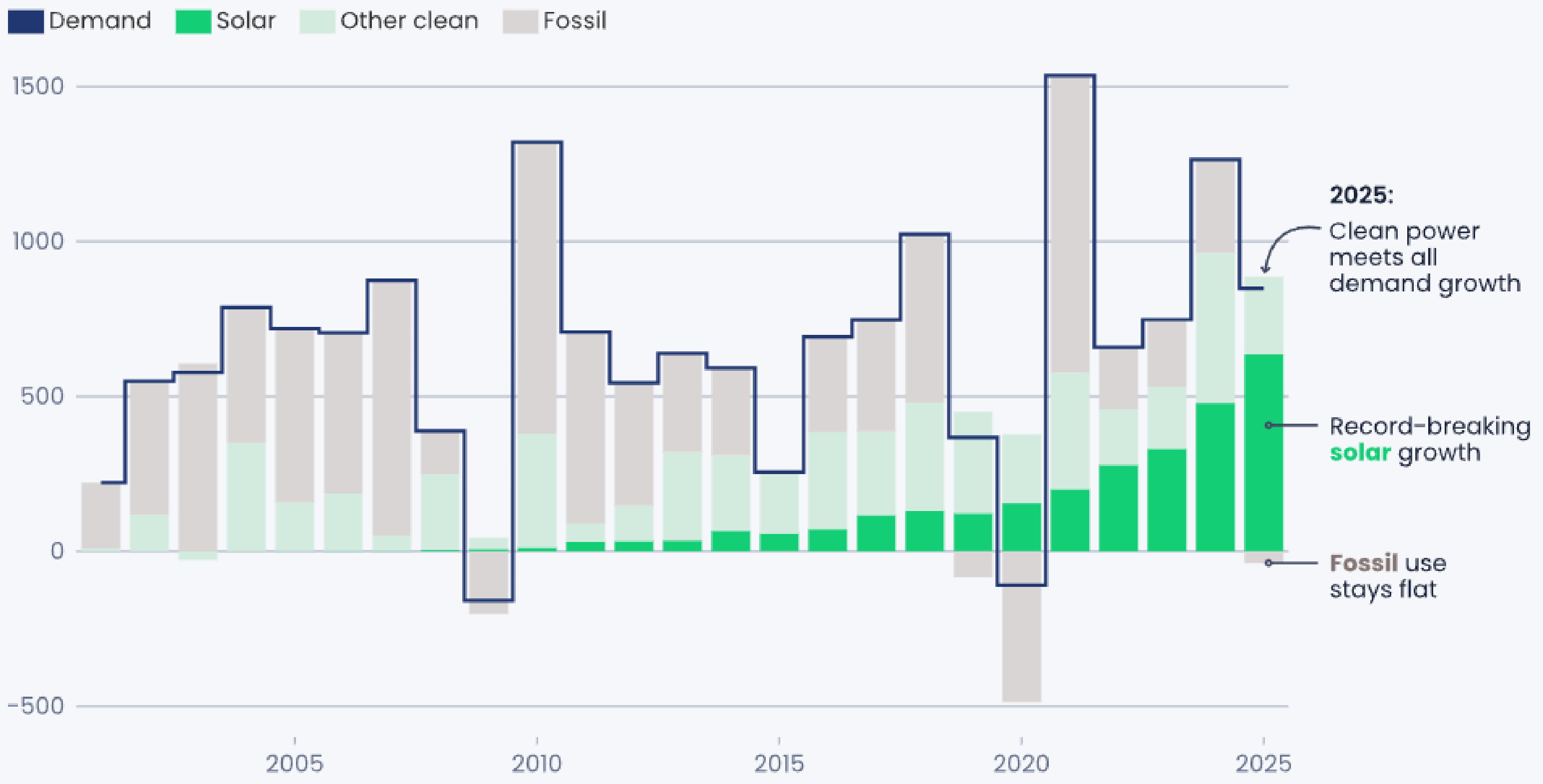
It is not the strongest of the species that survives, nor the most intelligent. It is the one that is most adaptable to change.

CHARLES DARWIN

Solar power cemented its role as the dominant driver of change in the global power sector, with its record growth meeting three-quarters of the net rise in electricity demand in 2025. Solar's rise was 18 times larger than that of gas, the only fossil fuel that increased in 2025. Global solar generation is now the same size as the total electricity demand of the EU.

## Clean power growth exceeded the rise in global electricity demand in 2025, keeping fossil generation flat

Annual change in electricity generation (TWh)




Source: Yearly electricity data, Ember • 'Other clean' includes nuclear, wind, hydro, bioenergy and other renewables such as geothermal

EMBER

98
Countries and 1 region reviewed

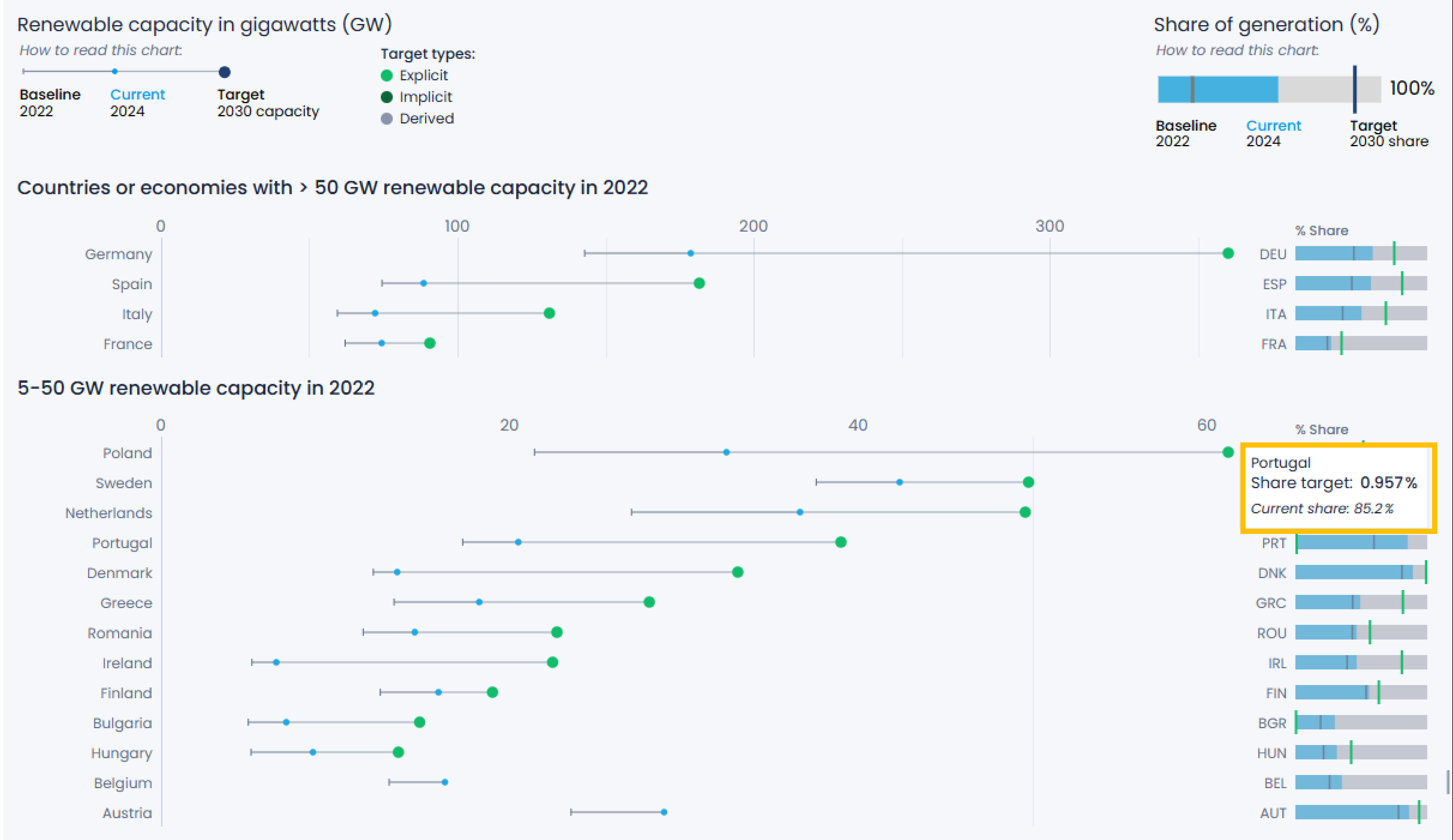
7742 GW
Estimated global 2030 renewable capacity targets

97 %
Percentage of global renewable capacity covered

# Global renewable capacity: trajectory and targets

Capacity in gigawatts (GW)

**Total capacity** | Yearly additions



Renewable capacity in gigawatts (GW)
How to read this chart:
Baseline 2022
Current 2024
Target 2030 capacity
Target types:
Explicit
Implicit
Derived
Share of generation (%)
How to read this chart:
100%
Baseline 2022
Current 2024
Target 2030 share
Countries or economies with > 50 GW renewable capacity in 2022
0
100
200
300
% Share
Germany
Spain
Italy
France
DEU
ESP
ITA
FRA
5-50 GW renewable capacity in 2022
0
20
40
60
% Share
Poland
Sweden
Netherlands
Portugal
Denmark
Greece
Romania
Ireland
Finland
Bulgaria
Hungary
Belgium
Austria
Portugal
Share target: 0.957%
Current share: 85.2%
PRT
DNK
GRC
ROU
IRL
FIN
BGR
HUN
BEL
AUT

# Portugal's existing renewable capacity vs targets

Capacity in gigawatts (GW)

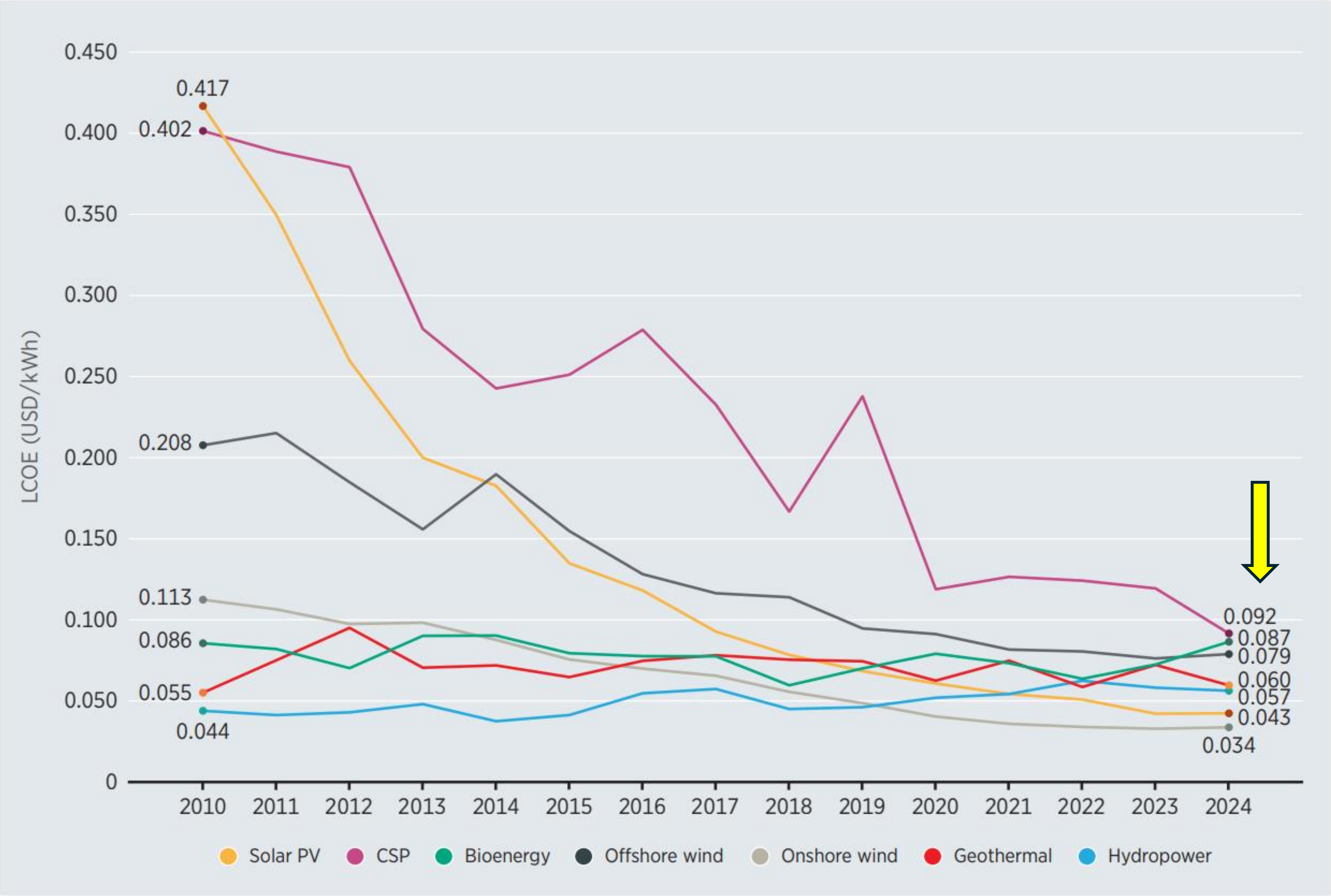
**Total capacity** Yearly additions

**Table S1** Total installed cost, capacity factor and LCOE trends by technology, 2010 and 2024

| | Total installed costs (2024 USD/kW) | | | Capacity factor (%) | | | Levelised cost of electricity (2024 USD/kWh) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2010 | 2024 | Percent change | 2010 | 2024 | Percent change | 2010 | 2024 | Percent change |
| Bioenergy | 3 082 | 3 242 | 5% | 72 | 73 | 1% | 0.086 | 0.087 | 1% |
| Geothermal | 3 083 | 4 015 | 30% | 87 | 88 | 1% | 0.055 | 0.060 | 9% |
| Hydropower | 1 494 | 2 267 | 52% | 44 | 48 | 9% | 0.044 | 0.057 | 30% |
| Solar PV | 5 283 | 691 | -87% | 15 | 17 | 13% | 0.417 | 0.043 | -90% |
| CSP | 10 703 | 3 677 | -66% | 30 | 41 | 37% | 0.402 | 0.092 | -77% |
| Onshore wind | 2 324 | 1 041 | -55% | 27 | 34 | 26% | 0.113 | 0.034 | -70% |
| Offshore wind | 5 518 | 2 852 | -48% | 38 | 42 | 11% | 0.208 | 0.079 | -62% |

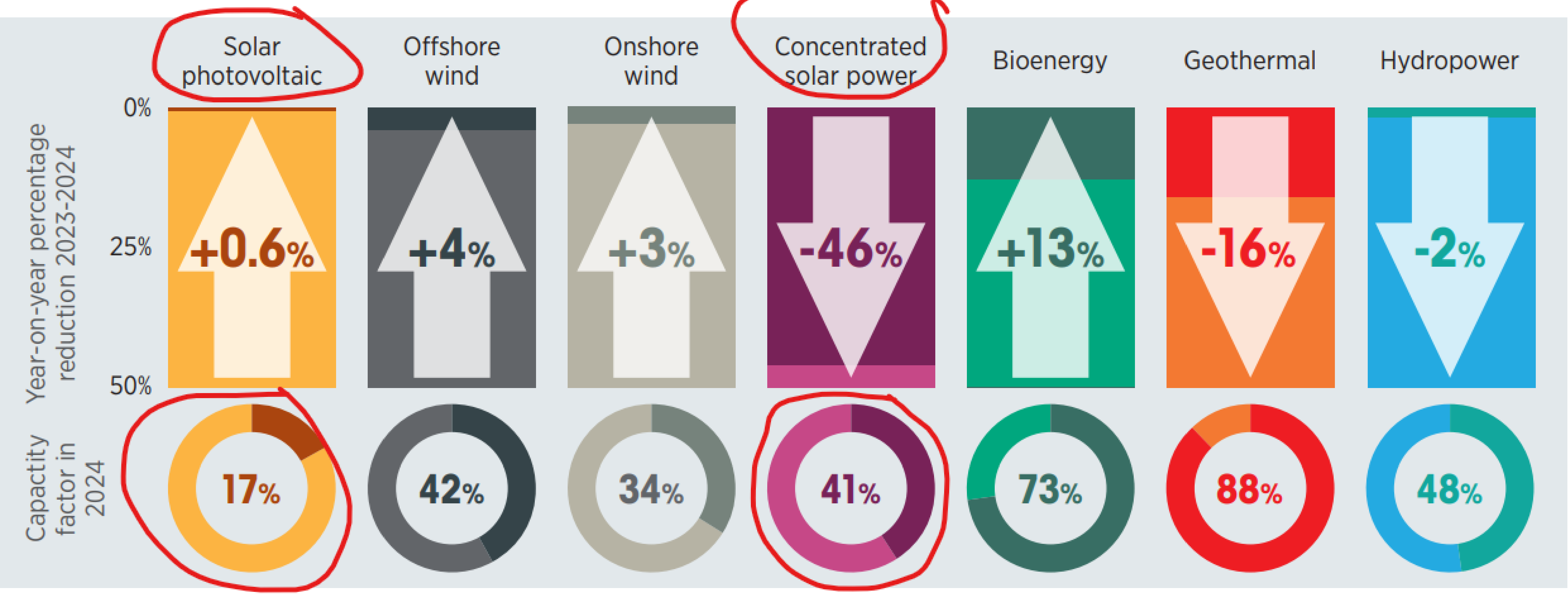
**Notes:** CSP = concentrated solar power; kW = kilowatt; kWh = kilowatt hour; USD= United States dollars.

**Figure S1** Renewable energy LCOE decline, 2010-2024



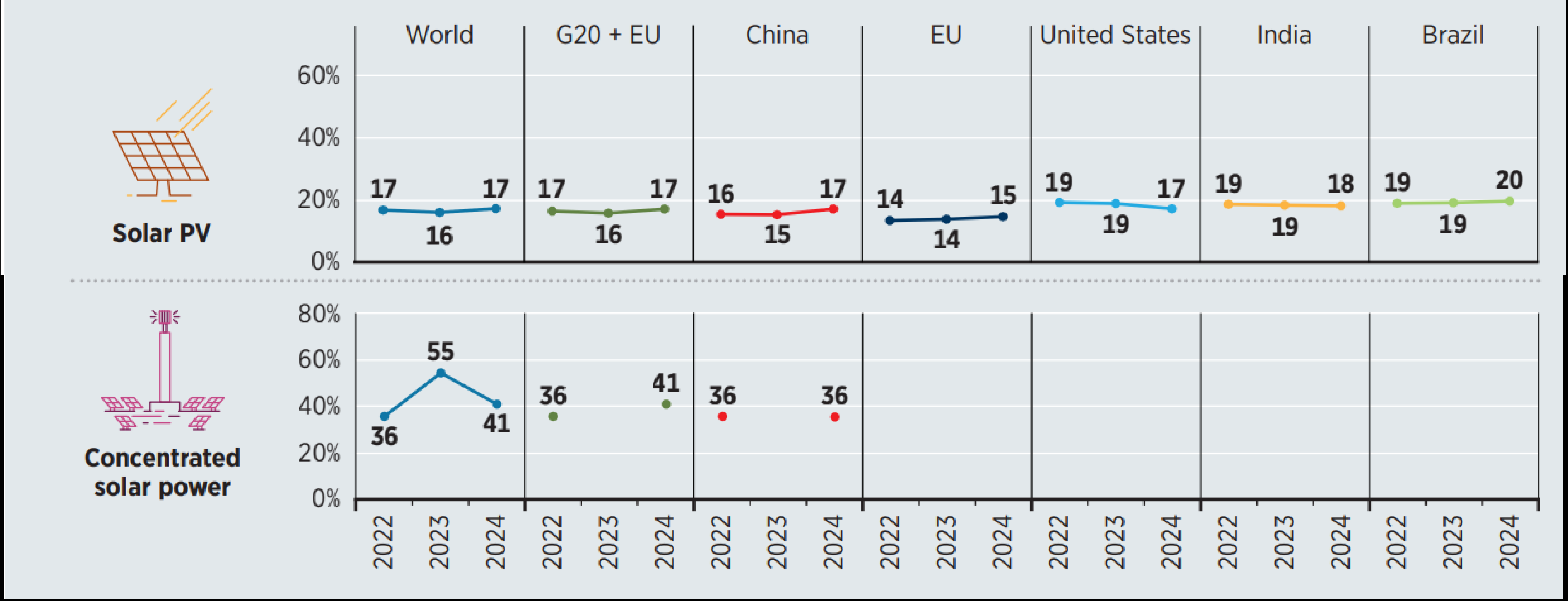

**Notes:** CSP = concentrated solar power; kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; USD = United States dollar.

**Figure S4** Global weighted-average LCOE reduction and capacity factor from newly commissioned utility-scale renewable power technologies, 2024

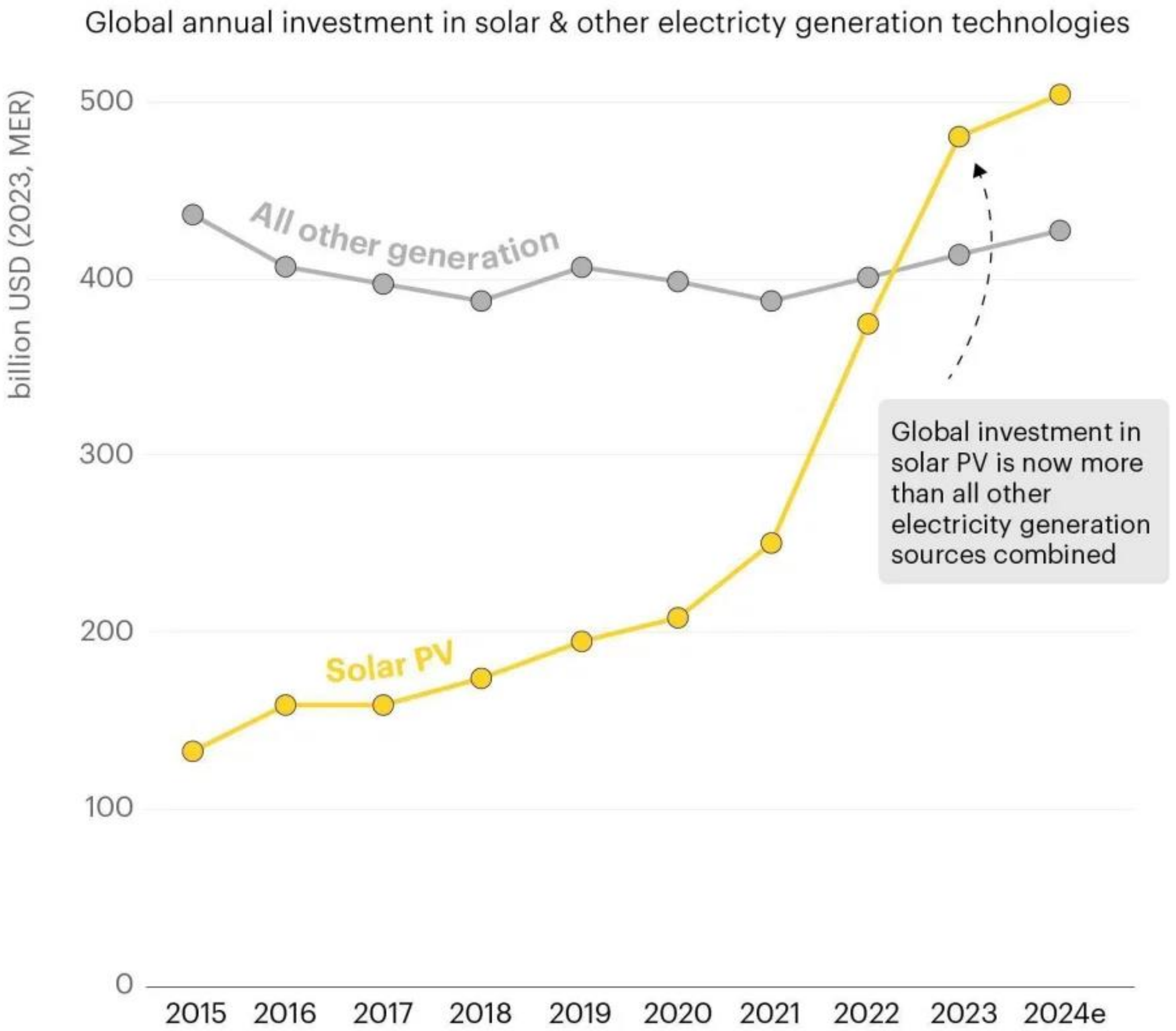



**Note:** The colour shading indicates the year-on-year percentage LCOE reduction (increase or decrease), starting from top (0%) to bottom (50%).

**Figure 1.4** Capacity factor trajectories of variable technologies in selected regions, 2022-2024



# More money is now going into solar PV than all other electricity generation technologies combined

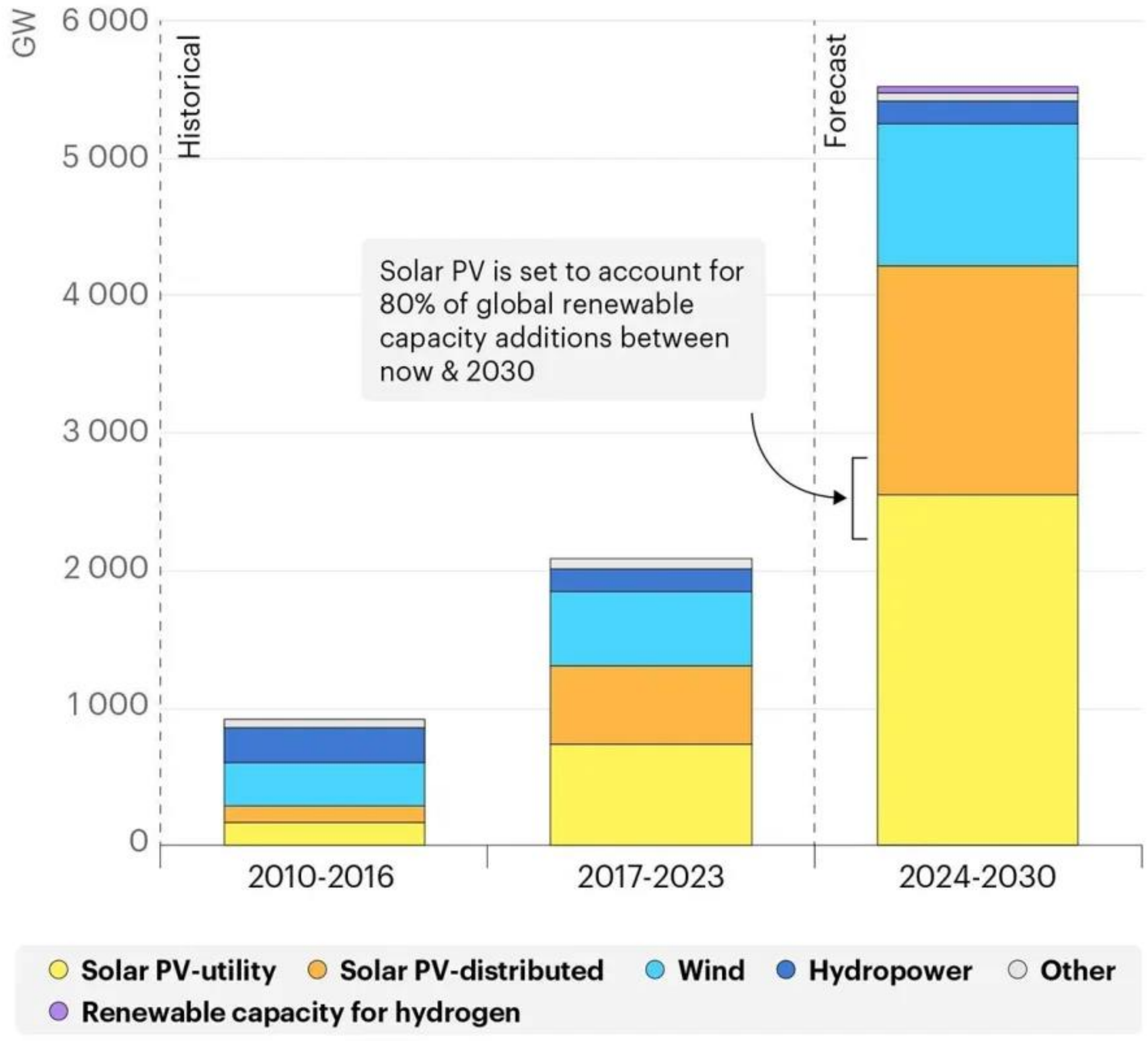



Note: e = estimate

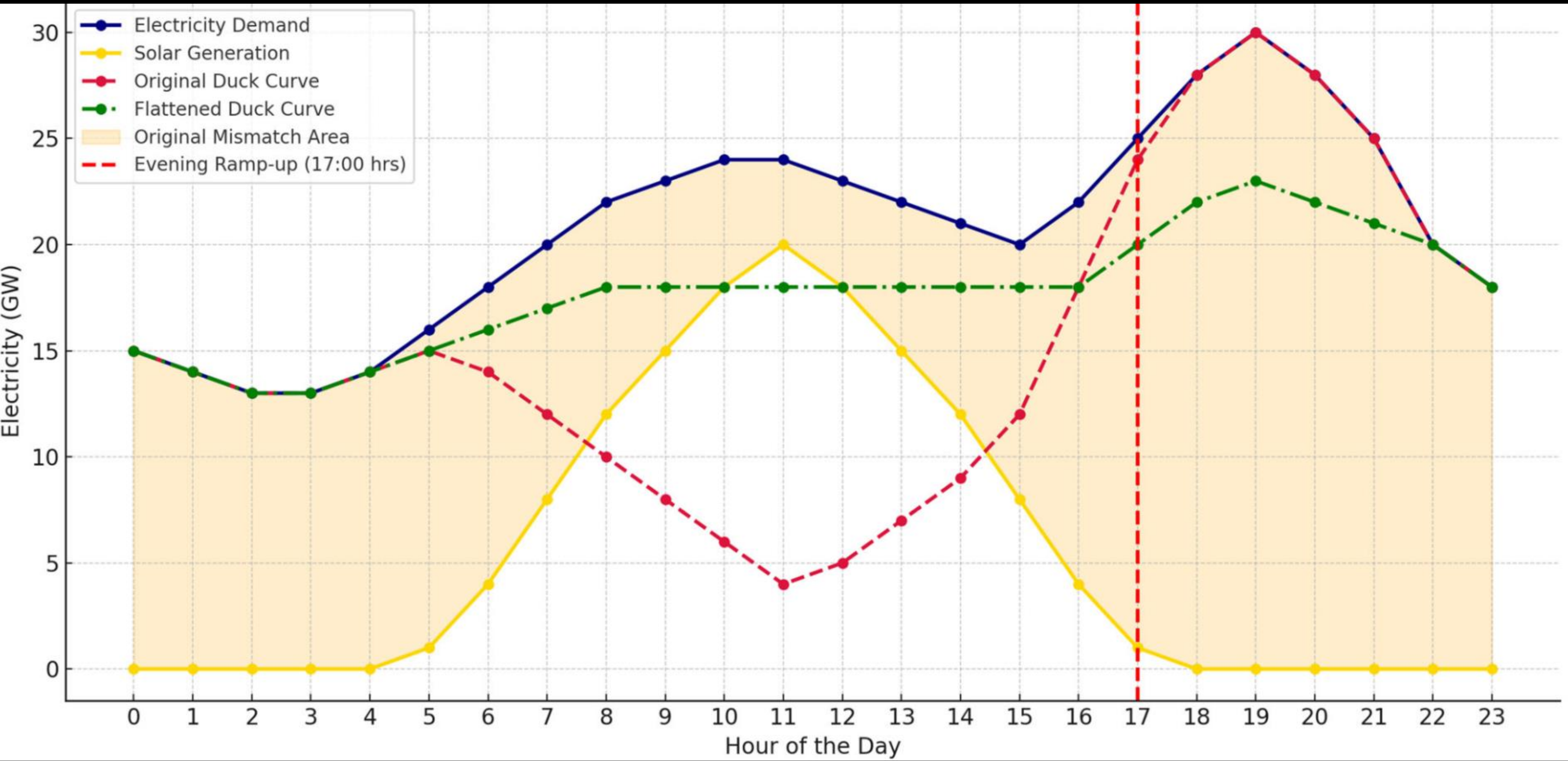
International Energy Agency

# Solar PV is set to dominate renewables' expansion between now & 2030

Renewable capacity growth by technology, historical data & main case forecast

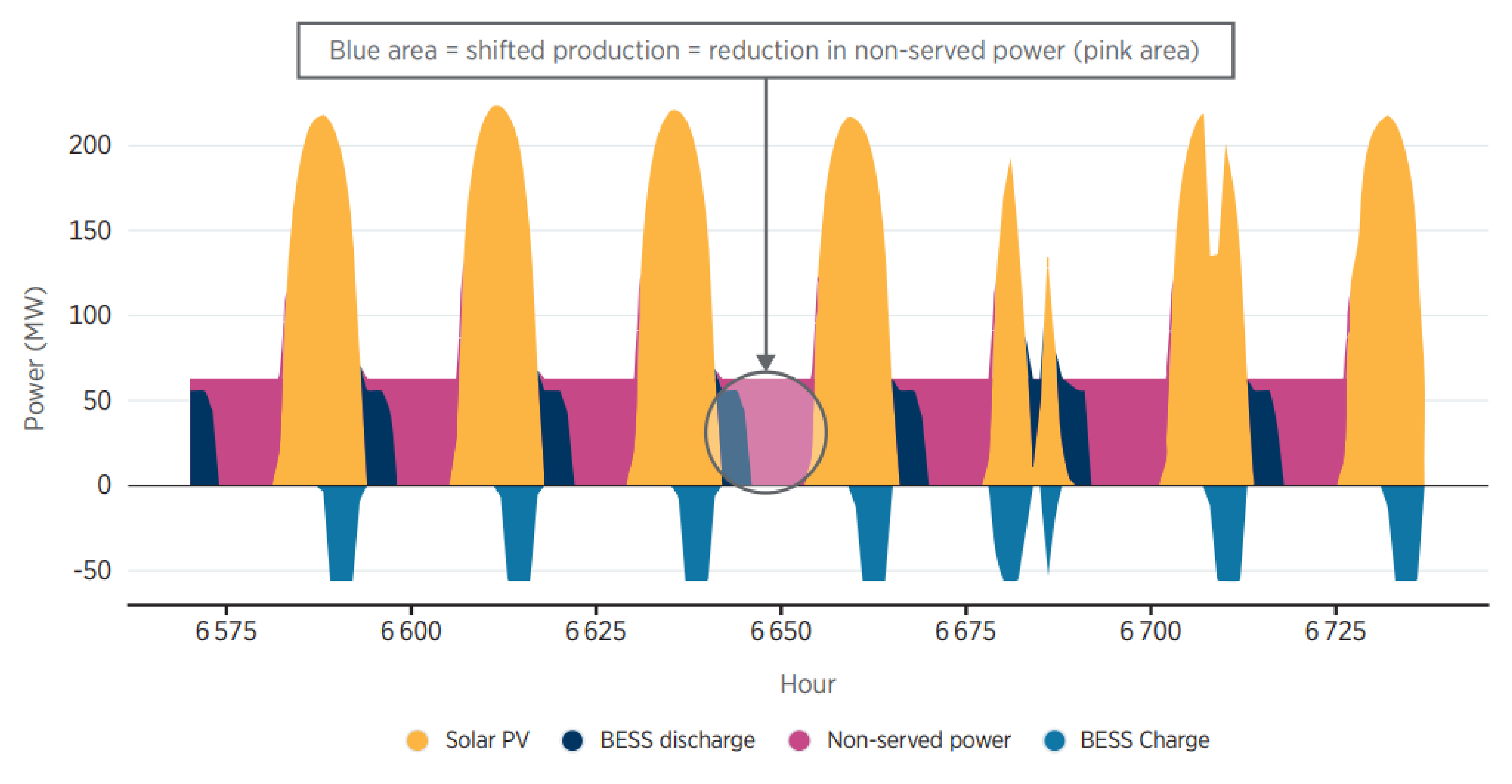



International Energy Agency



Electricity Demand
Solar Generation
Original Duck Curve
Flattened Duck Curve
Original Mismatch Area
Evening Ramp-up (17:00 hrs)
Electricity (GW)
Hour of the Day
0
5
10
15
20
25
30
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23

**Figure B1.7** Hourly output profiles of solar and batteries (illustrative calculation)



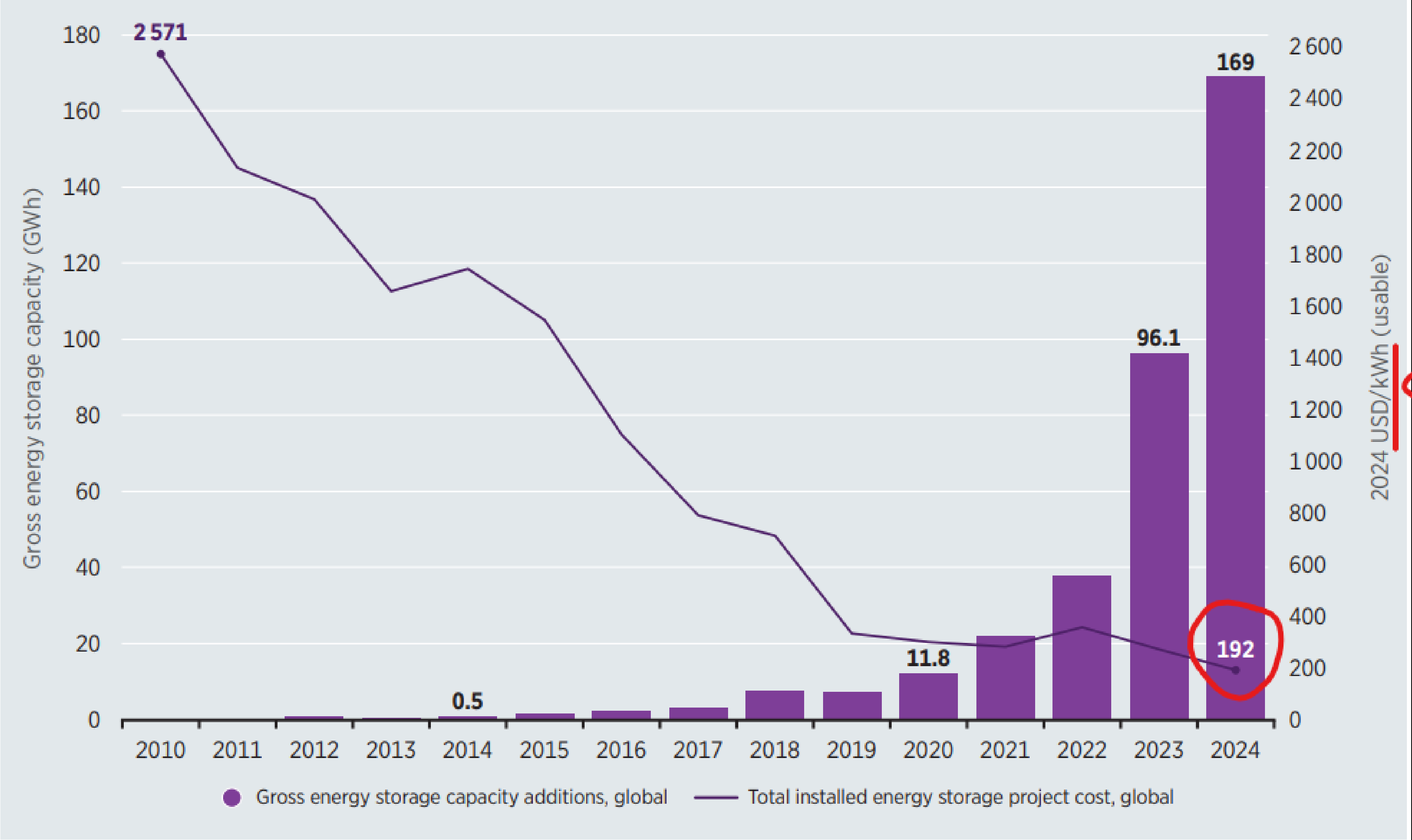

**Notes:** BESS = battery energy storage systems; MW = megawatt; PV = photovoltaic.

The effective capacity factor (ECF) is then calculated as:

ECF = CF + (reduction in non-served power − battery losses) ÷ (8 760 hours × installed capacity)

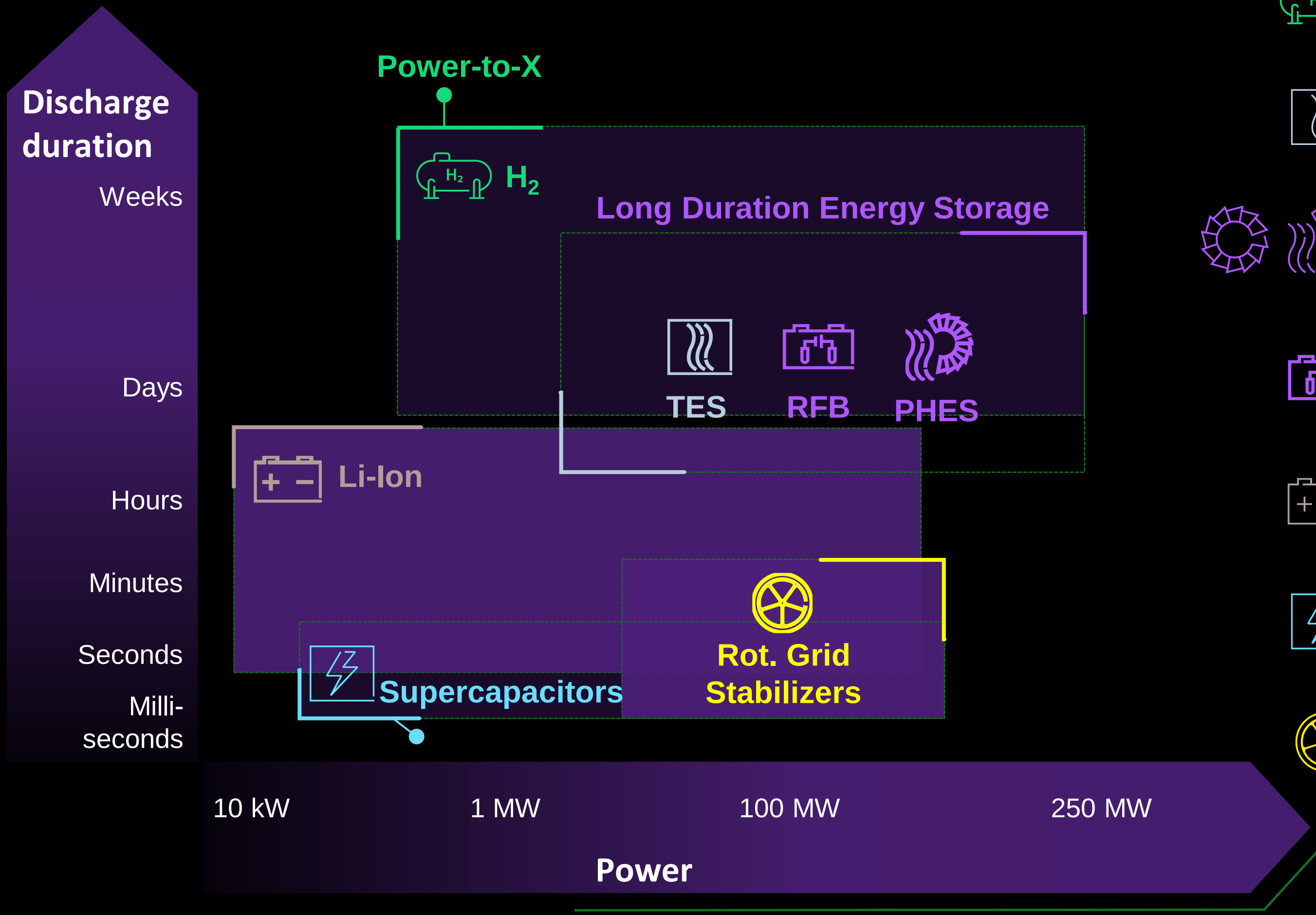
CF is the capacity factor of the VRE generator in the "without" scenario.

**Figure 9.2** Global gross battery storage capacity additions by year and total installed electricity storage project costs per kWh, 2010–2024




**Source:** (BNEF, 2024; Schmidt and Staffell, 2023).

**Notes:** Cost data from 2010 to 2015 was calculated based on the capacity, price and experience curve regression data for electrical energy storage technologies model developed by Oliver Schmidt and Iain Staffell; GWh = gigawatt hour; kWh = kilowatt hour; USD = United States dollar.




Long-term storage based on **hydrogen** and Synfuels enables the coupling of all sectors of the economy.

**Thermal Energy Storage - TES** enables decarbonization of industrial heat e.g., by providing high-quality process steam.

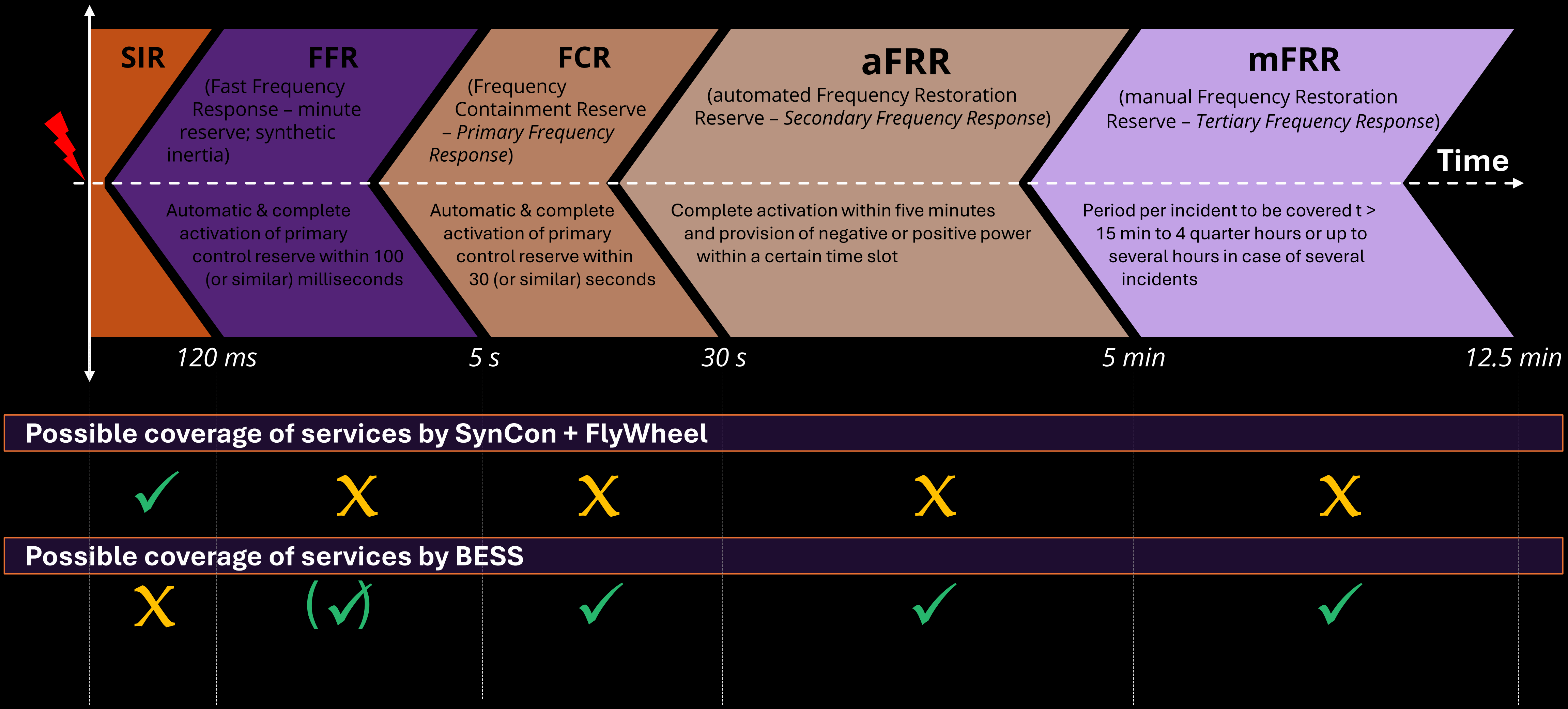
**(Thermo-) Mechanical Storage - (T)MES** stores energy when demand is low and reuses it when demand is high. It also enables renewable-firming and long-term storage.

**Redox Flow Battery (RFB)** stores energy when demand is low and reuses it when demand is high. It also enables renewable-firming and long-term storage.

**Batteries** support fast and zero-carbon energy supply, enable shifting to renewable energy and avoid curtailment.

**Supercapacitors** store electric charges with a high-power density, thus delivering quickly high energy.

**Rotating Grid Stabilizers** enable the grid to handle fluctuating renewable infeed.


SIR
FFR
(Fast Frequency Response – minute reserve; synthetic inertia)
FCR
(Frequency Containment Reserve – *Primary Frequency Response*)
aFRR
(automated Frequency Restoration Reserve – *Secondary Frequency Response*)
mFRR
(manual Frequency Restoration Reserve – *Tertiary Frequency Response*)
Time
Automatic & complete activation of primary control reserve within 100 (or similar) milliseconds
Automatic & complete activation of primary control reserve within 30 (or similar) seconds
Complete activation within five minutes and provision of negative or positive power within a certain time slot
Period per incident to be covered t > 15 min to 4 quarter hours or up to several hours in case of several incidents
*120 ms*
*5 s*
*30 s*
*5 min*
*12.5 min*
Possible coverage of services by SynCon + FlyWheel
✓ X X X X
Possible coverage of services by BESS
X (✓) ✓ ✓ ✓

# Overview products / solutions for Ancillary Services
# Frequency / power

| Service | Req. response time | Equipment (example) | |
|---|---|---|---|
| SIR | < 120 ms | • Synchronous operating equipment<br>• SynCon | • FlyWheel<br>• Grid stabilizer Package |
| FFR | 100 ms – 5 s | • Supercapacitors<br>• BESS (Li-Ion, Blue Vault)<br>• Grid Stabilizer Package | • SVC Plus FS |
| PFR | 5 s – 30 s | • BESS (Li-Ion)<br>• Mandatory hot reserve GTs & coal<br>• Pumped hydro | • Thermal storage (boiler or cooling)<br>• Renewable curtailment |
| SFR | 30 s – 10 min | • BESS (Li-Ion)<br>• Hot reserve of thermal generators<br>• Aero- and industrial gas turbines<br>• Electrolyzer & $H_2$-storage<br>• Reciprocating internal combustion engines | • Thermal storage (boiler or cooling) |
| TFR | 10 min – 30 min | • Utility gas turbines cold<br>• BESS (Li-Ion & Redox Flow)<br>• Storage | • Electrolyzer & $H_2$-storage<br>• Industrial processes |
| Re-dispatch | 15 min – 24 h | • Thermal generation i.e. SCPP, CCPP<br>• BESS (Li-Ion & Redox Flow) for < 4 h<br>• Electrolyzer & $H_2$-storage | |

SIR – Synchronous Inertial Response
FFR – Fast Frequency Reserve
PFR – Primary Frequency Response
SFR – Secondary Frequency Response
TFR – Tertiary Frequency Response

**SHANNONBRIDGE B**
**SYNCHRONOUS CONDENSER AND BESS**

Synchronous condenser, including the flywheel
4000MWs of Inertia + 160 MWh

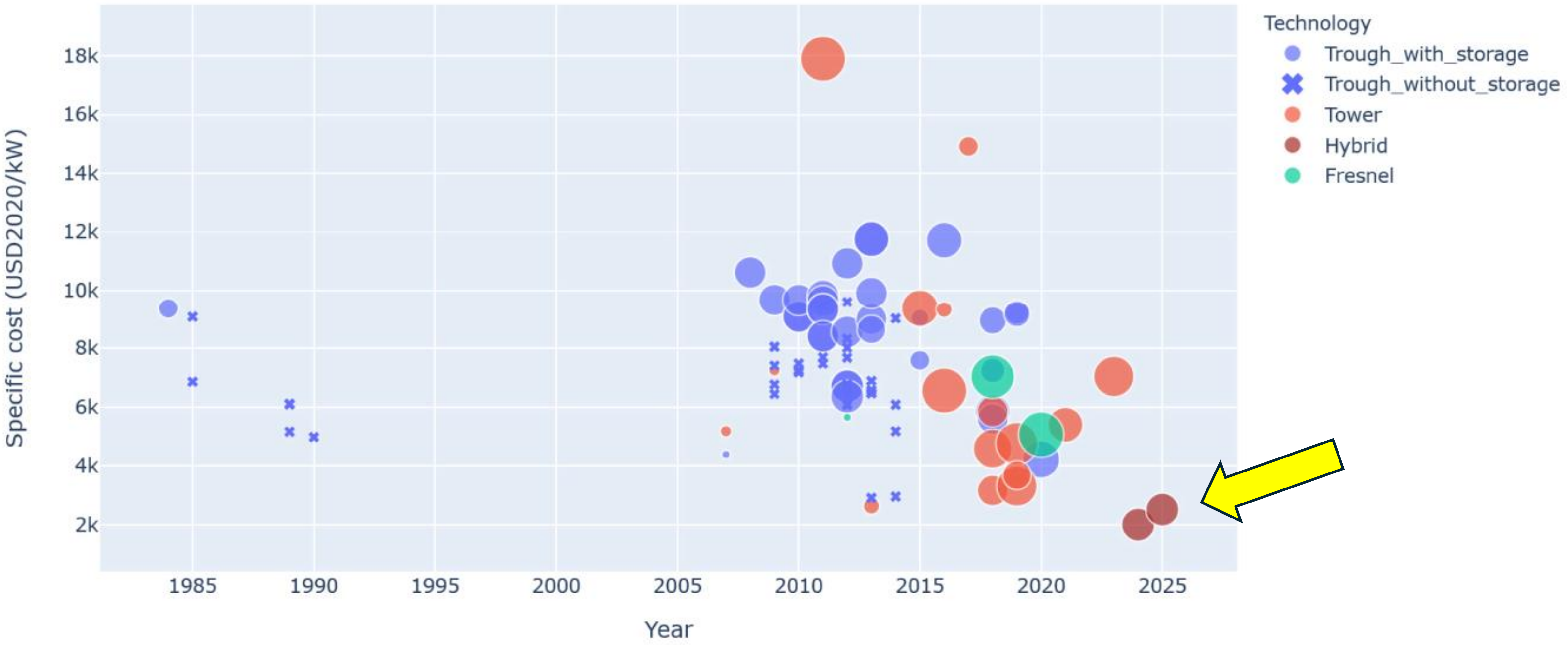
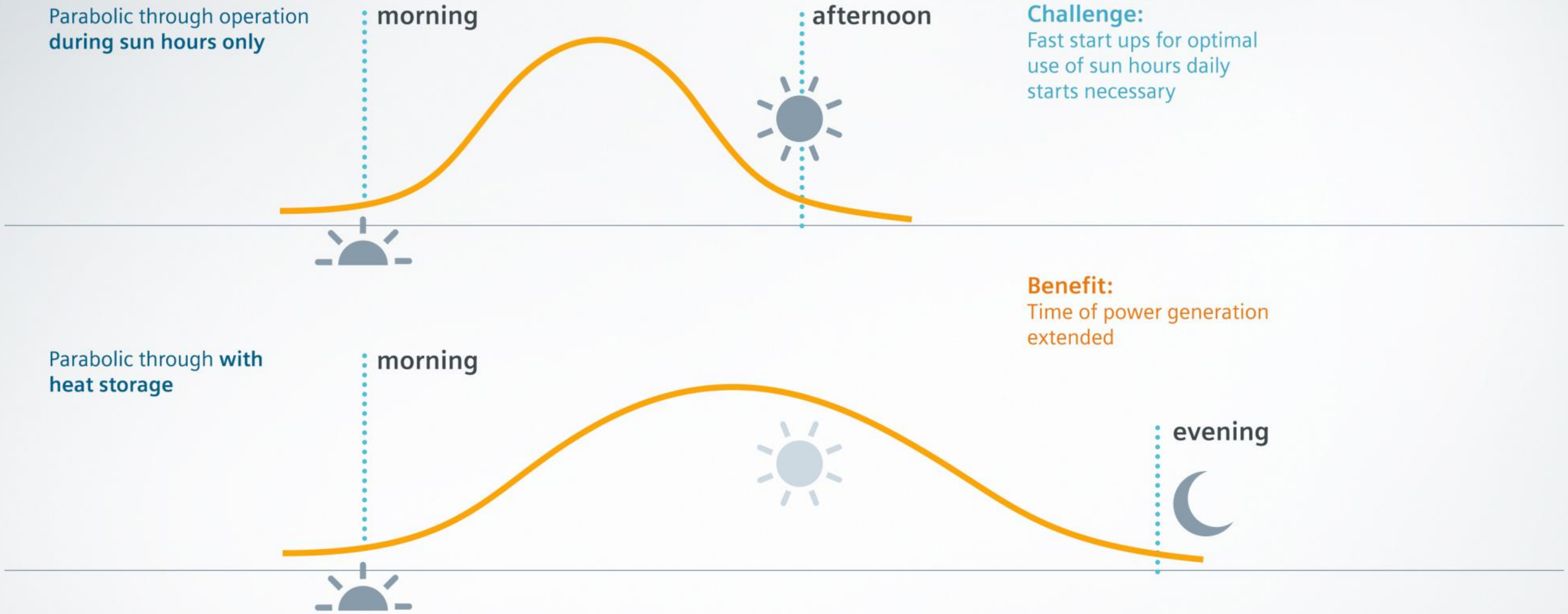
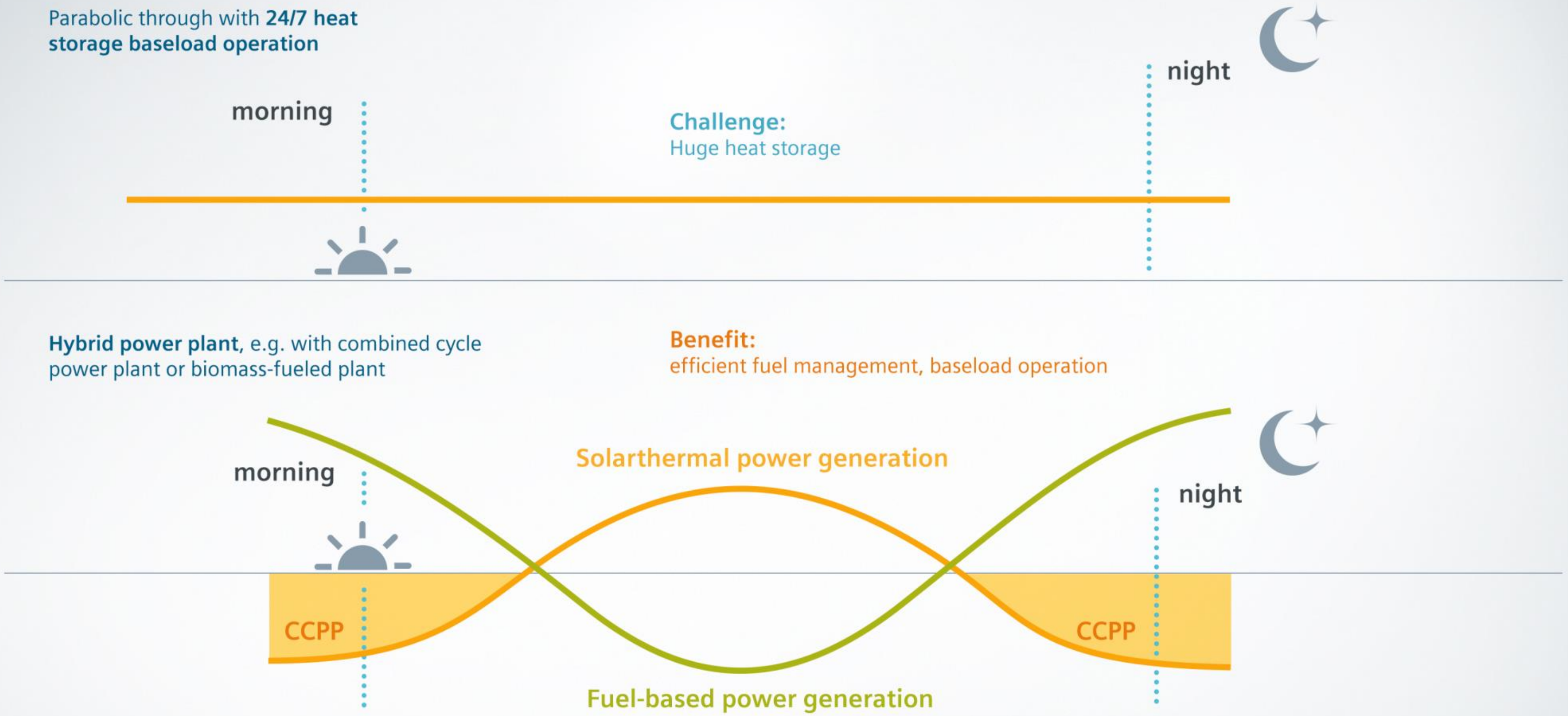
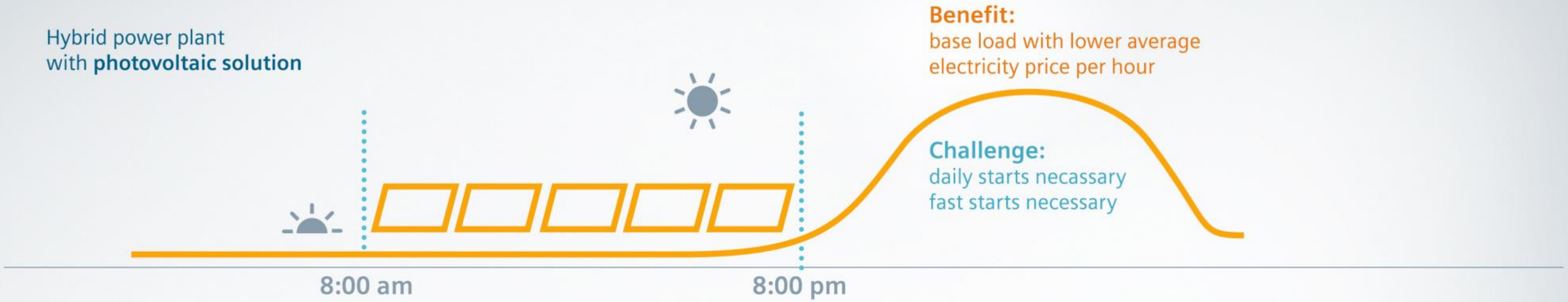


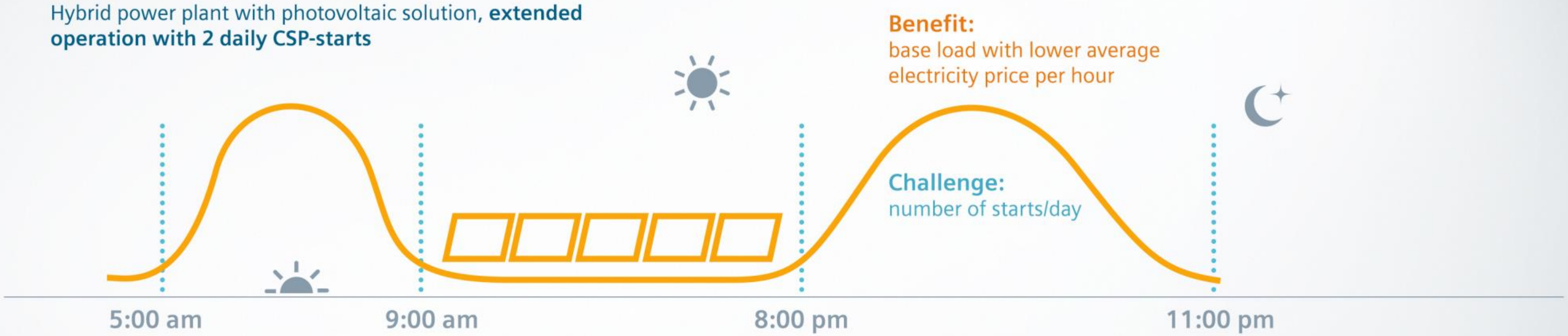

**Figure 7.** Specific investment costs for CSP plants since 1984 (blue: trough, red: tower, green: Fresnel, brown: hybrid plant). Circles refer to CSP plants with thermal storage with the size depending on the storage capacity. Crosses refer to CSP plants without storage.



Parabolic through operation
**during sun hours only**
morning
afternoon
**Challenge:**
Fast start ups for optimal
use of sun hours daily
starts necessary
**Benefit:**
Time of power generation
extended
Parabolic through **with**
**heat storage**
morning
evening


Parabolic through with 24/7 heat storage baseload operation
morning
Challenge:
Huge heat storage
night
Hybrid power plant, e.g. with combined cycle power plant or biomass-fueled plant
Benefit:
efficient fuel management, baseload operation
morning
Solarthermal power generation
night
CCPP
CCPP
Fuel-based power generation


Hybrid power plant
with **photovoltaic solution**
Benefit:
base load with lower average
electricity price per hour
Challenge:
daily starts necassary
fast starts necessary
8:00 am
8:00 pm

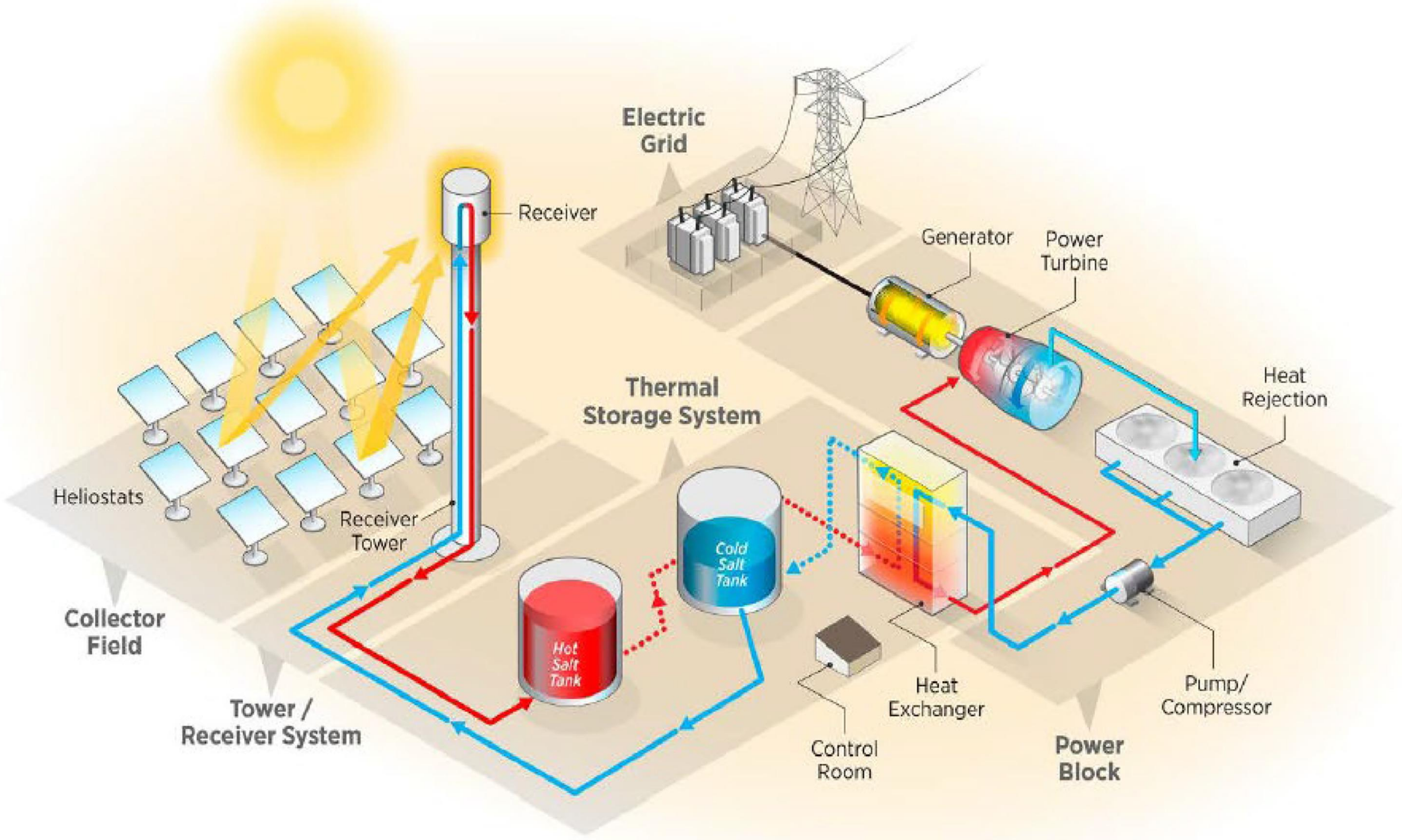

Hybrid power plant with photovoltaic solution, **extended operation with 2 daily CSP-starts**
Benefit:
base load with lower average
electricity price per hour
Challenge:
number of starts/day
5:00 am
9:00 am
8:00 pm
11:00 pm


**China Dunhuang Dacheng - 2020**
Fresnel CSP 50 MW – 15H Storage
Molten Salt as HTF and Storage

**Dubai - 2023**

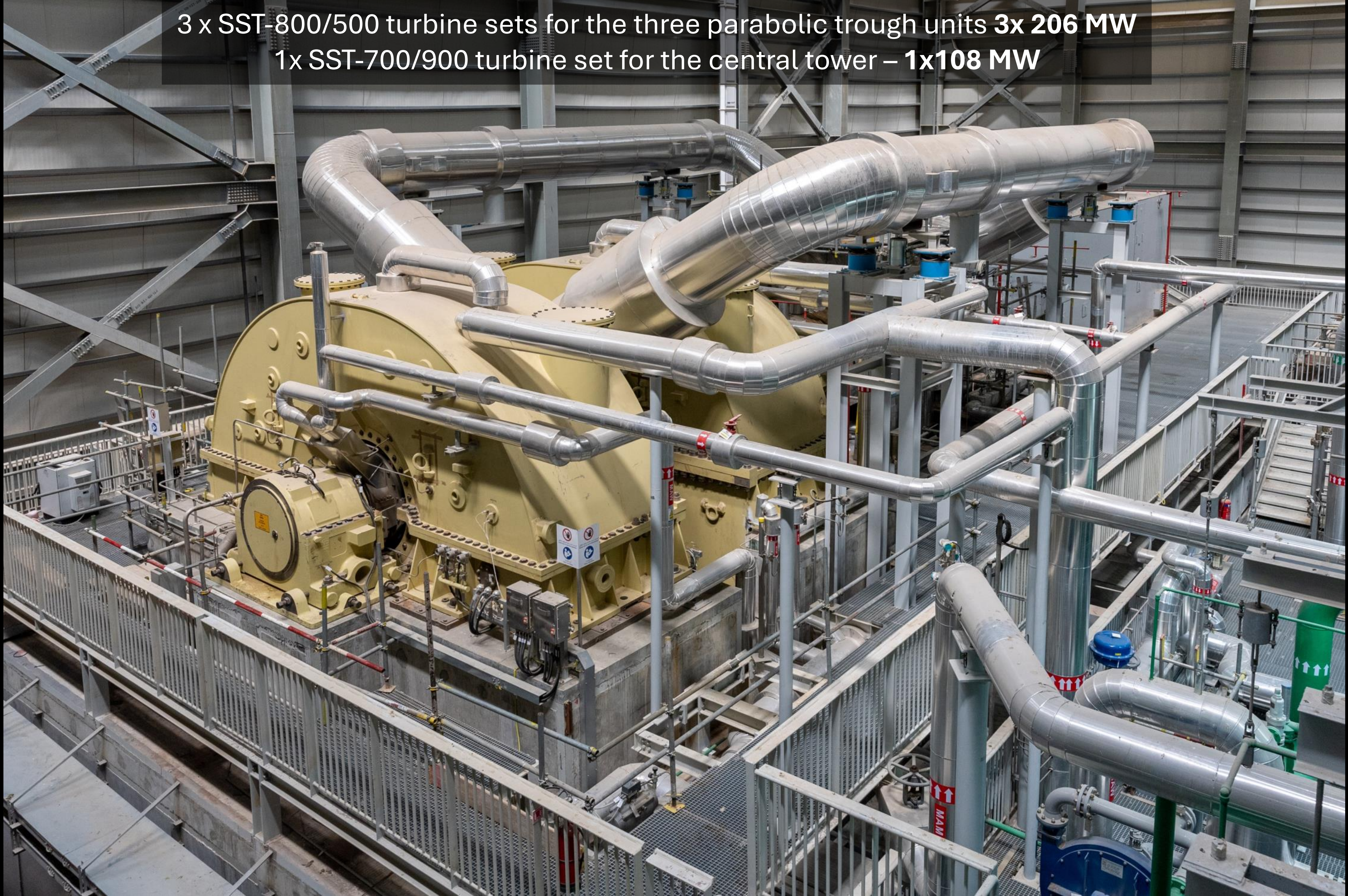
Noor Energy 1 - 950 MW Hybrid  Plant (CSP - 600+100) + PV plant (250MW)

12+15 Hours of Storage – HTF Tower Molten Salt – HTF CSP – Oil/VP1


Electric Grid
Receiver
Generator
Power Turbine
Heat Rejection
Thermal Storage System
Heliostats
Receiver Tower
Cold Salt Tank
Hot Salt Tank
Collector Field
Tower / Receiver System
Control Room
Heat Exchanger
Pump/ Compressor
Power Block

Noor Energy 1 - 950 MW Hybrid  Plant (CSP - 600+100) + PV plant (250MW)
12+15 Hours of Storage – HTF Tower Molten Salt – HTF CSP – Oil/VP1

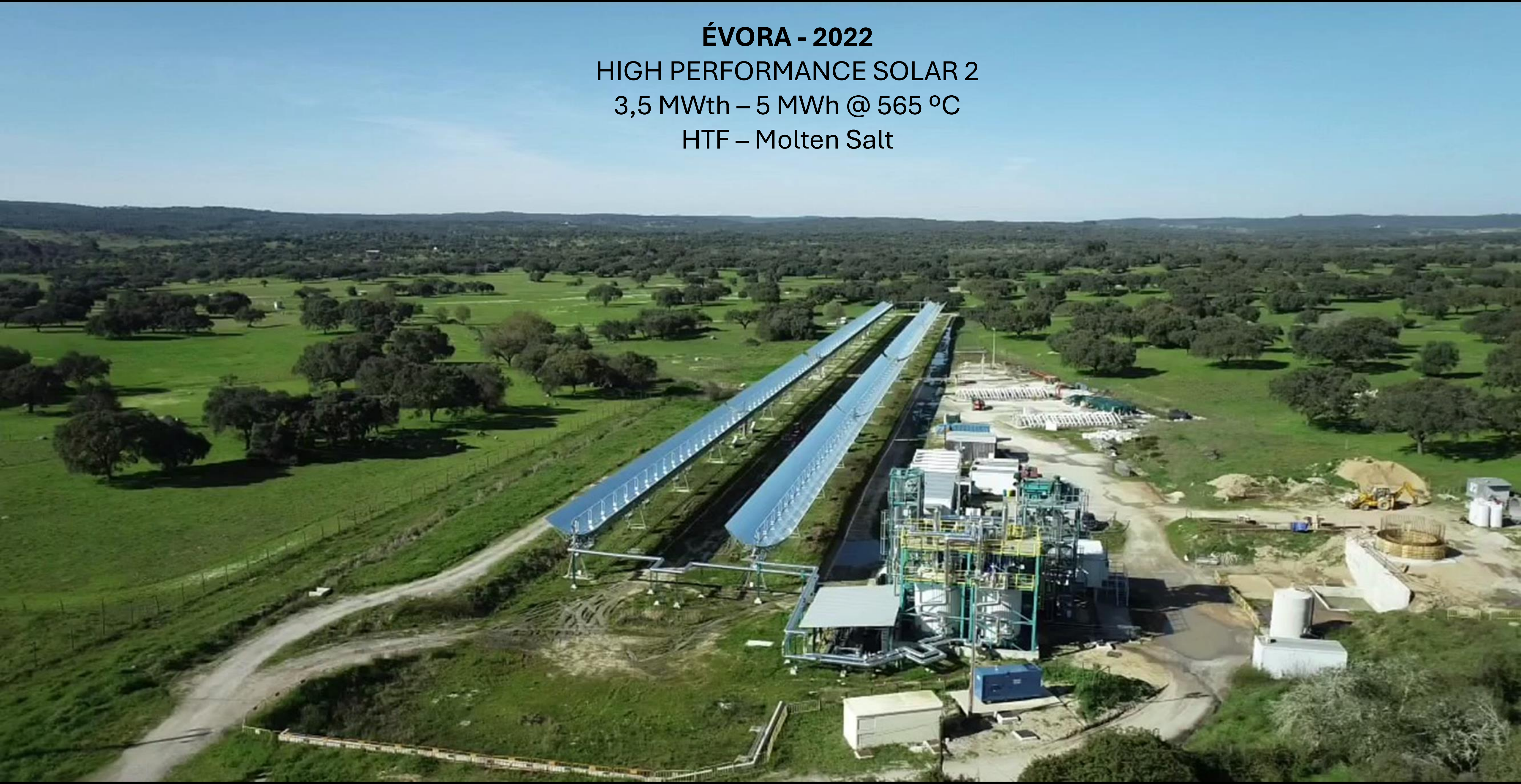
3 x SST-800/500 turbine sets for the three parabolic trough units **3x 206 MW**
1x SST-700/900 turbine set for the central tower – **1x108 MW**



## China Three Gorges Hami - 2025

Fresnel CSP **100 MW** – 8H Storage + PV **900 MW**

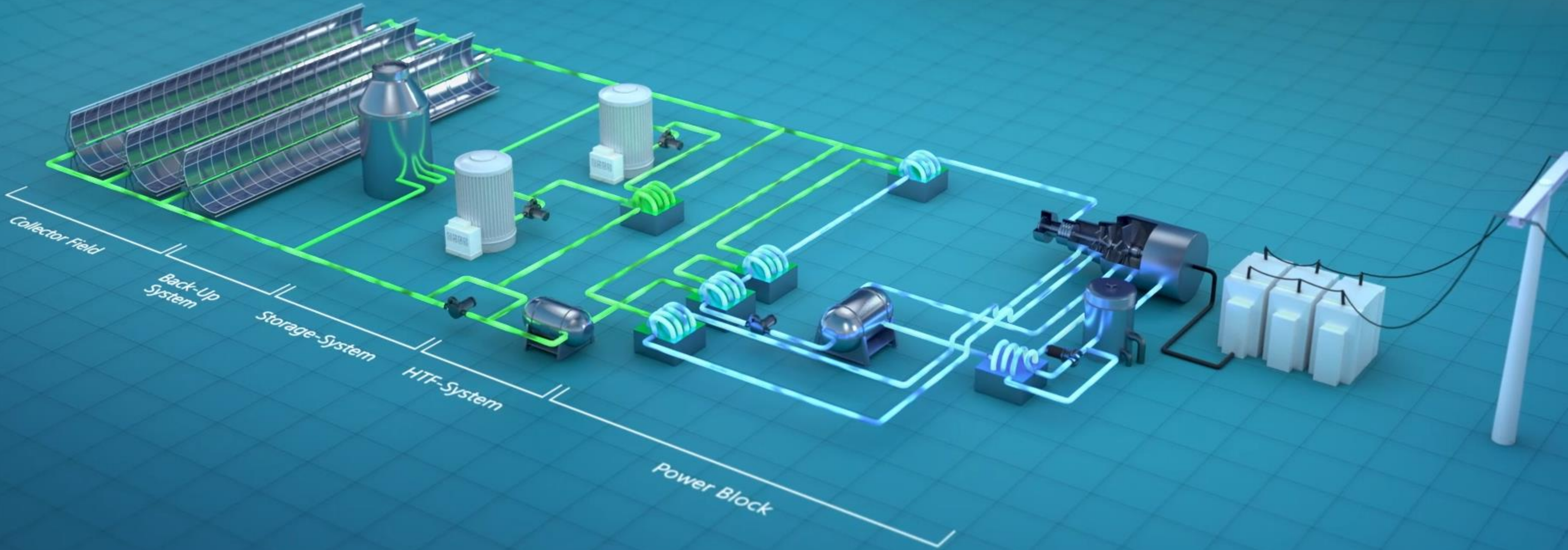
Molten Salt as HTF


**ÉVORA - 2022**
HIGH PERFORMANCE SOLAR 2
3,5 MWth – 5 MWh @ 565 ºC
HTF – Molten Salt


Évora Molten Salt Platform

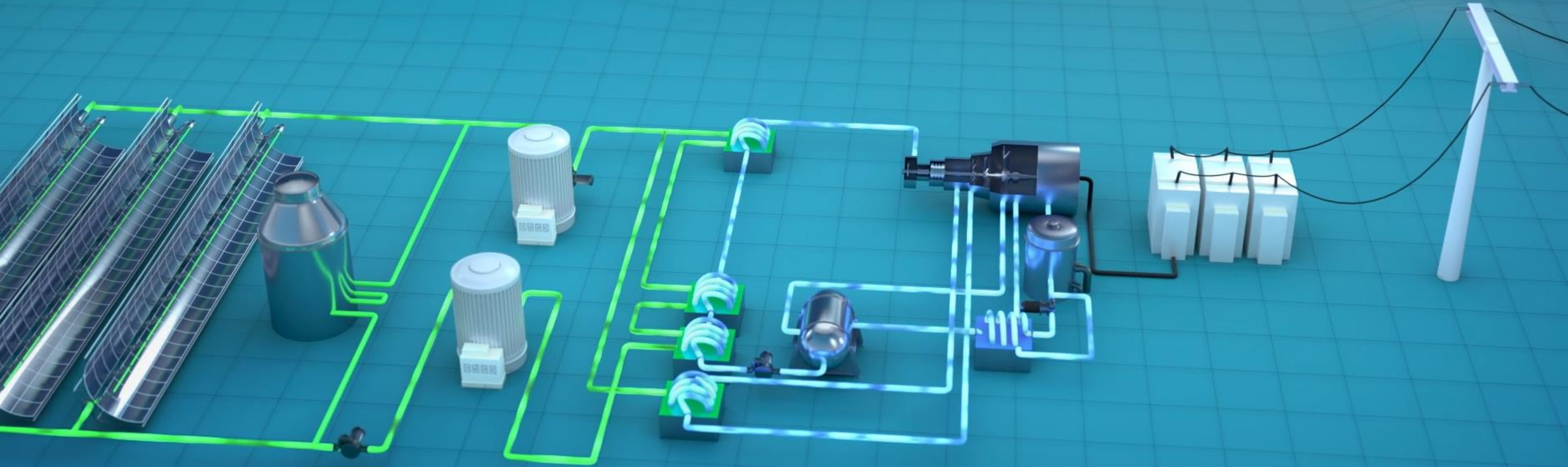
# CSP plants' efficiency with thermal oil: ~38%

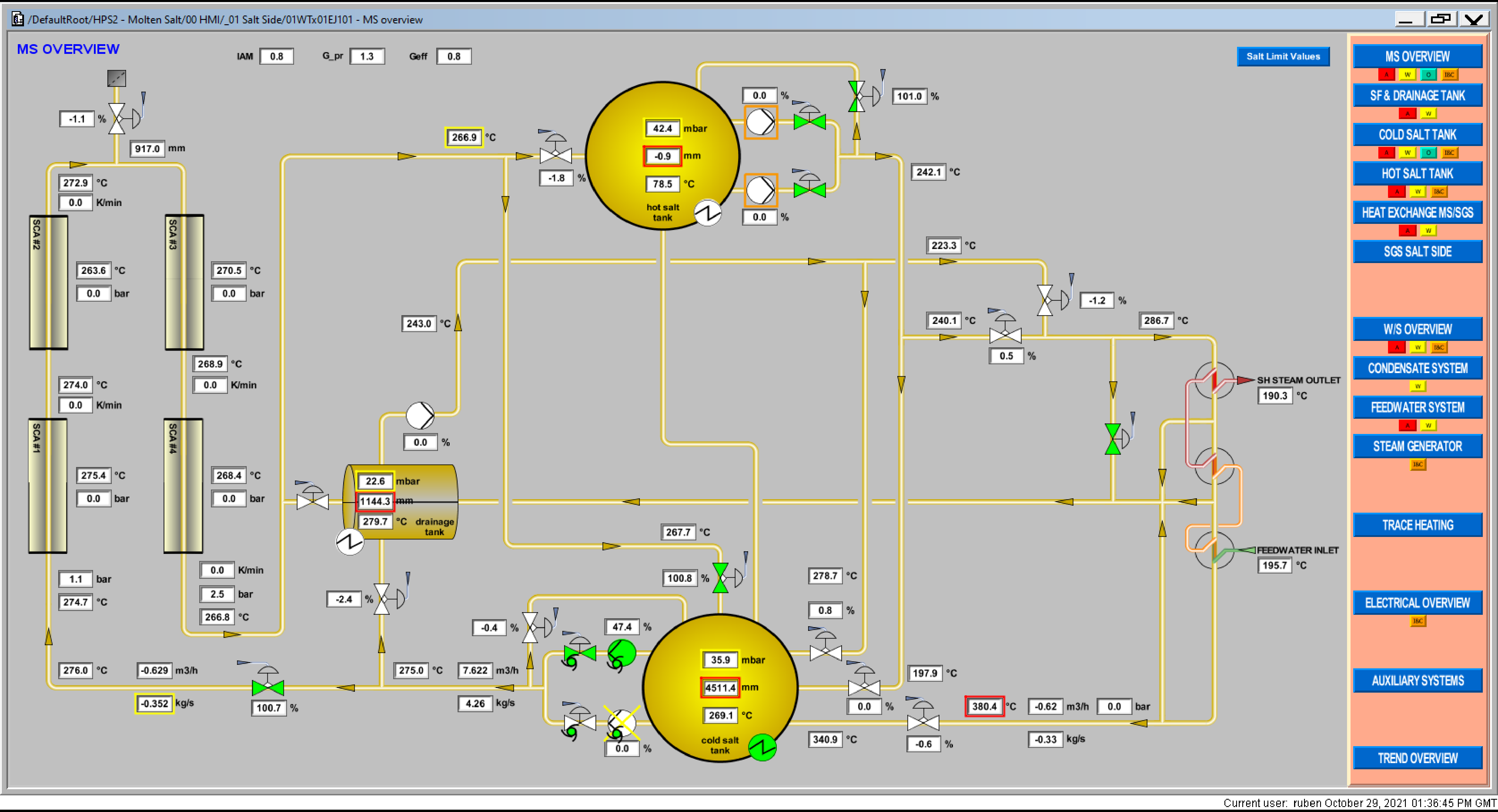
HPS2
High Performance Solar 2
DLR



# CSP plants' efficiency with molten salt: ~42%

HPS2
High Performance Solar 2
DLR



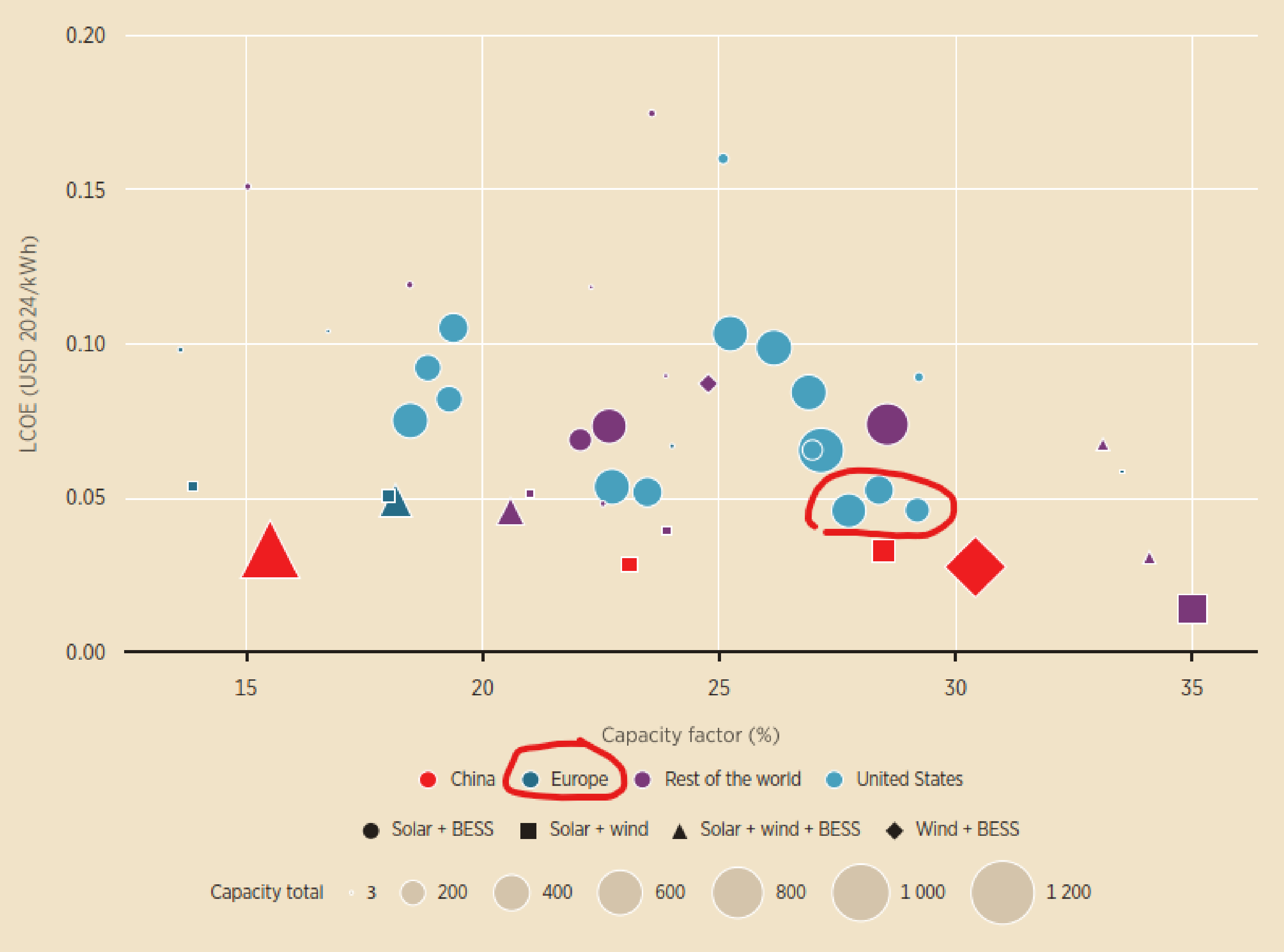

/DefaultRoot/HPS2 - Molten Salt/00 HMI/_01 Salt Side/01WTx01EJ101 - MS overview
MS OVERVIEW
IAM 0.8
G_pr 1.3
Geff 0.8
Salt Limit Values
SCA #1
SCA #2
SCA #3
SCA #4
hot salt tank
42.4 mbar
-0.9 mm
78.5 °C
drainage tank
22.6 mbar
1144.3 mm
279.7 °C
cold salt tank
35.9 mbar
4511.4 mm
269.1 °C
SH STEAM OUTLET
190.3 °C
FEEDWATER INLET
195.7 °C
-1.1 %
917.0 mm
272.9 °C
0.0 K/min
263.6 °C
0.0 bar
270.5 °C
0.0 bar
268.9 °C
0.0 K/min
274.0 °C
0.0 K/min
275.4 °C
0.0 bar
268.4 °C
0.0 bar
0.0 K/min
2.5 bar
266.8 °C
1.1 bar
274.7 °C
276.0 °C
-0.629 m3/h
-0.352 kg/s
100.7 %
275.0 °C
7.622 m3/h
4.26 kg/s
-2.4 %
243.0 °C
0.0 %
266.9 °C
-1.8 %
0.0 %
0.0 %
101.0 %
242.1 °C
223.3 °C
240.1 °C
0.5 %
-1.2 %
286.7 °C
267.7 °C
100.8 %
-0.4 %
47.4 %
0.0 %
278.7 °C
0.8 %
0.0 %
197.9 °C
-0.6 %
340.9 °C
380.4 °C
-0.62 m3/h
0.0 bar
-0.33 kg/s
MS OVERVIEW
SF & DRAINAGE TANK
COLD SALT TANK
HOT SALT TANK
HEAT EXCHANGE MS/SGS
SGS SALT SIDE
W/S OVERVIEW
CONDENSATE SYSTEM
FEEDWATER SYSTEM
STEAM GENERATOR
TRACE HEATING
ELECTRICAL OVERVIEW
AUXILIARY SYSTEMS
TREND OVERVIEW
Current user: ruben October 29, 2021 01:36:45 PM GMT

Although there has been significant success in reducing costs since 2010, the CSP market remains small, with a limited number of new projects in the pipeline. As of the end of 2024, there were projects under construction in China and Europe which totalled 3.4 GW. These are expected to come online in the near future (SolarPaces, 2025).

A key advantage of CSP is its ability to provide dispatchable and renewable power to the grid. Research shows that for storage durations exceeding four hours, CSP with thermal energy storage can be more competitive than PV combined with batteries. However, in many countries, current regulations and market structures do not adequately reward the value of dispatchable generation. To enable CSP to compete on a level playing field, electricity markets must evolve to recognise and incentivise this technology's unique capabilities (Schöniger *et al.*, 2021).

Figure 9.6 shows that solar + wind systems tend to have lower LCOE, as they do not include the additional cost of batteries. Their weighted average LCOE was USD 0.021/kWh, calculated based on a sample of ten projects deployed in 2023 and 2024 across different regions.

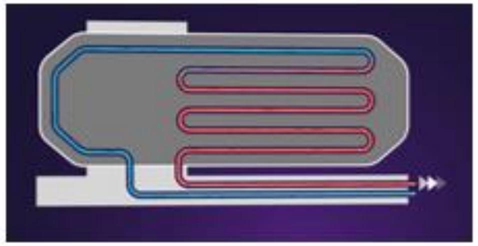
**Figure 9.6** Characteristics of hybrid projects plants deployed in 2023 and 2024 by country




**Notes:** This analysis is based on a sample of projects with available cost data and does not represent the entire hybrid market; BESS = battery energy storage system; kWh = kilowatt hour; LCOE = levelised cost of electricity; USD = United States dollar.

# Innovative Solutions for Electrification of Heat → the Inductive Heater

- ✓ Only technology with broad application to ***Medium Voltage***
- ✓ Only ***non-contacting technology***
- ✓ ***Modular*** and easily ***scalable*** *with* ***High Power Density***
- ✓ Flexibility to ***heat a wide variety of process fluids***
- ✓ **Molten salt** selected as process fluid for **pilot implementation** and **initial commercial offering**



*Single Phase of a 60 MW Molten Salt module*

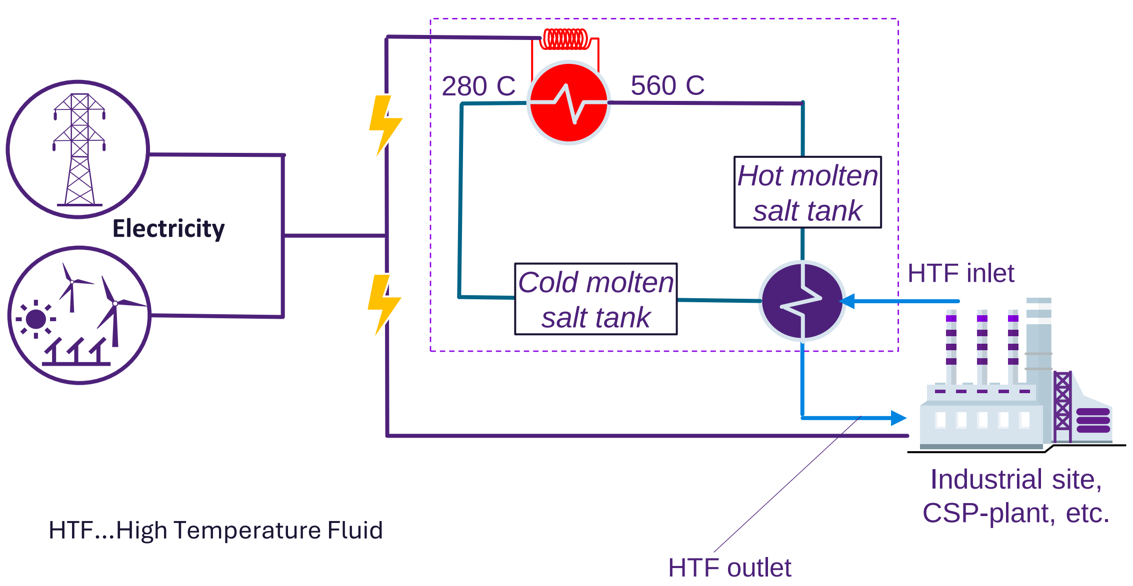
- ▶ **Unique inductive technology** based on well proven **Siemens Energy** generator and transformer technology
- ▶ Input Voltage range**: 11kV to 22kV**
- ▶ Power range per unit**: 5 to >50 MW**
- ▶ Thermal/electrical efficiencies**: > 99%**
- ▶ Design covers wide range of thermal applications with modular approach
- ▶ Temperature limit on process side**: ~1200°C**

500kW demonstrator used to successfully heat compressed air and thermal oil

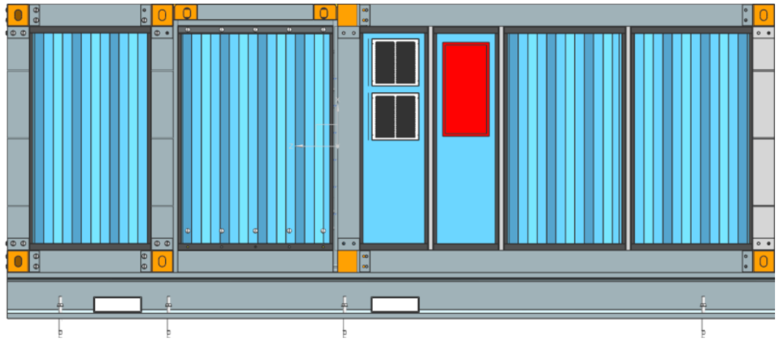
MW scale prototype implementation in preparation at several locations

# Siemens Energy Electric Heater

## SMedium Voltage based Molten Salt Heating




HTF…High Temperature Fluid



Main dimensions for one single-phase 20 MW module: ~6m x ~2,5m x ~2,5m (LxWxH)
→ Three single-phase modules are combined into one 3-phase 60MW unit

SIEMENS energy

| | Electric heater + molten salt heat storage |
|---|---|
| Operating regime | **For charging**, the molten salt is pumped from the cold molten tank via the electric heater towards the hot molten salt tank.<br><br>**For discharging**, the hot molten salt is pumped towards the heat consumers and further towards the cold molten salt tank. |
| Heat transfer/ storage fluid | "Solar salt" (60%wt $NaNO_3$, 40%wt $KNO_3$)<br><br>"HITEC" (53%wt $KNO_3$, 40%wt $NaNO_2$, 7%wt $NaNO_3$) |
| Typical capacity range for molten salt heat storage | **50 $MWh_{th}$ – 5 $GWh_{th}$**<br><br>(up to **2.6 $GWh_{th}$** with 1 cold + 1 hot tank) |
| Temperature range of storage system | Cold molten salt tank: ~170°C (HITEC); ~**280°C** (Solar salt)<br><br>Hot molten salt tank: ~460°C (HITEC); **~560°C** (Solar salt) |