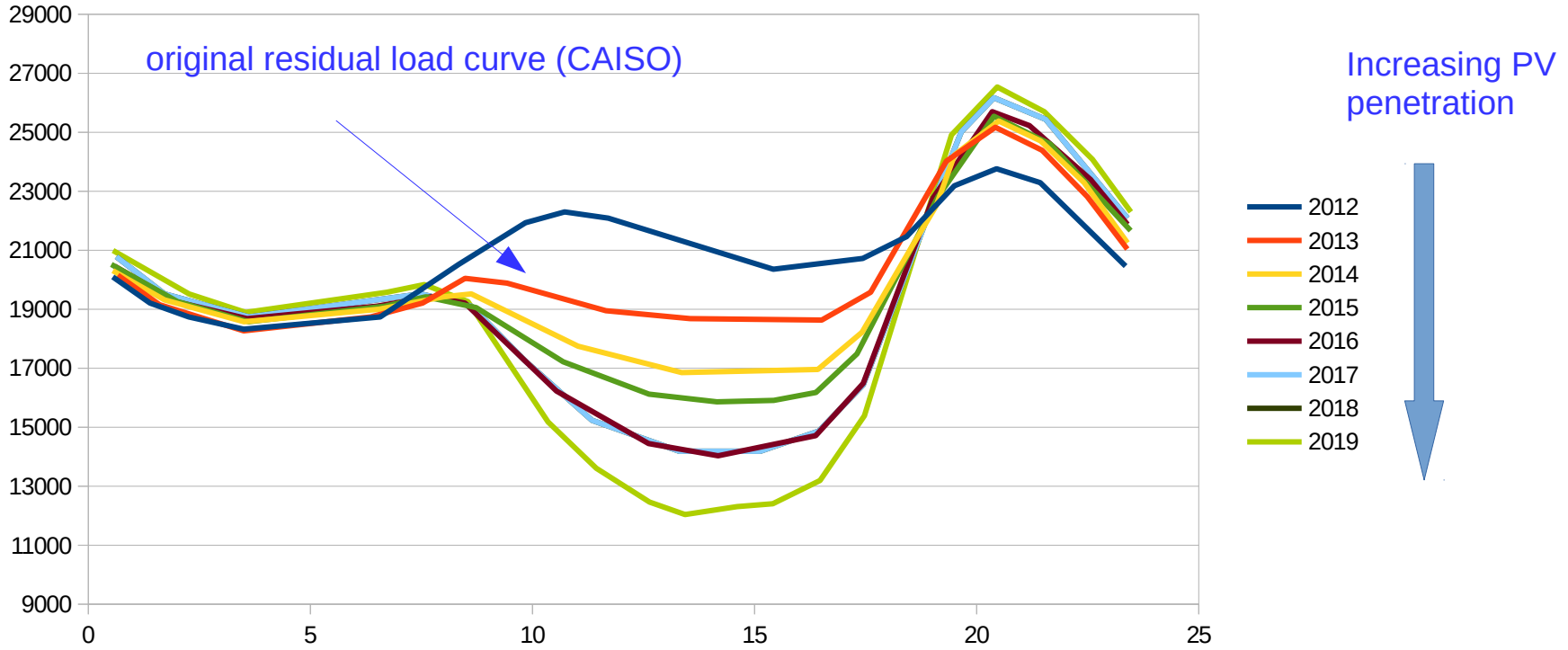


The “Duck curve”

A funny new name to highlight a well known problem

Sources of the problem:

1. **Time shift between solar PV production and load curve**
2. **Huge increase of solar electricity penetration (mainly PV)**



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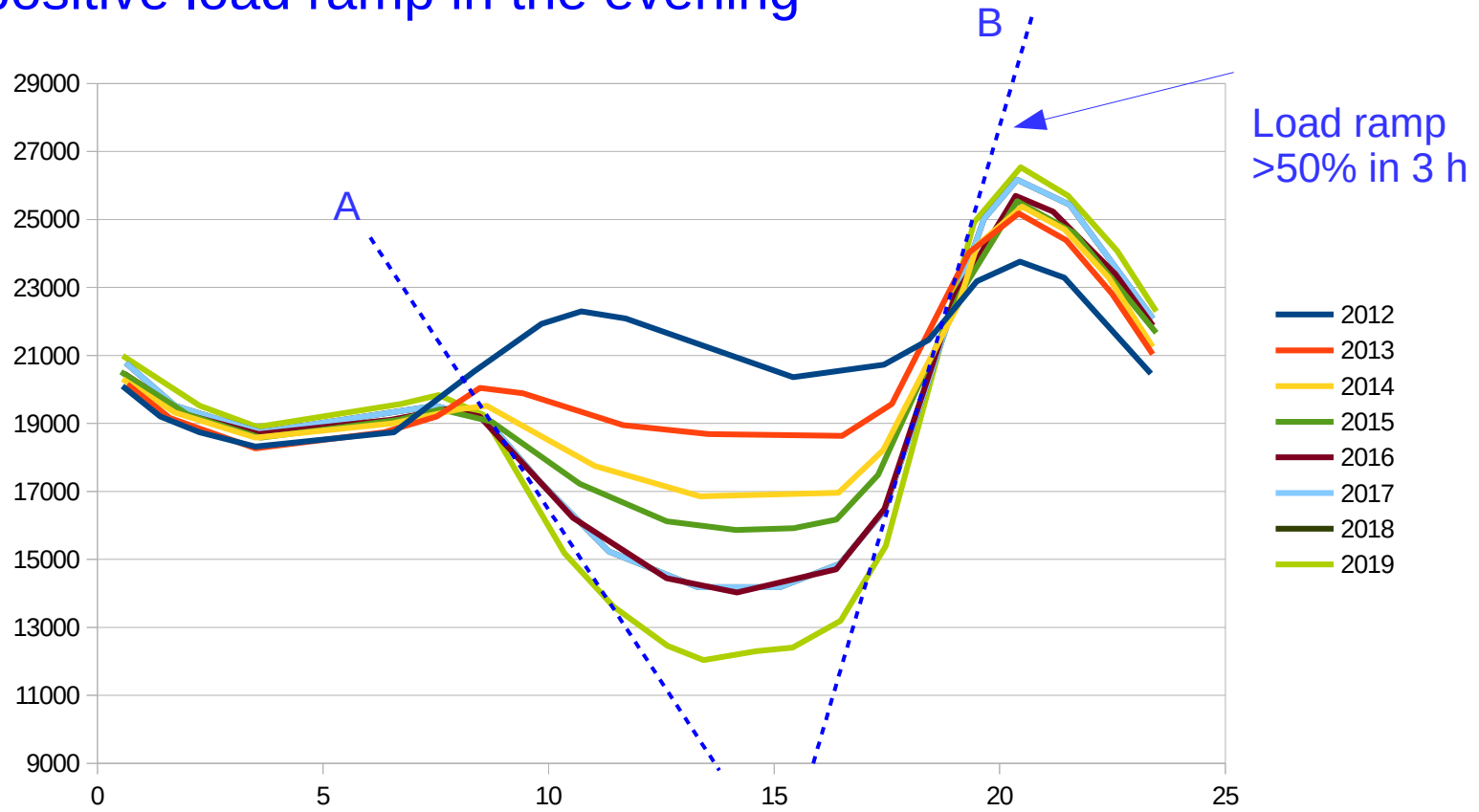
Technology Advisor

The “Duck curve”

A- sudden fall of residual load demand

B- high positive load ramp in the evening



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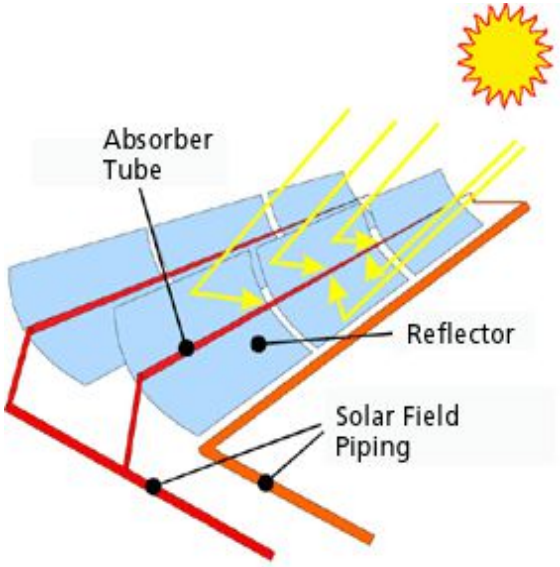
CSP
Main Plant Types

Parabolic Linear Systems
"Parabolic Trough"

- Good conversion efficiency
- Simple sun tracking (single axis)
- Mature technology



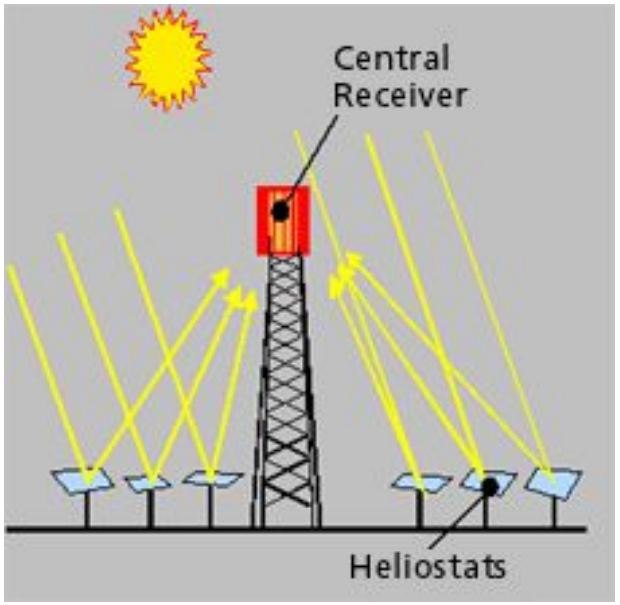
Concentration factor

50 - 100

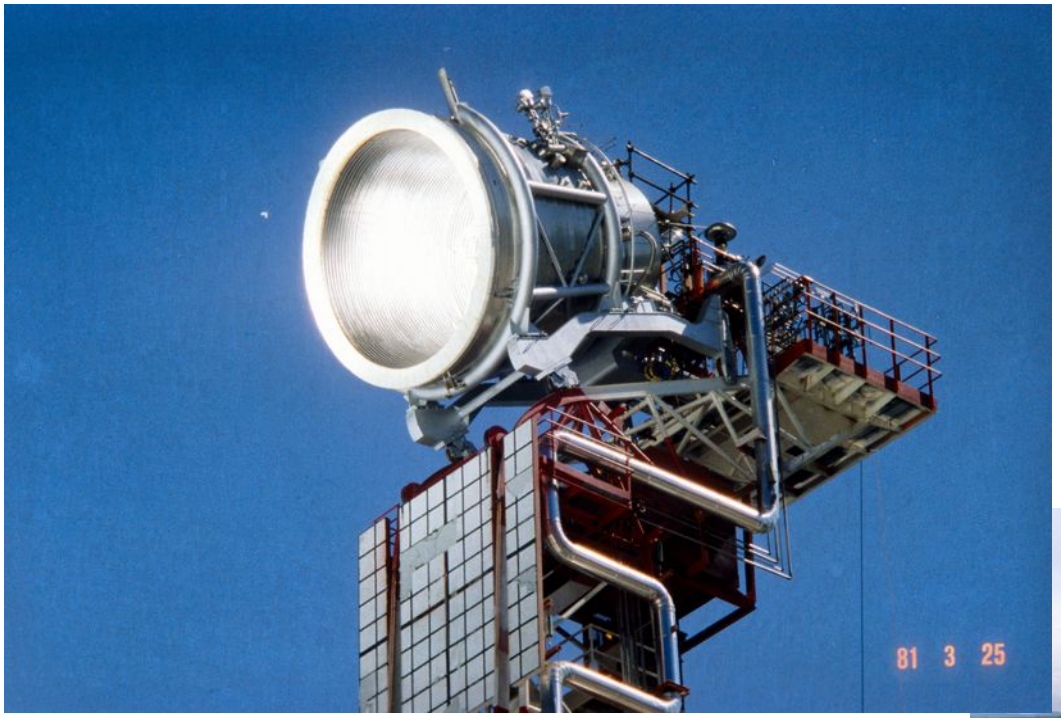
Tower Systems
"Central Receiver"

- Higher temperatures
- Centralized systems

200 - 1000



Eurelios
1MWe 1981

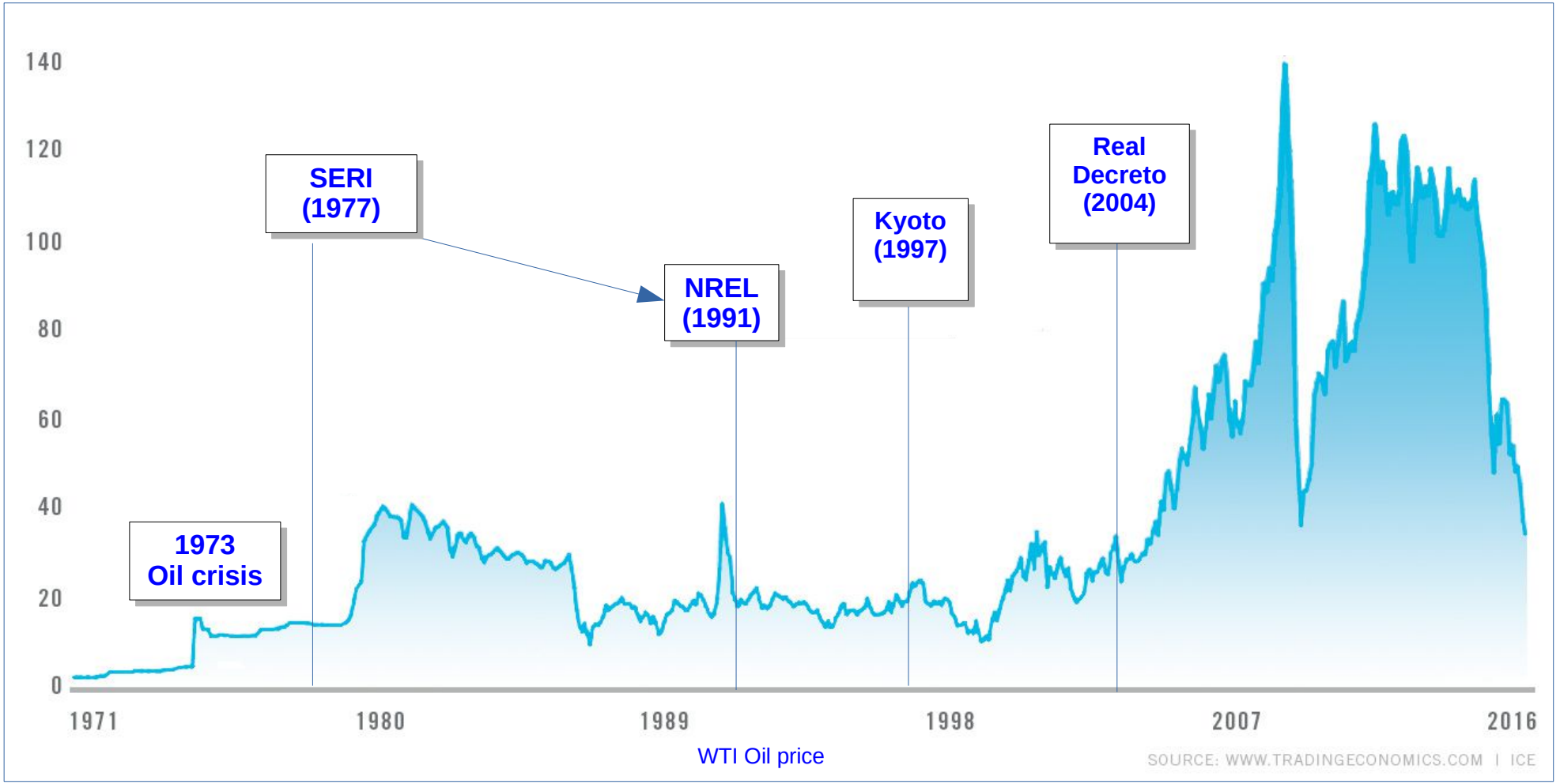


Joint project by FR,DE,IT
Funded by EC

Location: Adrano (Sicily)
Central receiver
Direct steam generation
1MWe
180 heliostats 6200 m2
0.5 h molten salt storage

First (ever) CSP plant connected to the grid June 1981

CSP development



CSP development

SEGS plants in continous commercial operation until now

Real Decreto (2004)

140
120
100
80
60
40
20
0

1971 1980 1989 1998 2007 2016

SEGS (USA) 430 MWe

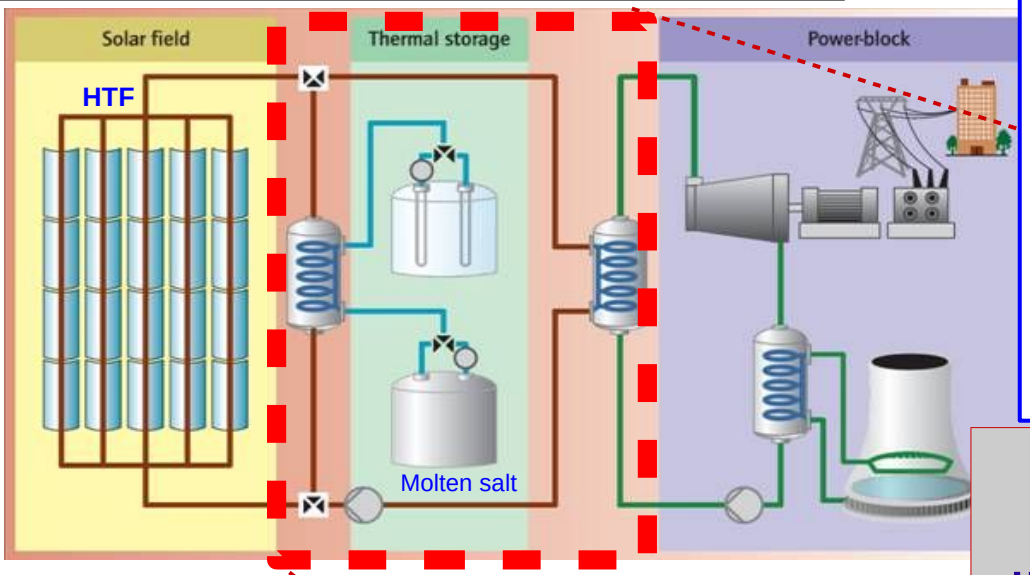
2.5 GW (Spain)

WTI Oil price

≈ 5.5 GWe in operation in 2018

Parabolic Trough CSP with Thermal Energy Storage

Max steam temp. limited to 400°C by synthetic oil HTF used in the solar field



Typical plant data: (Andasol 3)

Power:	50 MWe
Collector area	500000 m^2
Land area	200 ha
cycle eff	36%
Storage	7.5 h

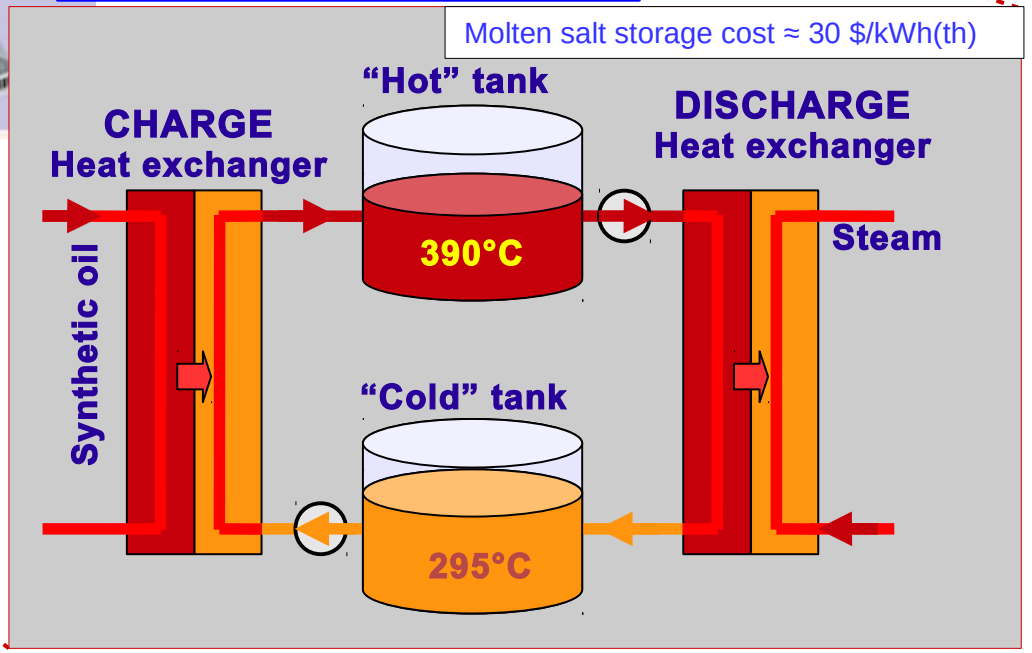
molten salt mass 28000 t
est. capacity factor 43%
Commissioning: Aug 2011

"Solar salt"
KNO_3 40 %
$NaNO_3$ 60 %

Freezing 235 °C
Max temp 600 °C

δ = 1960 kg/m3
C_p = 1.6 kJ/kg/°C

Molten salt storage cost ≈ 30 $/kWh(th)



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CSP
Molten salt Tower system with integral TES

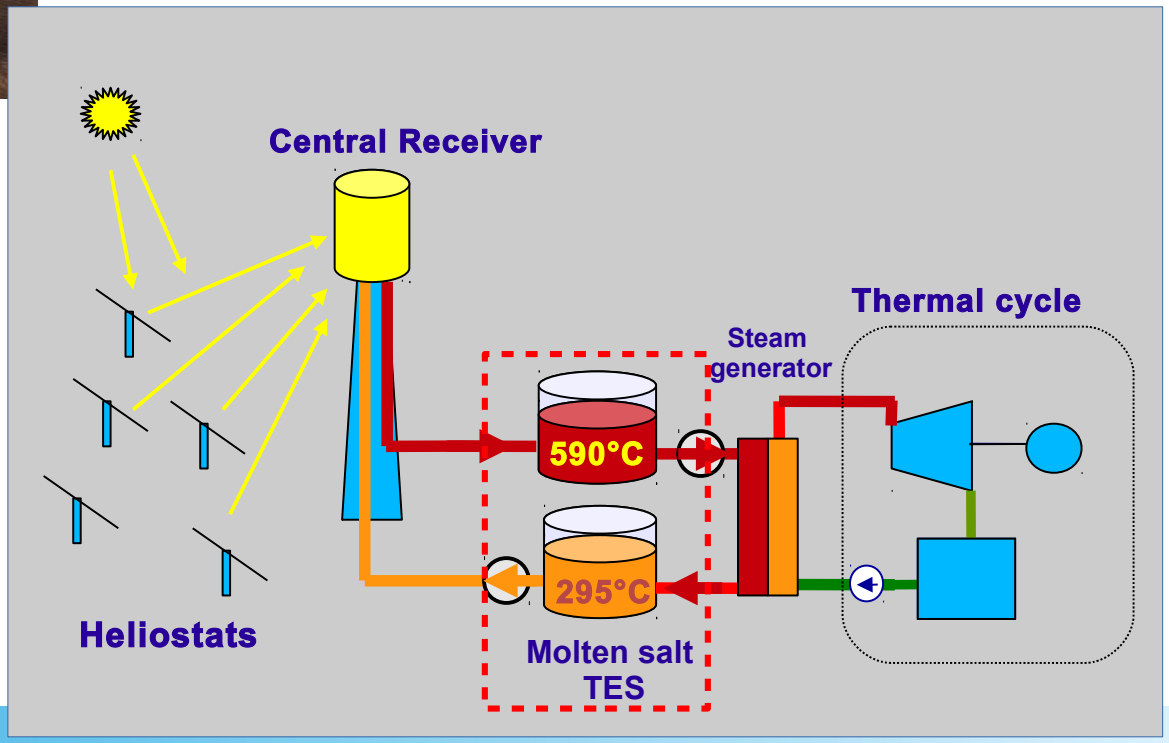
Better performance than PT

Higher steam temperature 550°C
Higher cycle efficiency 40%
Higher storage capacity
for the same mass of salt ≈ 2.5x

Gemasolar plant data:

Power:	19.9 MWe
Heliostats	2650 (120m^2)
Tower:	140 m
Land area	185 ha
Concentration	1000:1
Storage	15h
molten salt mass	8000 t
capacity factor	≈55%

24h operation capability
Commissioning: 2011



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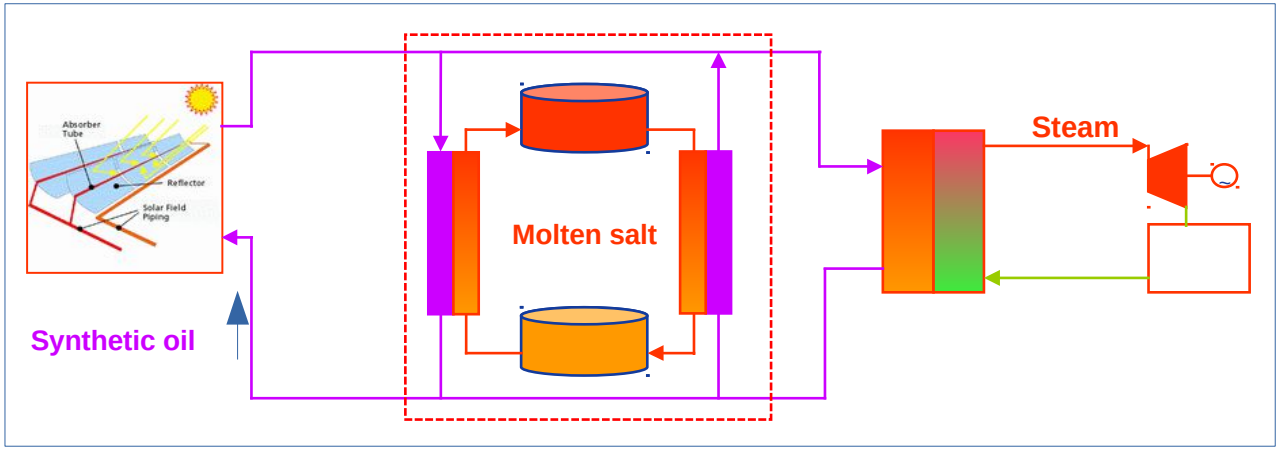
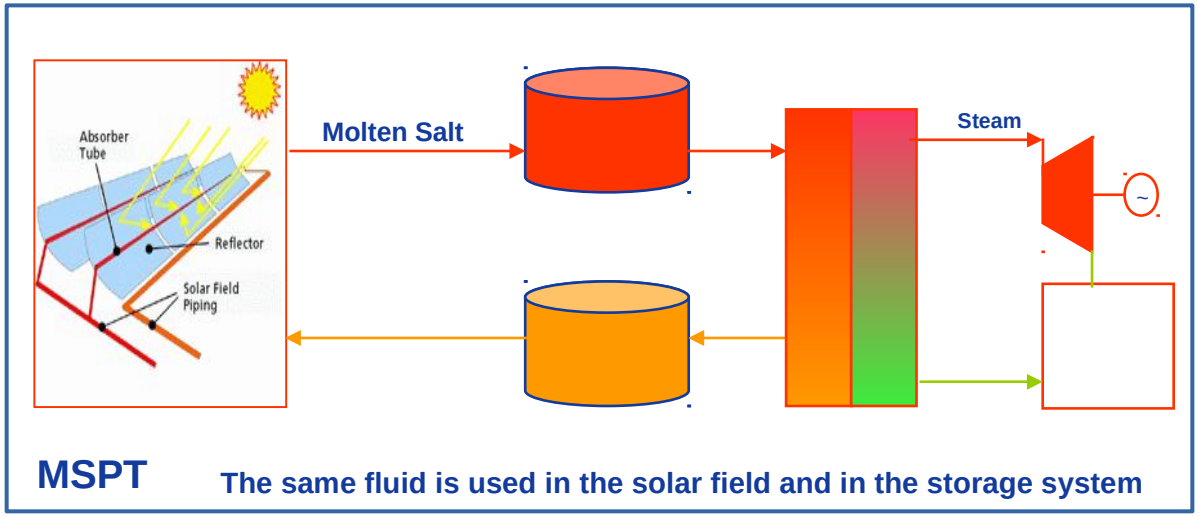
The Molten Salt PT technology (MSPT)



Traditional PT Technology (Thermal Oil w. storage)

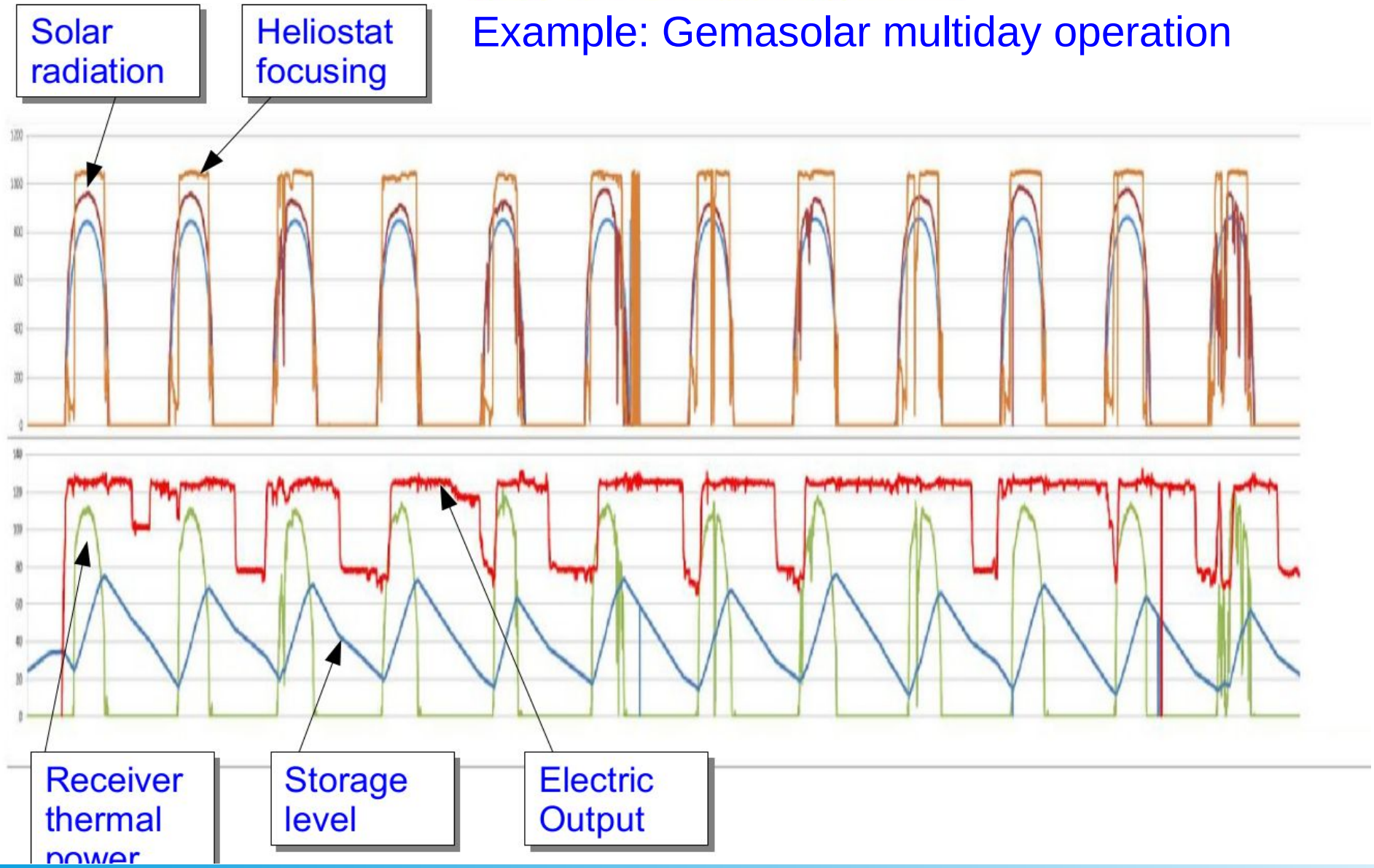
MSPT
Integrated Technology
Simpler and cheaper system



- Two heat exchangers removed
- Higher conversion efficiency
- Higer operational flexibility
- Smaller storage tanks
- No toxicity
- No flammability
- Lower cost of HTF
- Lower cost of the plant
- Require special receiver tubes

CSP output (including TES)

Example: Gemasolar multiday operation



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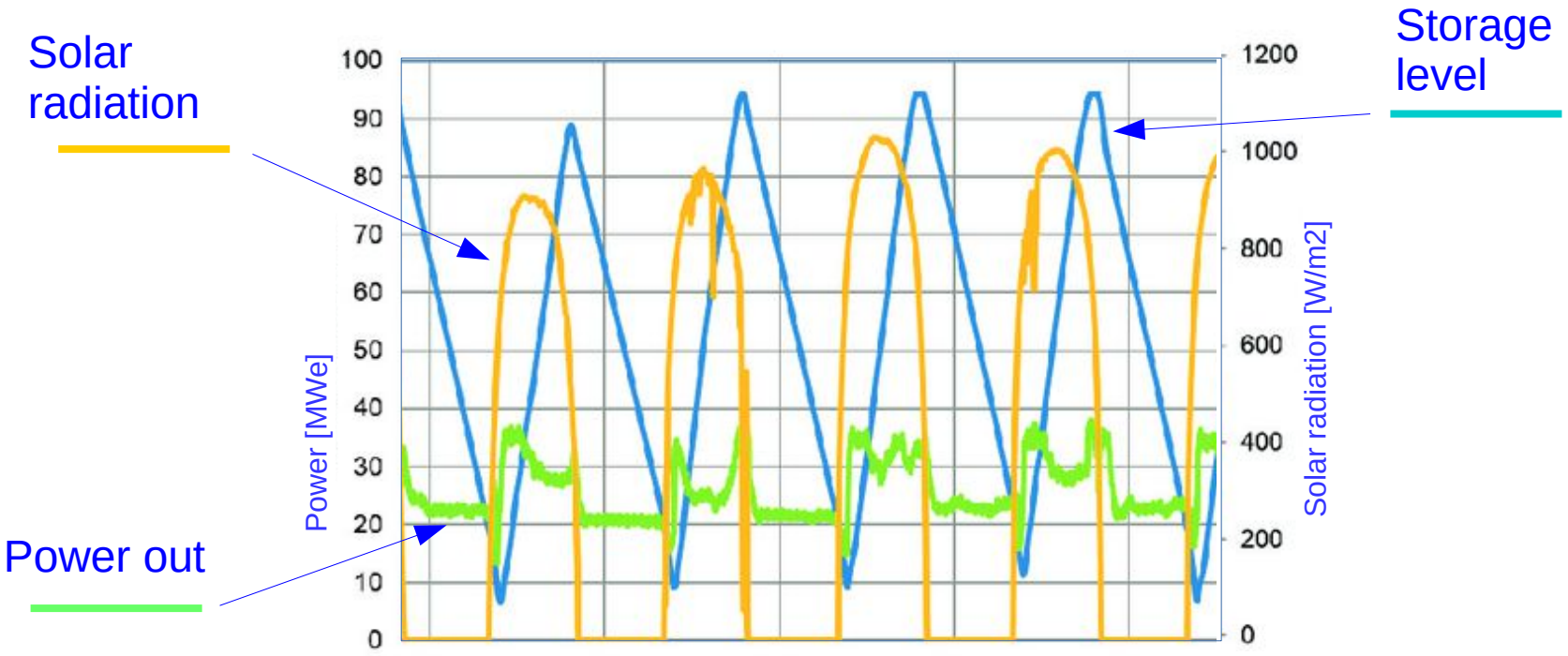
CSP output (including TES)

Example: Andasol 3 operation
24 h continuous generation trial



Although the plant is designed for 7.5 h storage, uninterrupted operation is possible at reduced output power

CSP recent developments

The most recently commissioned Molten Salt Tower: (Oct. 2019)

Luneng (PRC)

- 50 MWe
- 600000 m^2
- 12 h TES
- 160 GWh/y

DNI=1950 kWh/m^2/y

The most recent signed project: (Nov 11th. 2019)

MINOS (Crete)

- Molten Salt Tower
- 50MWe
- 5 h TES
- 160 ha

DNI=2150 kWh/m^2/y

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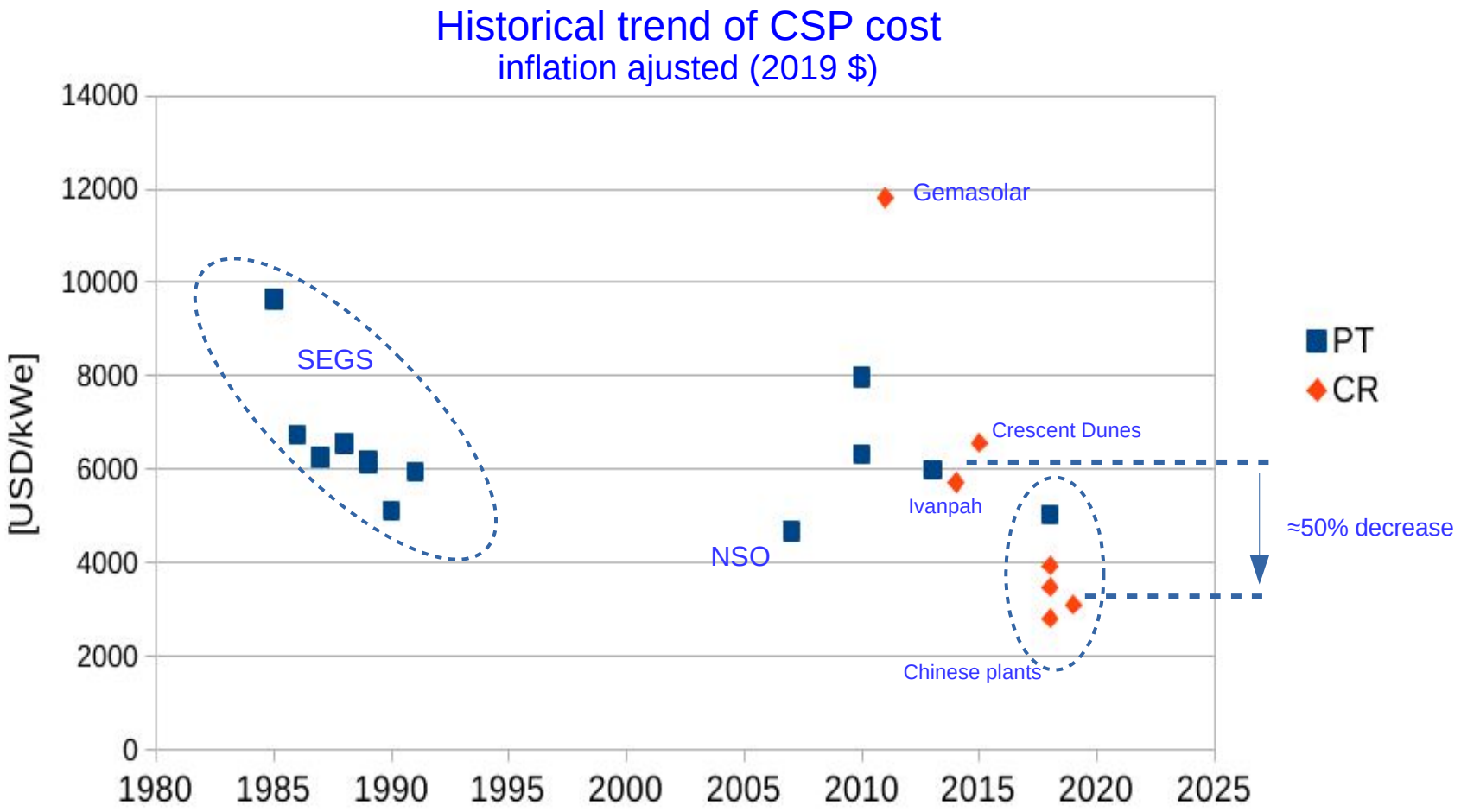
Technology Advisor

CSP costs



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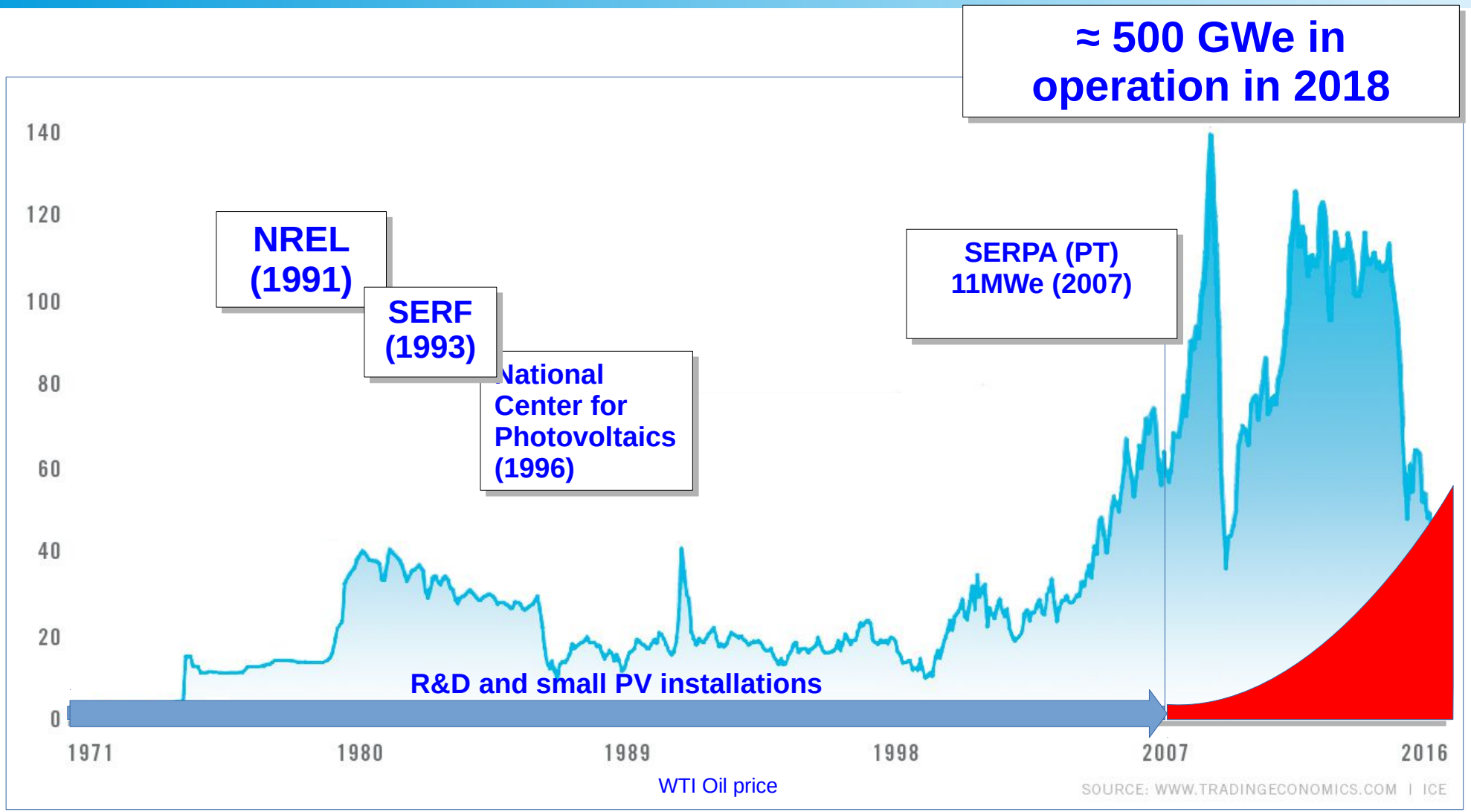
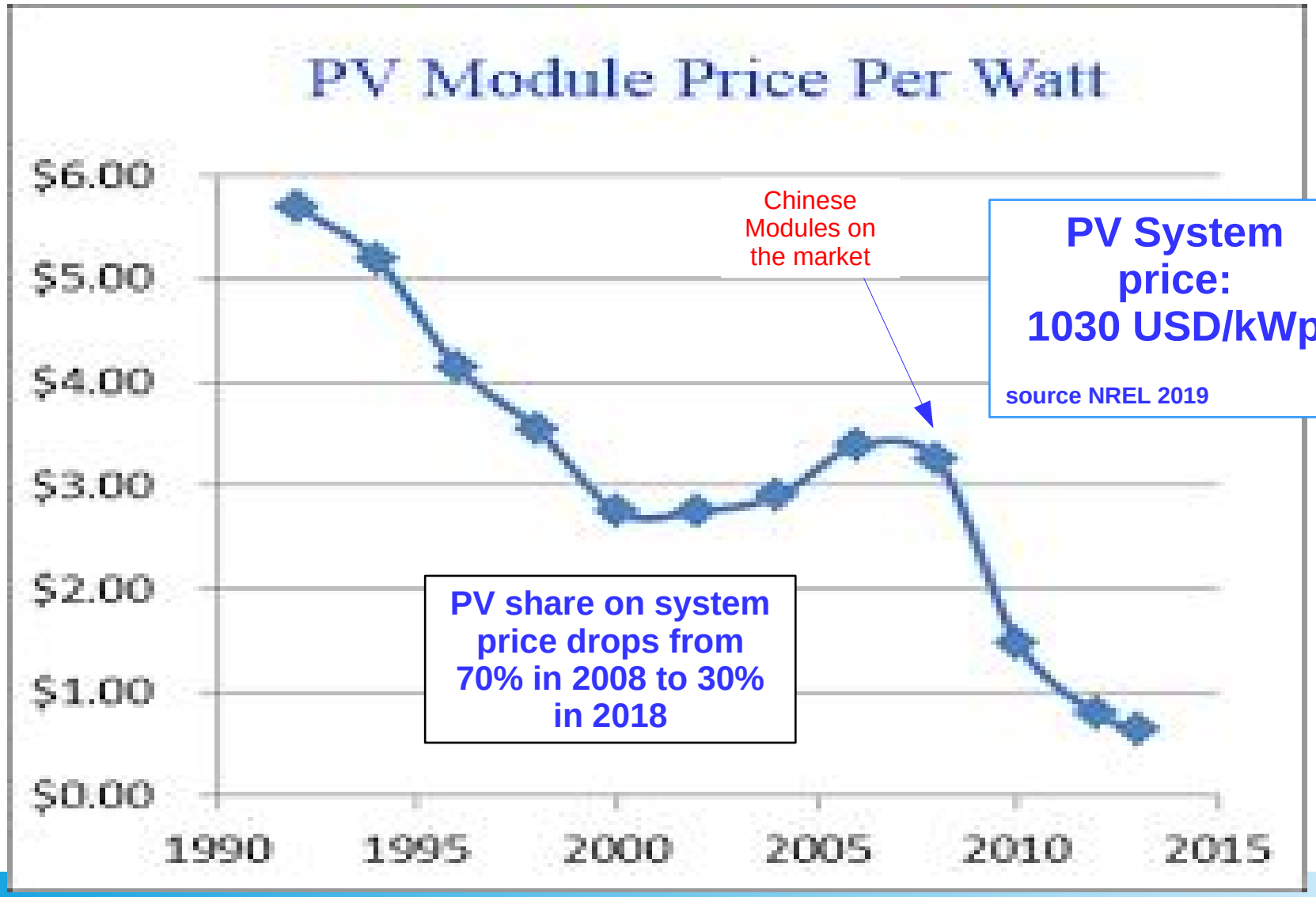
PV development



PV module cost evolution

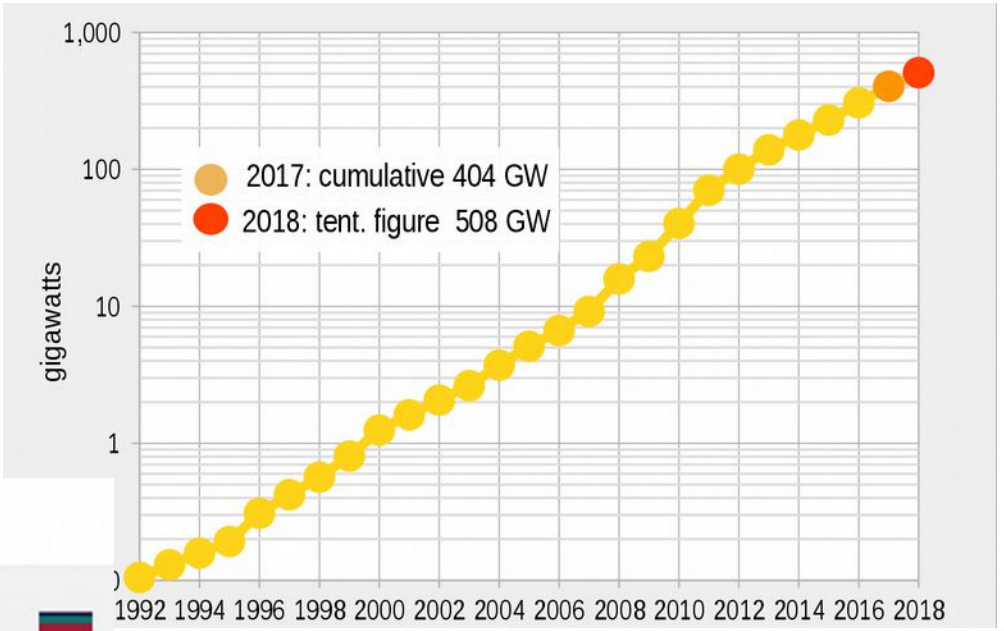


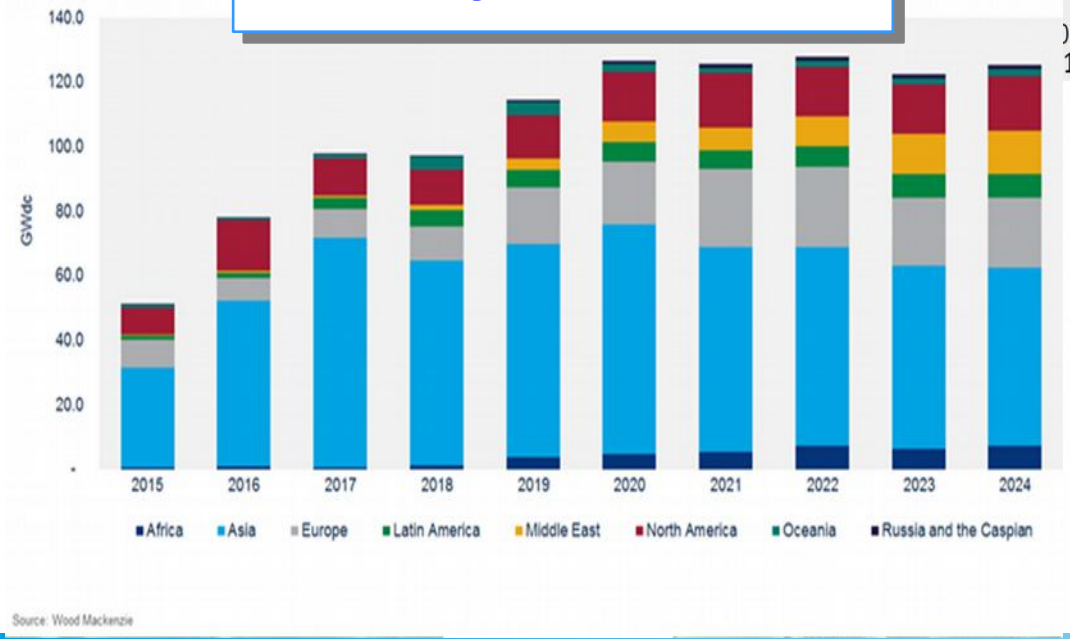
PV development

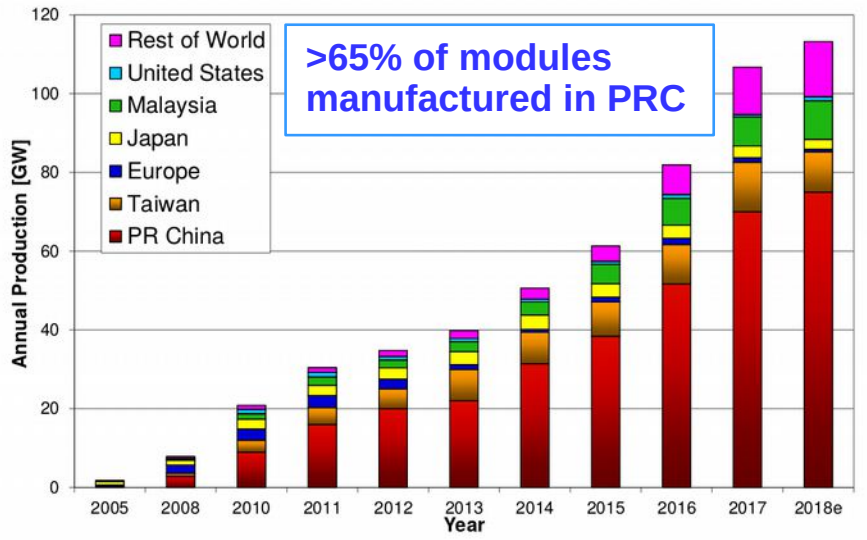
Historical data show an exponential growth of PV

In 2019 PV annual addition exceeded for the first time 100 GWe

In the next years PV is expected to increase by >100 GW/y







>65% of modules manufactured in PRC

EU-JRC pv_status_report_2018_online.pdf

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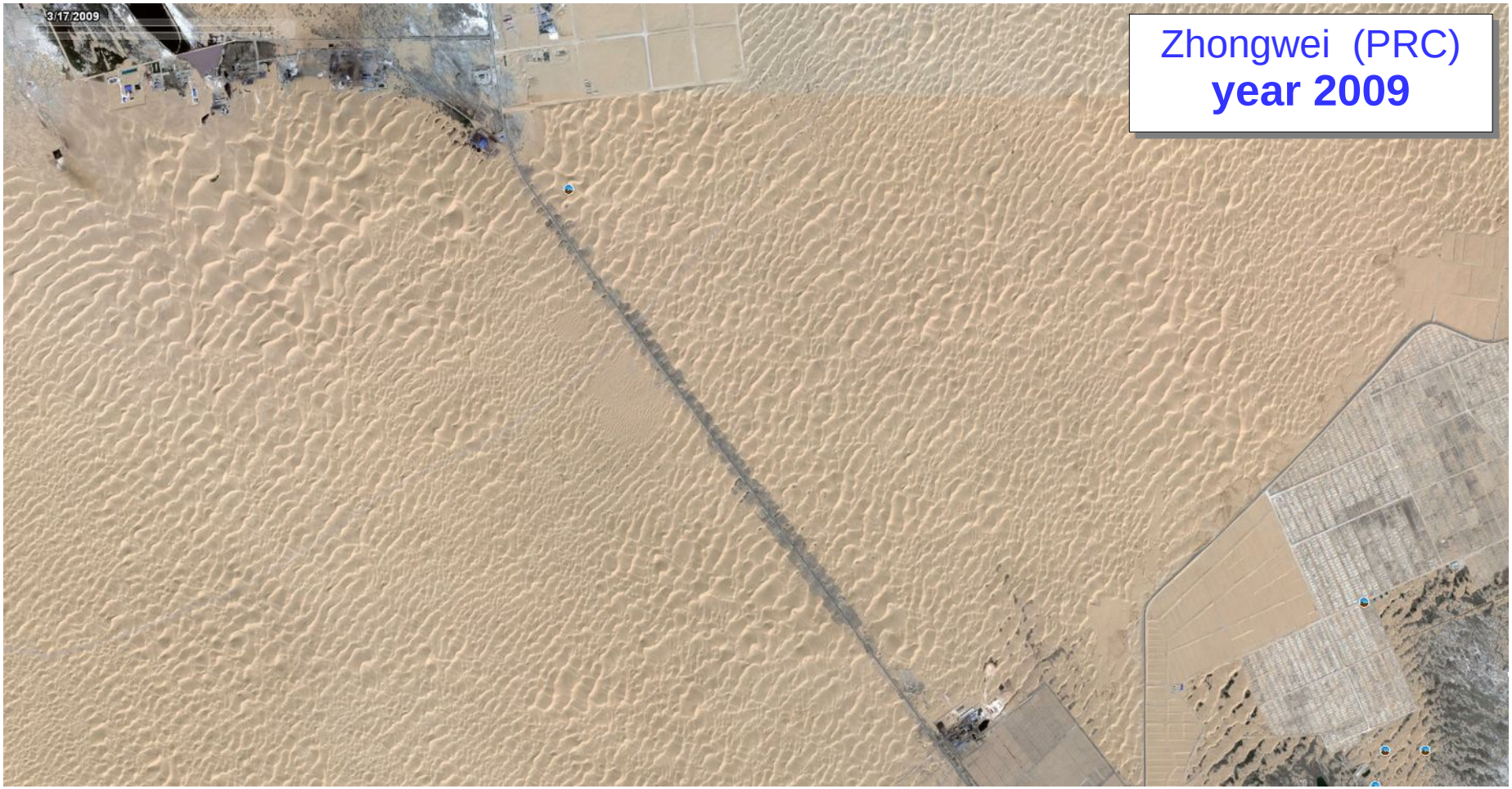
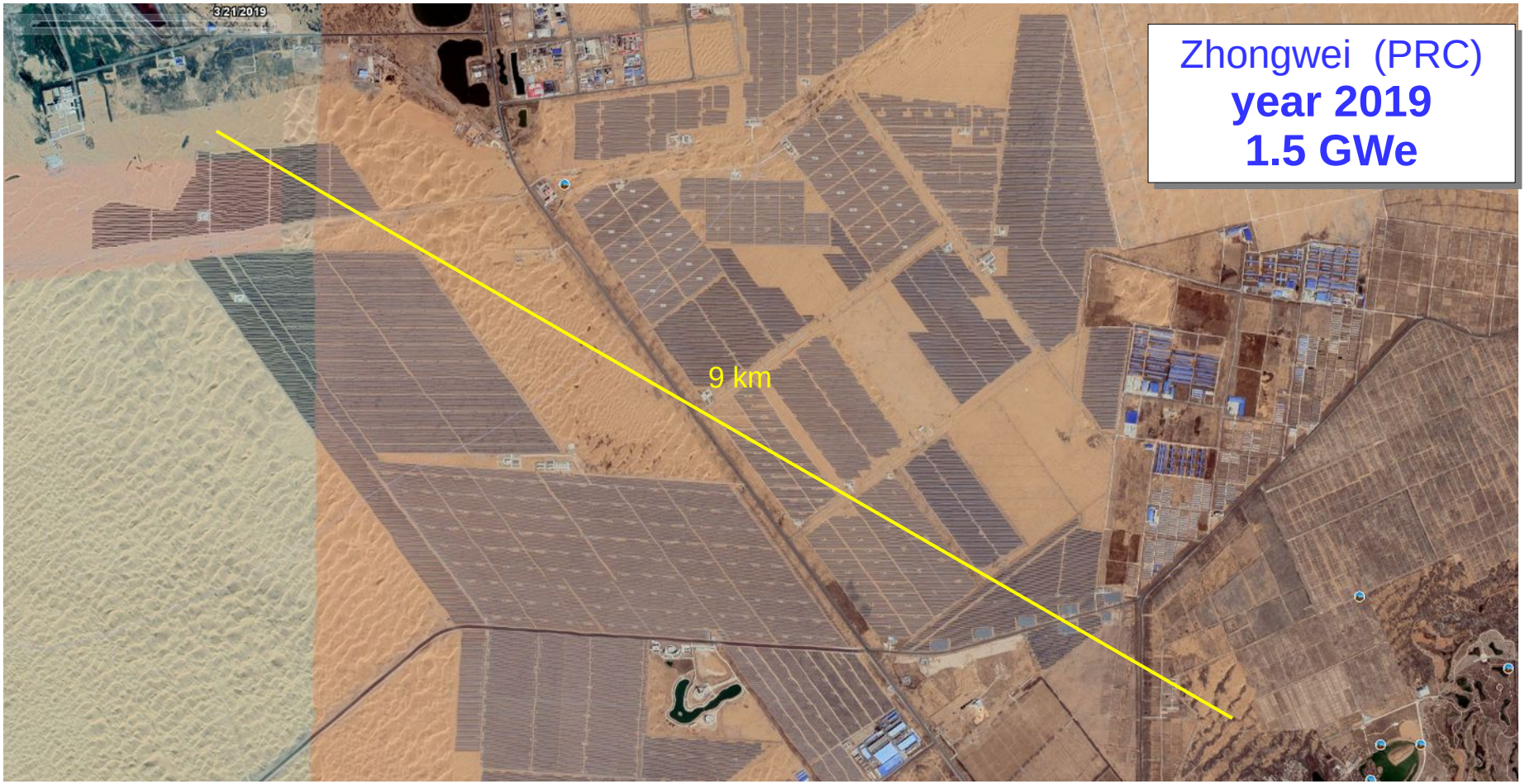
PV development



PV development



PV development

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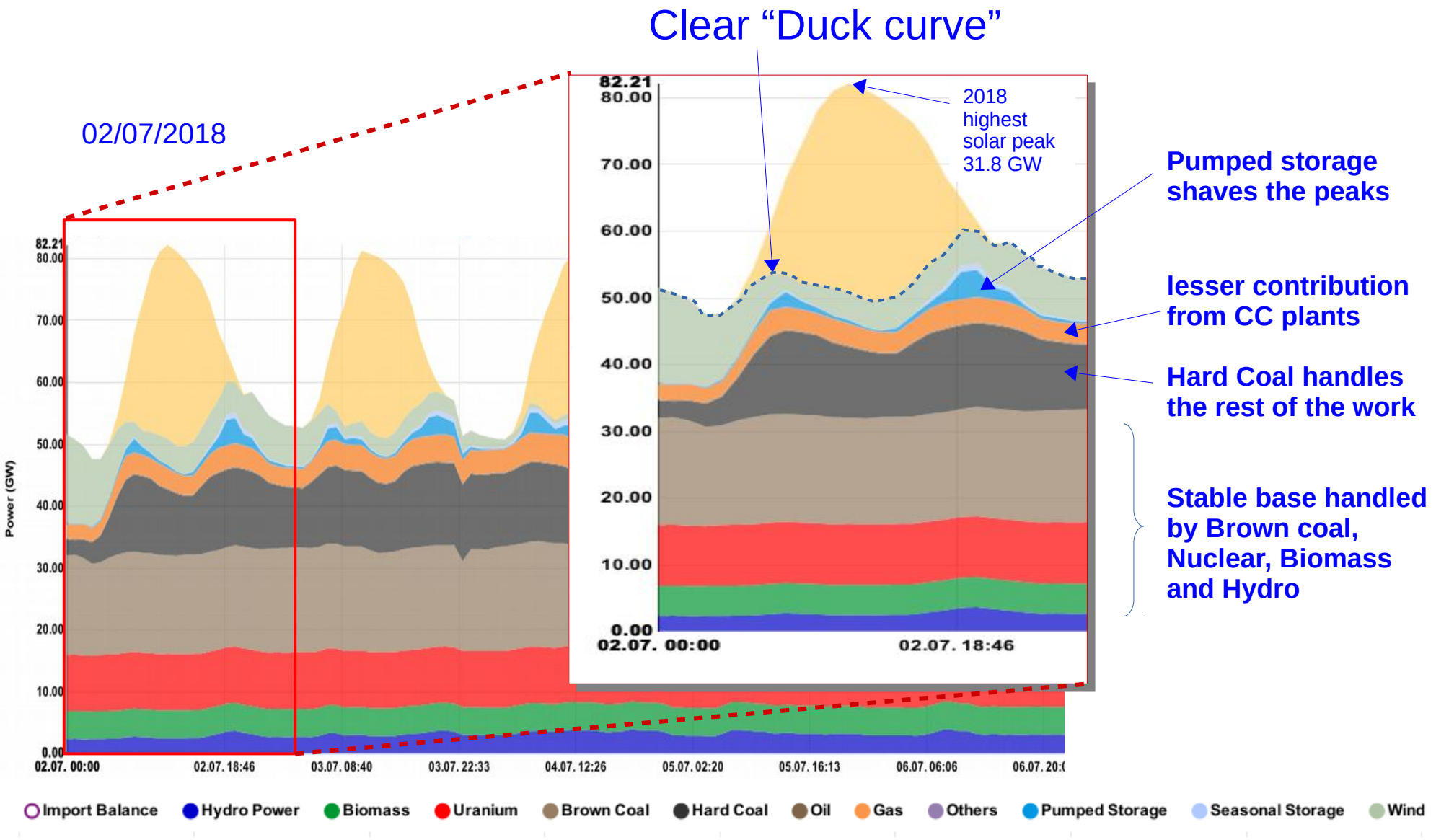
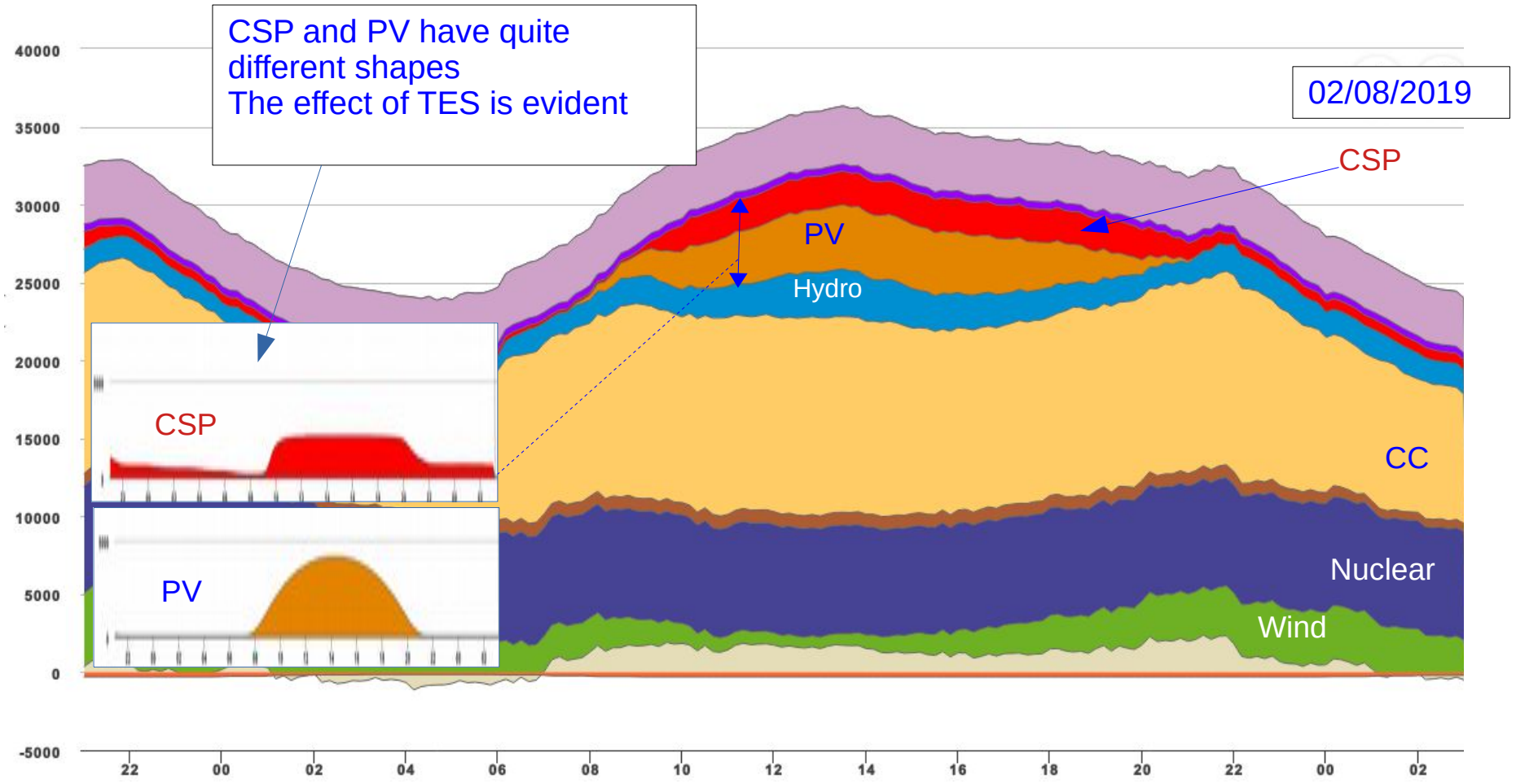
Technology Advisor

“Duck curve” in Germany



source: Fraunhofer ISE 2018
https://www.energy-charts.de/power.htm?source=all-sources&year=2018&week=27

Shaping the load
Load splitting in Spain



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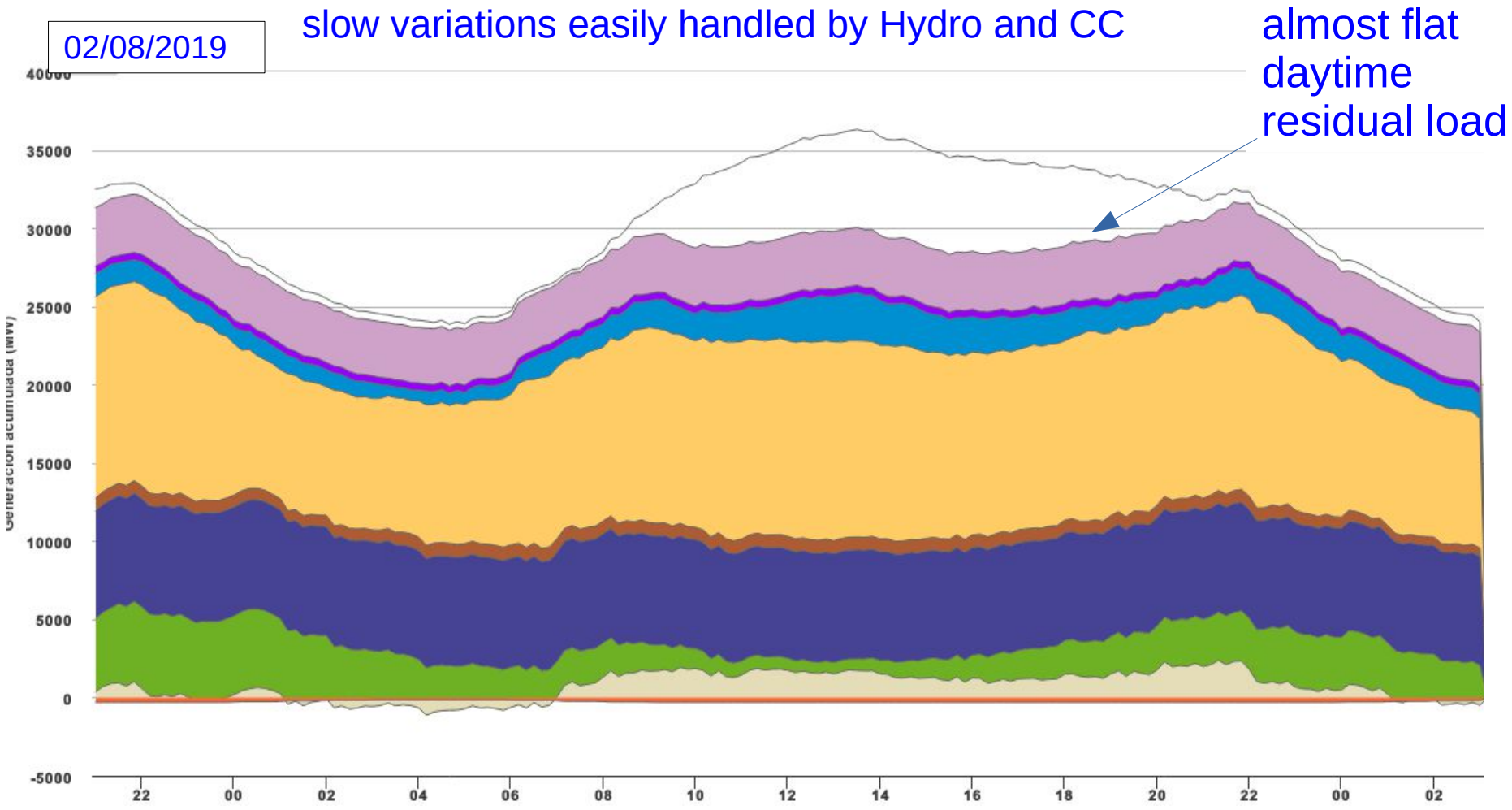
Data source: https://demanda.ree.es/visiona/peninsula/demanda/acumulada/2019-08-02

Spain grid residual load after PV & CSP removal



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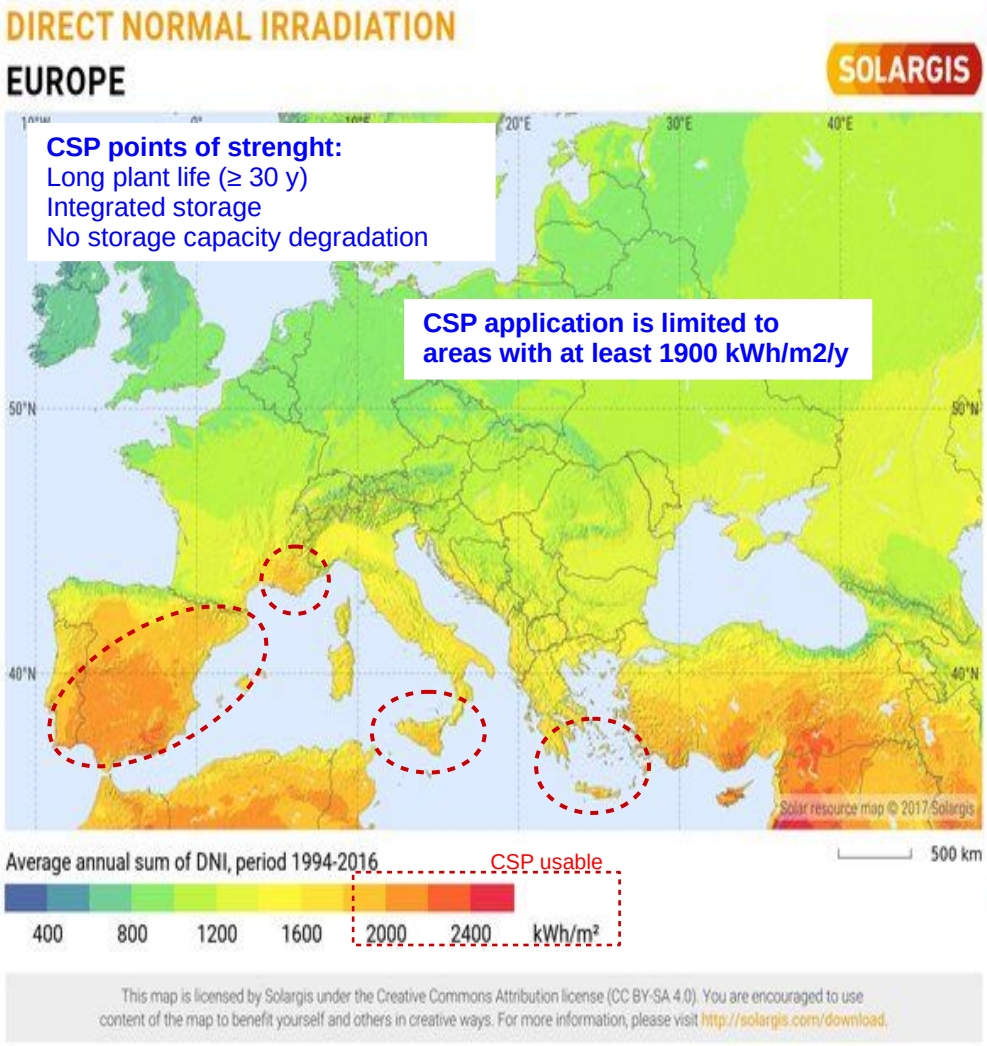
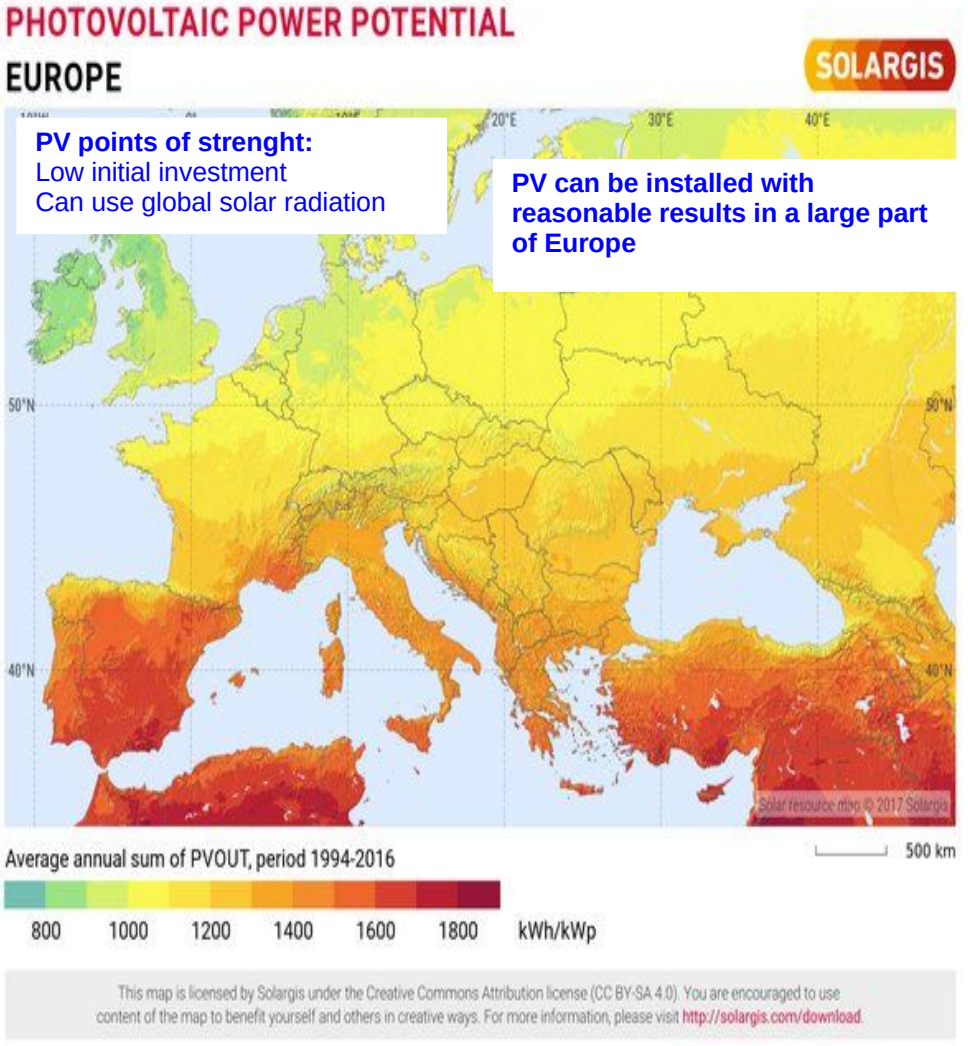
Solar resource in Europe





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Technology Advisor

Possible solutions to reduce “duck curve” effects

Method	Time frame
• Increase conventional plant flexibility	**MID TERM**
• Enhance grid interconnections	**LONG TERM**
• Increase DSM	**MID/LONG TERM**
• Increase system storage capabilities	**SHORT/MID TERM**
• **Use of CSP plant with storage for new additions** (where possible)	**SHORT TERM**

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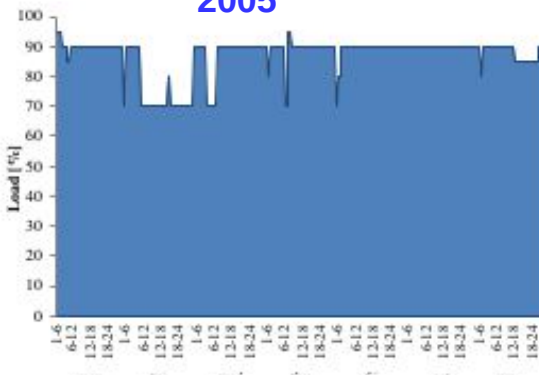
Conventional plant flexibility

CCGT example

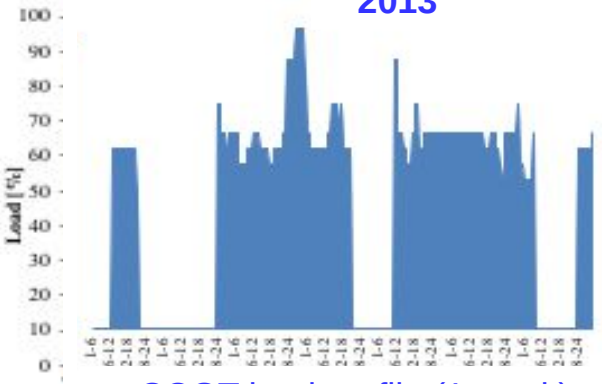
year 2005



CCGT load profile (1 week)

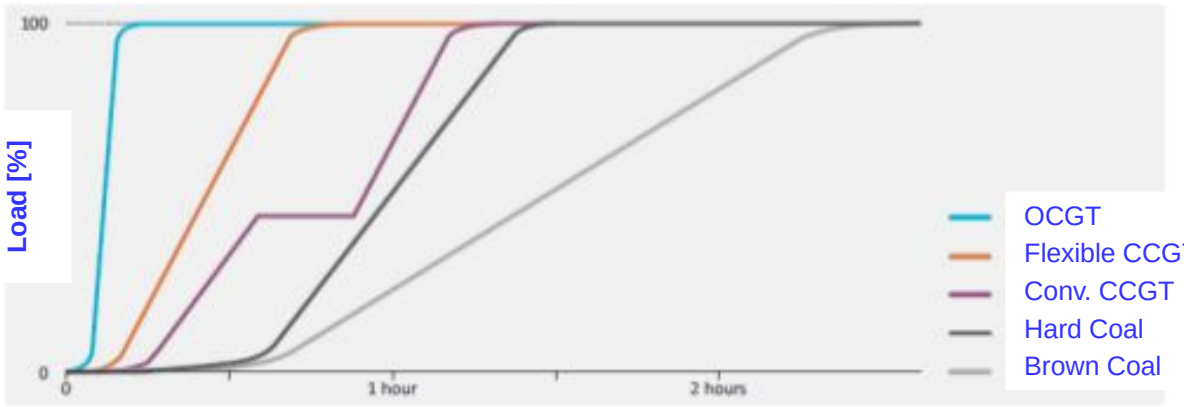
CC use shifted from baseload to modulated operation

year 2013



CCGT load profile (1 week)

BUT… Emissions increase at partial loads



Plant startup ramps

large coal units (>500 MWe) have problems with load variations

- limited load ramp (typ. 1%/min)
- high minimum load
- loss of life

Newer units designed for 120 - 200 startups/year

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Technology Advisor

Batteries

- efficient system (round trip eff. ≈85%)
- compact, modular systems
- all electronic extremely fast reactive
- standalone operation (no local operator)
- Still expensive ≈300 $/kWh(*)
- high initial investment
- periodical battery substitution to maintain efficiency
- recycling costs
- possible Lithium shortage ?

(*)Initial capital cost Source: 2018 - lazards-levelized-cost-of-storage-version-40-vfinal

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Technology Advisor

Is a PV system + batteries cheaper than CSP ?

Comparison procedure

STEPS:

- Choose a reference CSP plant
- Define an “equivalent” PV+B plant
  - Same yearly electric energy output as CSP reference
  - Same split between on-sun and off-sun energy
  - Same geographical location
- Compute the “equivalent investment” for reference CSP plant and PV+B

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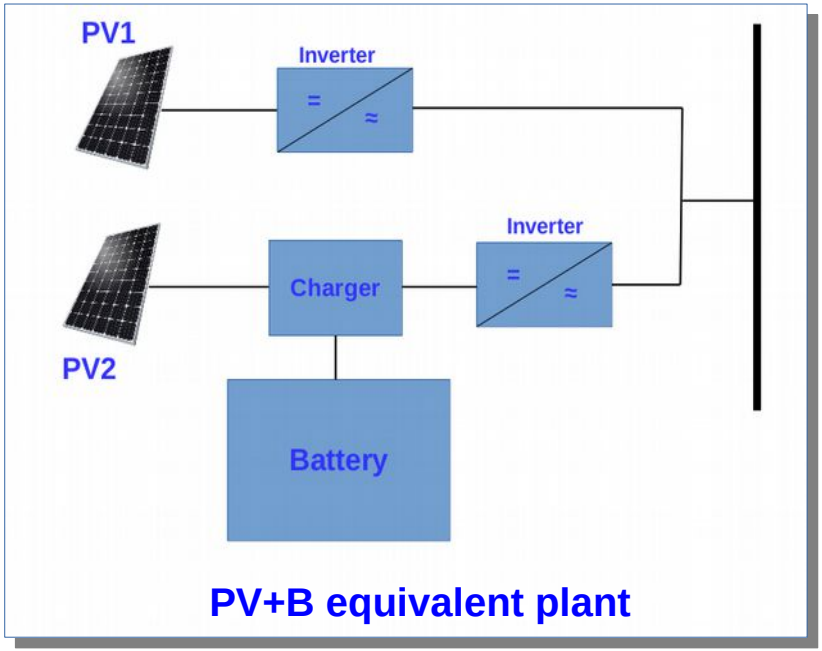
Technology Advisor

CSP vs PV+Battery Comparison



PV+B equivalent plant

PV1 : on-sun operation only
PV2 : only for battery charging (off-sun operation)

“Equivalent” means:

Same geographical location
Same storage capacity (electrical)
Same total annual energy output [MWh]
Same off-sun annual energy output [MWh]

Comparison based on on **NPV** of all life-long expenditures:

- Initial investment (incl. EPC)
- O&M
- battery replacement

Plant life:30 y

Actualization rate 5%

PV and battery system cost source:

Lazards: 2018 Levelized cost of storage version 4.0

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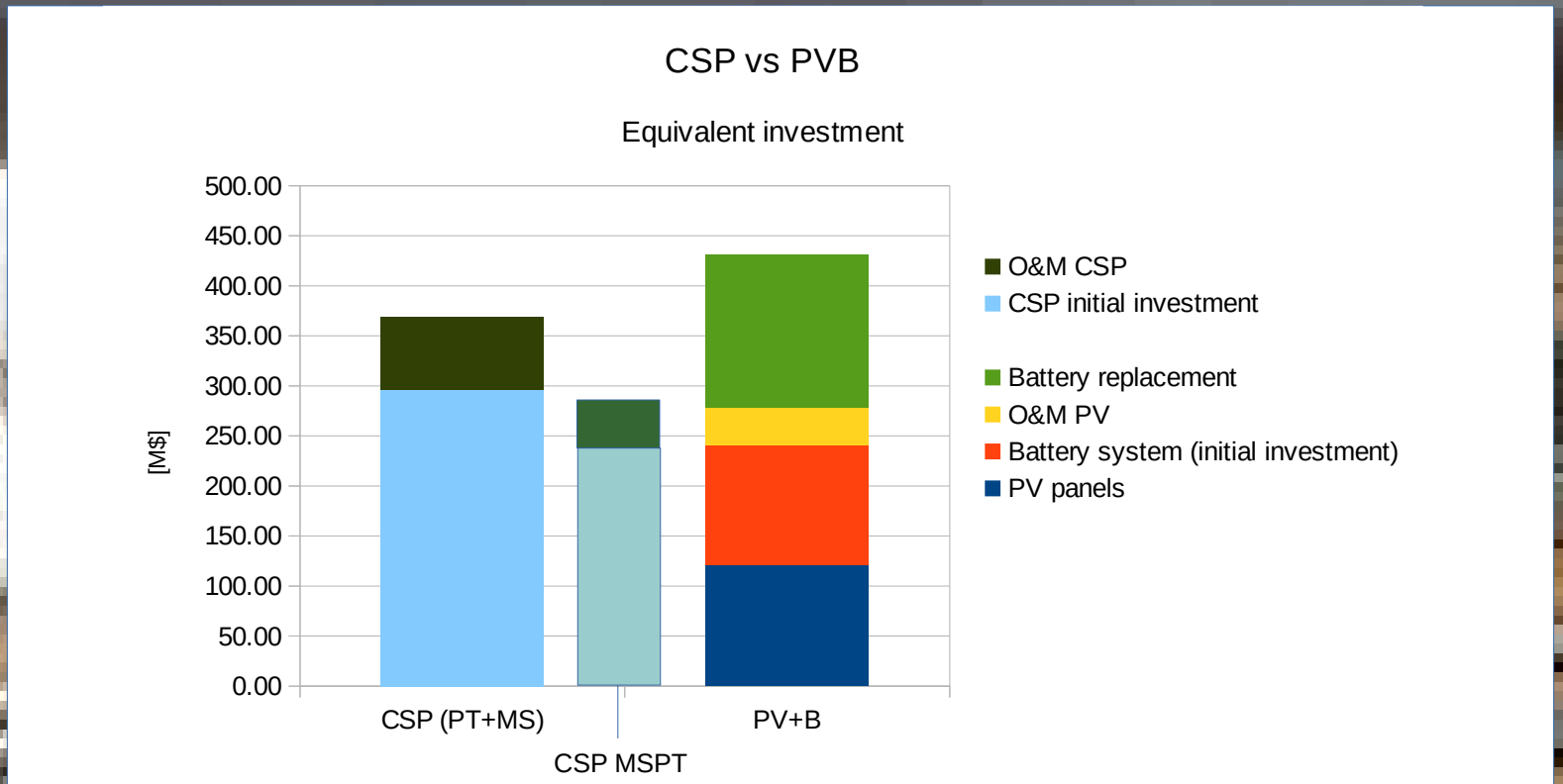
Technology Advisor

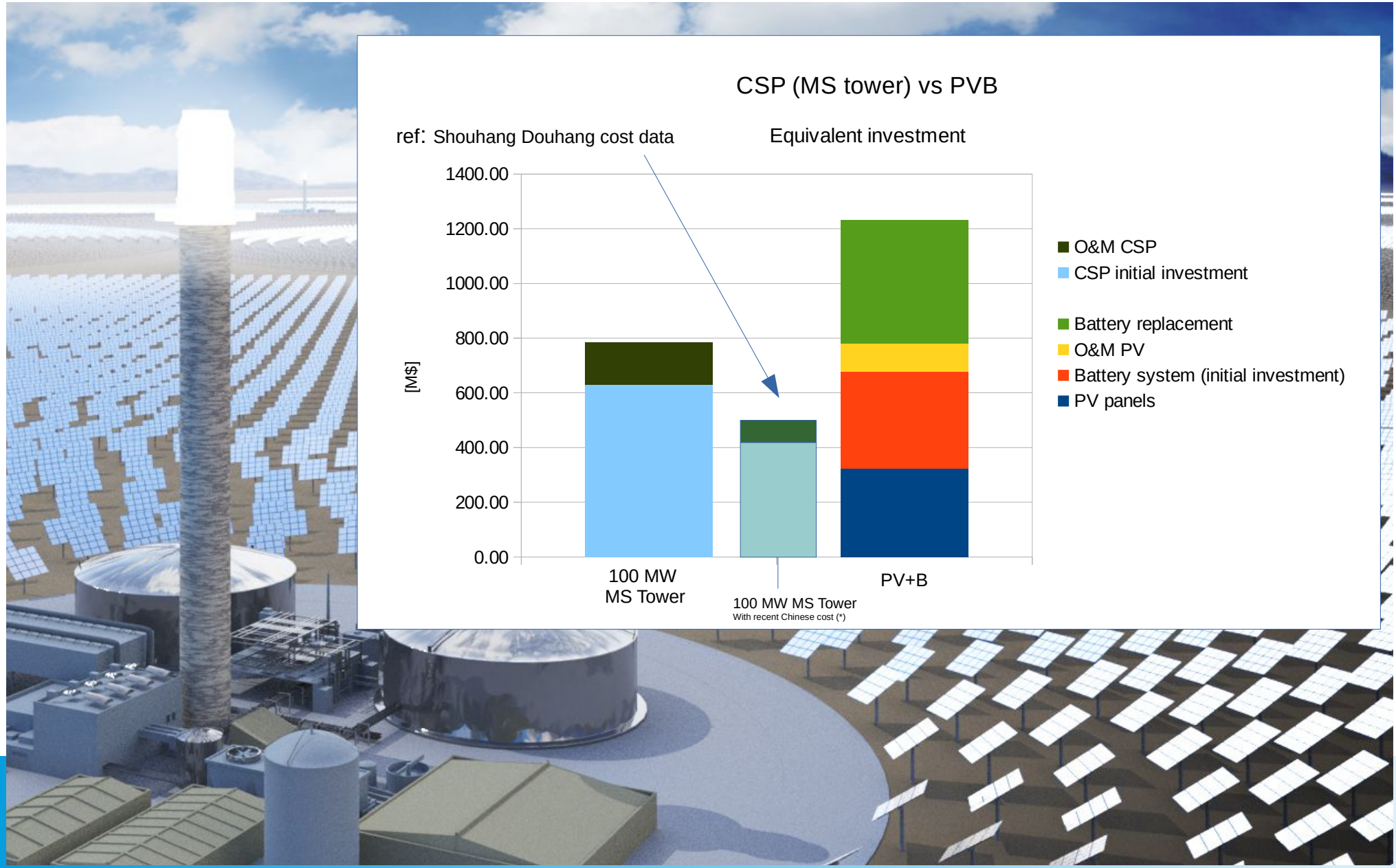
CSP vs PV+Battery

Results

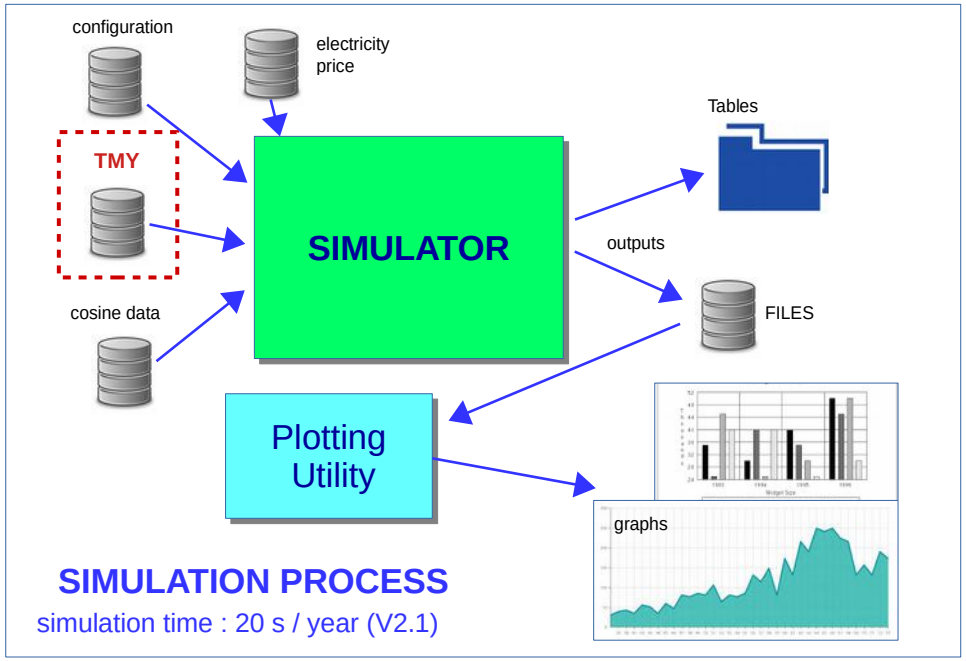


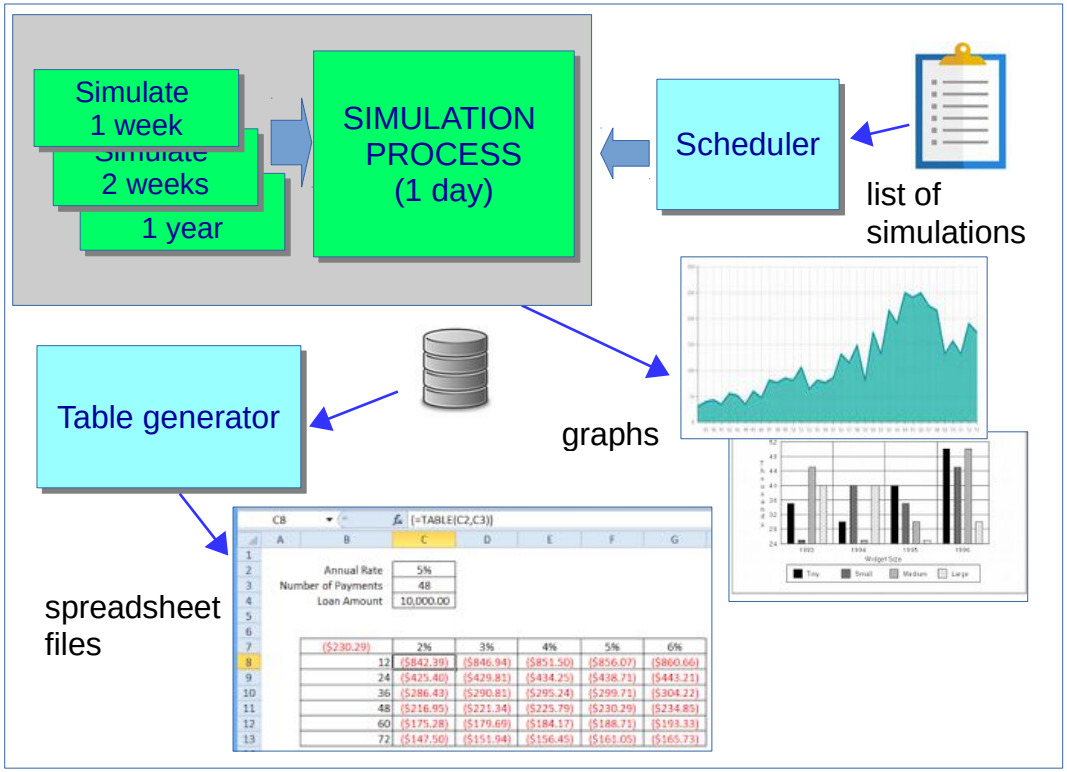
CSP vs PV+Battery

Results



CSP simulator





Specialized simulation tool:

Uses TMY files for the specific location
Simulates plants with programmable time steps
Simulates **PT, Tower, Beam down, PV with and w/o TES**
Simulates Steam turbine / ORC power blocks

Uses energy price data files to compute plant revenues

Computes economic parameters NPV,IRR,LCOE

Performs flexible multivariate programmed simulations with comparison tables and graphs

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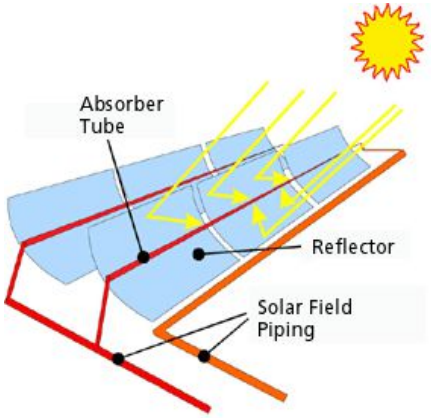
Technology Advisor

CSP thermal applications



- Water Desalination
- EOR
- Geothermal enhancement
- Brine crystallization
- Food industry
- . . . . .

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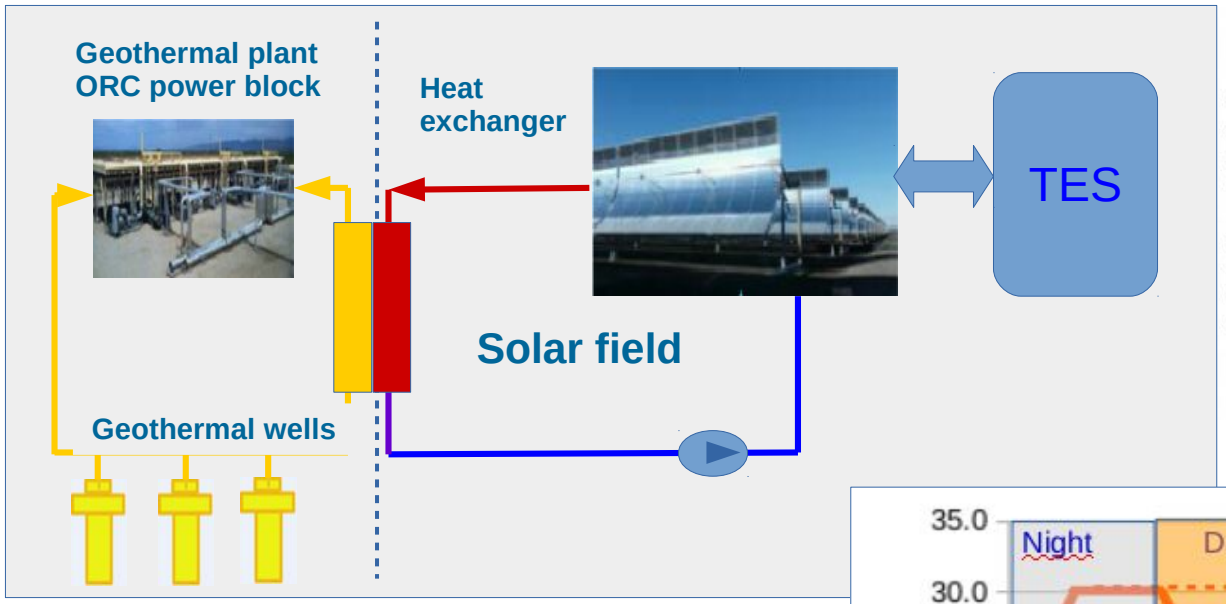
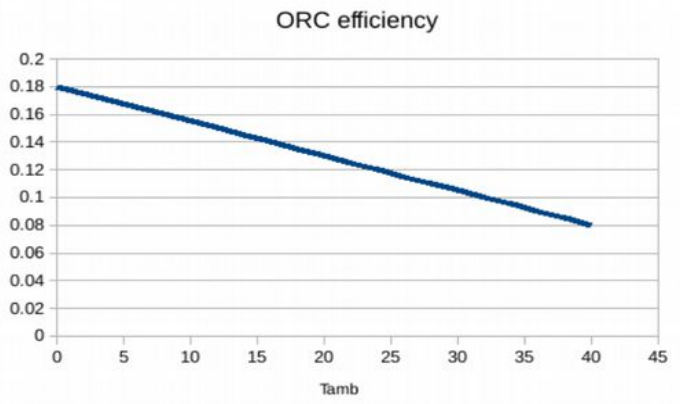
Technology Advisor

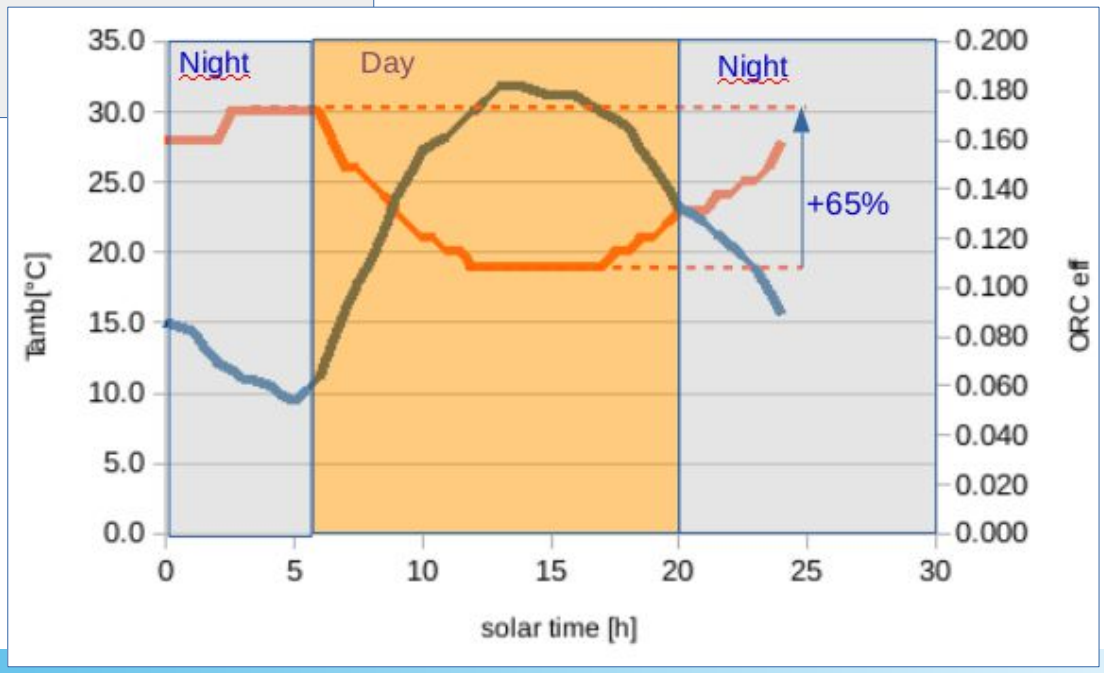
Solar/Geothermal hybrid application





Increase geothermal fluid quality
Low temperature, low cost solar field
Low cost sand or concrete TES

TES used to shift solar heat to night hours where ORC efficiency is much higher



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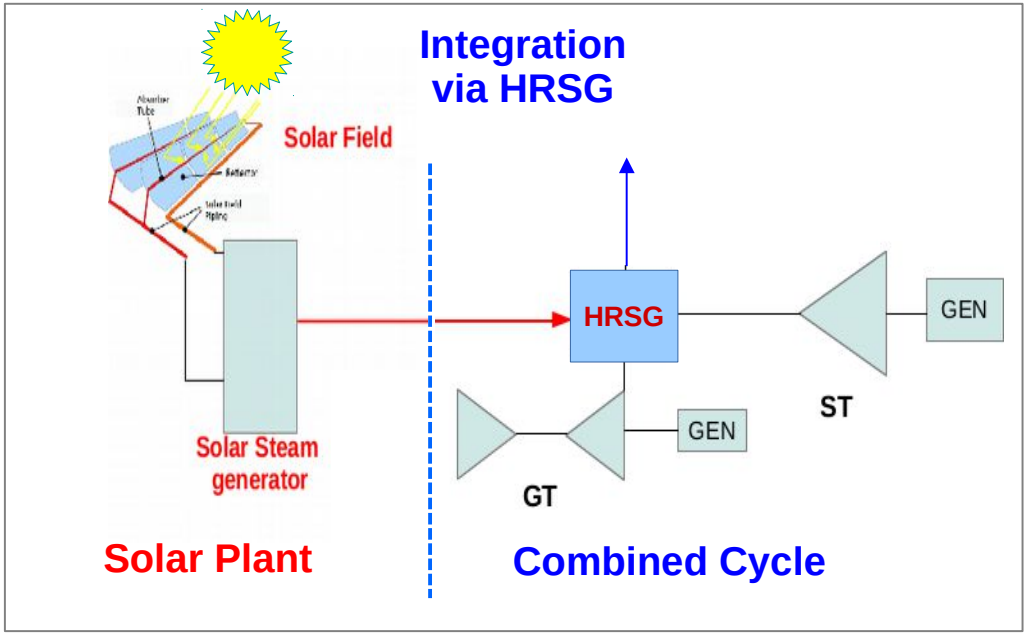
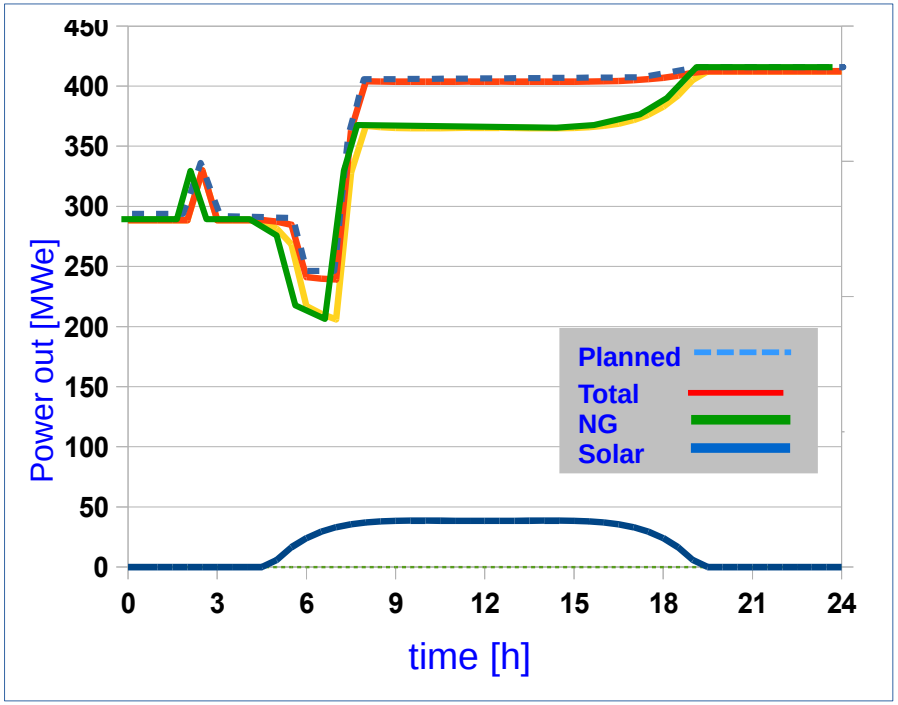
Hybrid Solar / CC Plant



Example:
C/C GE STAG109 FB (410 MWe 57%)
PT solar field: 120000 m^2
Location: Southern Spain (DNI=2200 $kWh/m^2/y$)

Hybrid plant power output



Integrates 10% el. power from solar source

High solar efficiency (41%)

Fossil fuel displaced by solar heat

Shared Steam Turbine (reduced solar investment)

It can include a TES (with a larger solar field) for increased flexibility and dispatch-ability

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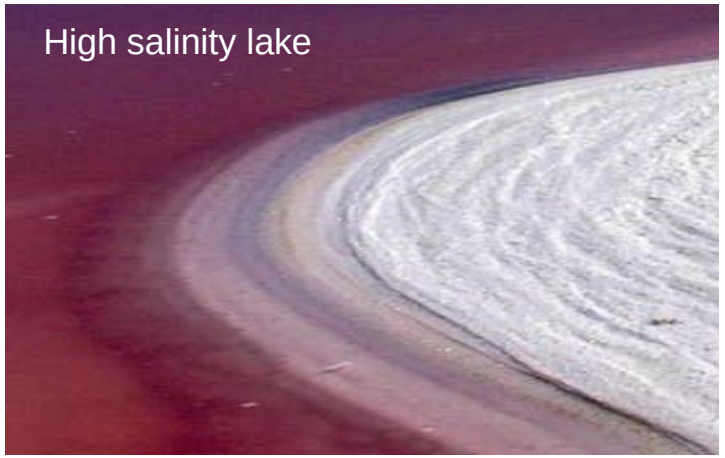
Technology Advisor

Solar assisted brine crystallization



Steam

Hot air

Electricity

Crystallization plant

Salt

Multiple CSP energy utilization

24 h capability

Suitable for isolated locations with no electric connection

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Technology Advisor

Thermal applications

Potato chips drying (Frit-o-lay) Modesto (CA)

5000 m^2
2.4 MWth
250°C
HTF: pressurized water

Guglielmo Liberati
Technology Advisor

Thank you for the attention

Guglielmo Liberati
Technology Advisor