Air-based Solar Thermal Electricity for Efficient Renewable Energy Integration & Compressed Air Energy Storage

ASTERIx-CAESar project overview

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Funded by the European Union

UK participant in Horizon Europe Project ASTERIx-CAESar is supported by UKRI grant number 10097908 (Bluebox Energy).

This work has received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI).

Solar power sector background: PV is less costly than CSP

- **Photovoltaic**
  Global weighted average LCOE* for utility-scale projects:
  - 89% reduction from 2010 to 2022 (0.445 $/kWh → **0.049 $/kWh**)
  - Over 1047 GW installed by 2022
- **Concentrated Solar Power (CSP)**
  Weighted average LCOE of CSP plants:
  - 69% reduction from 2010 to 2022 (0.38 $/kWh → **0.12 $/kWh**)
  - Over 6.5 GW installed by 2022
- **Economic curtailments of CSP facilities**
- **New cost-effective CSP concepts are needed**

Source: IRENA, 2022
* Levelised Cost of Electricity

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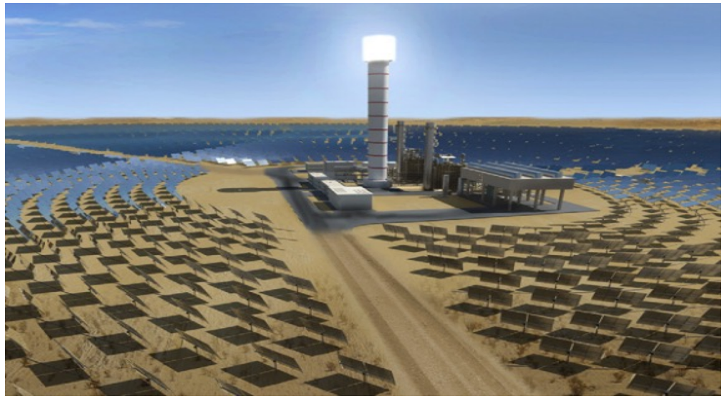
CSP sector background: Low efficiency

- Current **CSP technology:**
  - **S**olar-to-electric **efficiency: 14-16%** (annual)
  - **Power block efficiency: 30-40%** (steam Rankine)
- **State-of-the-art technologies**:
  - Parabolic trough (thermal oil [HTF] → 390°C max.)
  - Central receiver (molten salt [HTF] → 565°C max.)
  - LCOE ≈ 7-11 $c/kWh (depending on site and finance)



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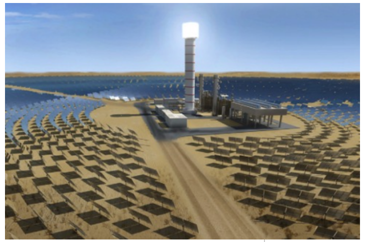
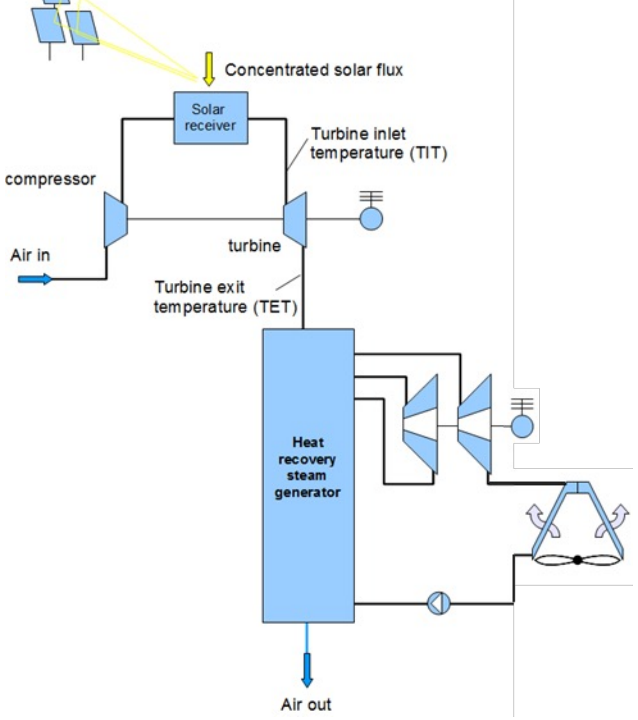
What is the best CSP technology? [1/2]

Is central receiver the best option for efficiency enhancement and cost reduction?

- High concentration → high $T_{receiver}$ (700-1000°C)
- Suitable for advanced cycles (e.g. **combined**):
  - **Up to 30% (peak)**
  - **Up to 22% (annual)**
- Combined cycle proven to be not economical (CAPTure)
- **CSP part of the problem today, not a solution**





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ASTERIx-CAESar objectives are defined by the current CSP sector's needs

- **Competitive (electrical) round-trip efficiency RTE>60%, at very low LCOS** of < 10-15 c€/kWh → adaptive operation in peak hours!
- **Optimal design of power cycle** (central receiver)**:**
  - Maximum temperatures: 750-800°C
  - **Flexible/adaptive operation** (quick start-up, shutdown and load variation)
- Propose **new operating strategy for CSP**:
  - Capitalising on efficient energy storage
  - Enabling **higher shares of renewables** in the grid

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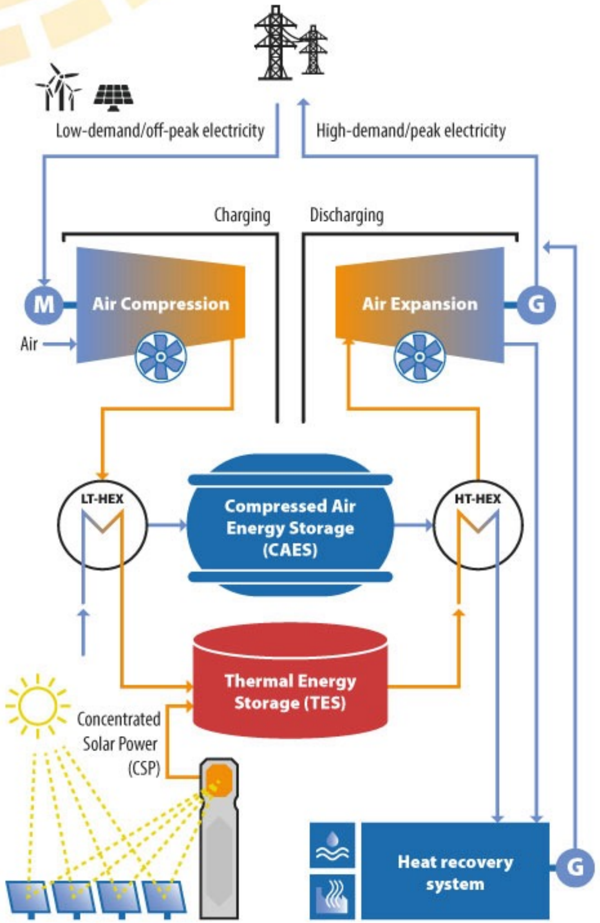
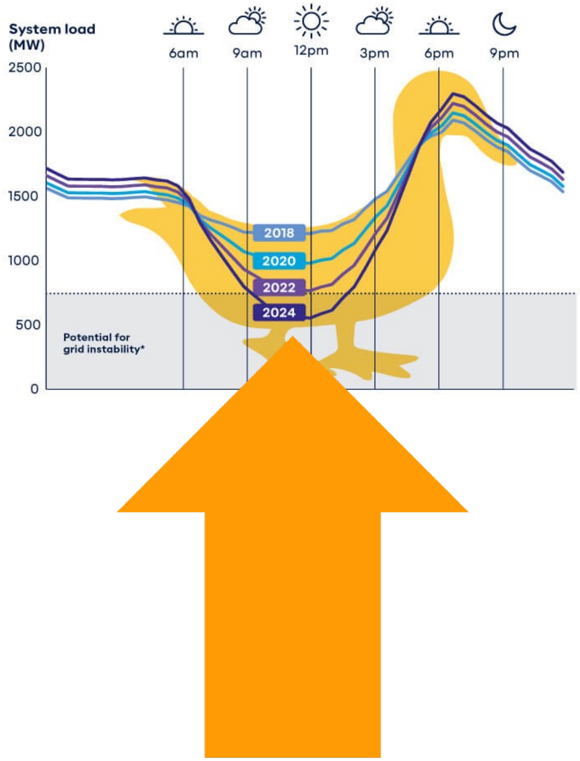
The project concept: CSP-CAES innovative & adaptive power plant [1/2]



- **Concept:** CSP + D-CAES
- **Off-peak low-price electricity used to drive compressor train** –
  - Air is stored
  - Heat of compression is also stored
- **Solar energy is stored**:
  - High-temperature heat (800°C)



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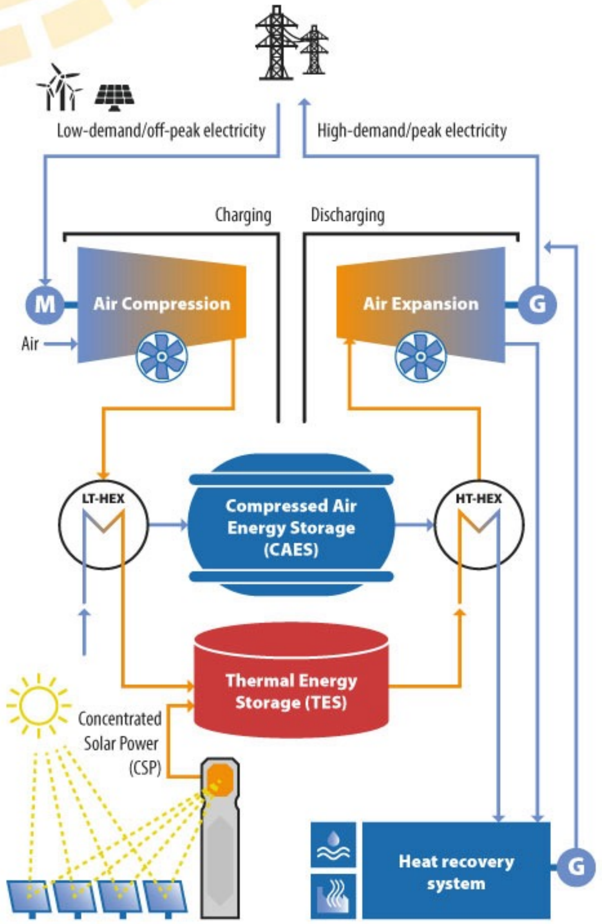
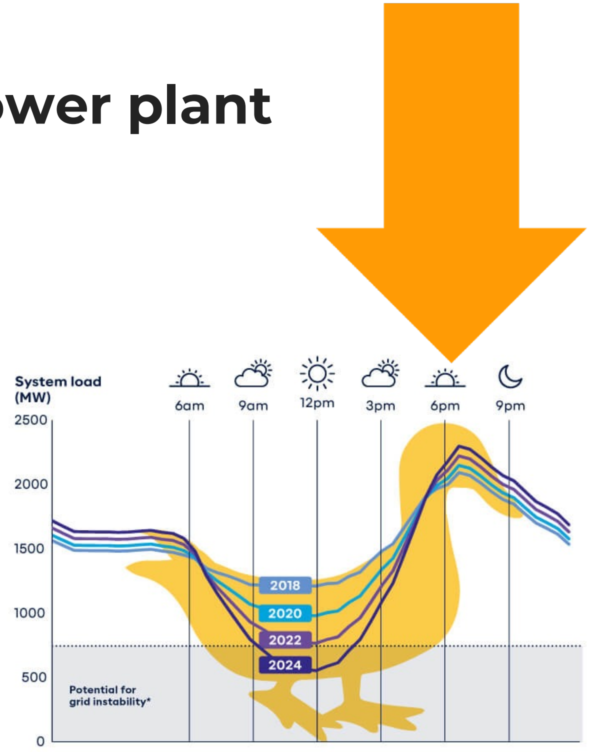
The project concept:
CSP-CAES innovative & adaptive power plant [2/2]



- **Peak-hours:**
  - Power generation: **combined cycle power plant**
- **Compressed air** delivered to expanders
- **Very high** solar-to-electric conversion efficiency: **40% peak**
- **Twice as high efficiency as state-of-the-art CSP**



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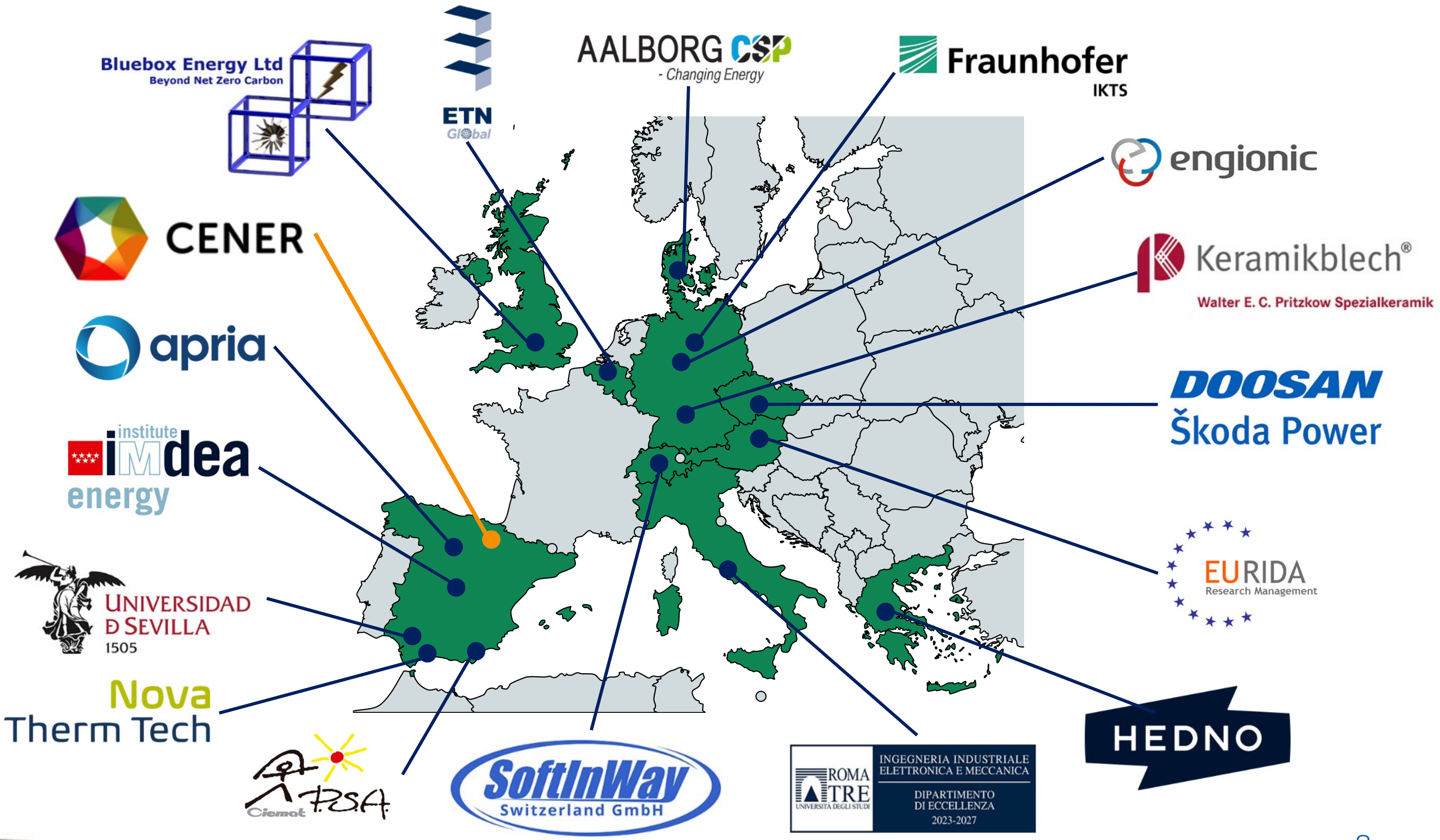
ASTERIx-CAESar: Concept and research areas

- **Total Budget**
  7.2 M€ (EU 5.2)
- **Funding**
  Horizon Europe
- **Duration**
  Oct 2023 – Oct 2027
- **Consortium:** (17)



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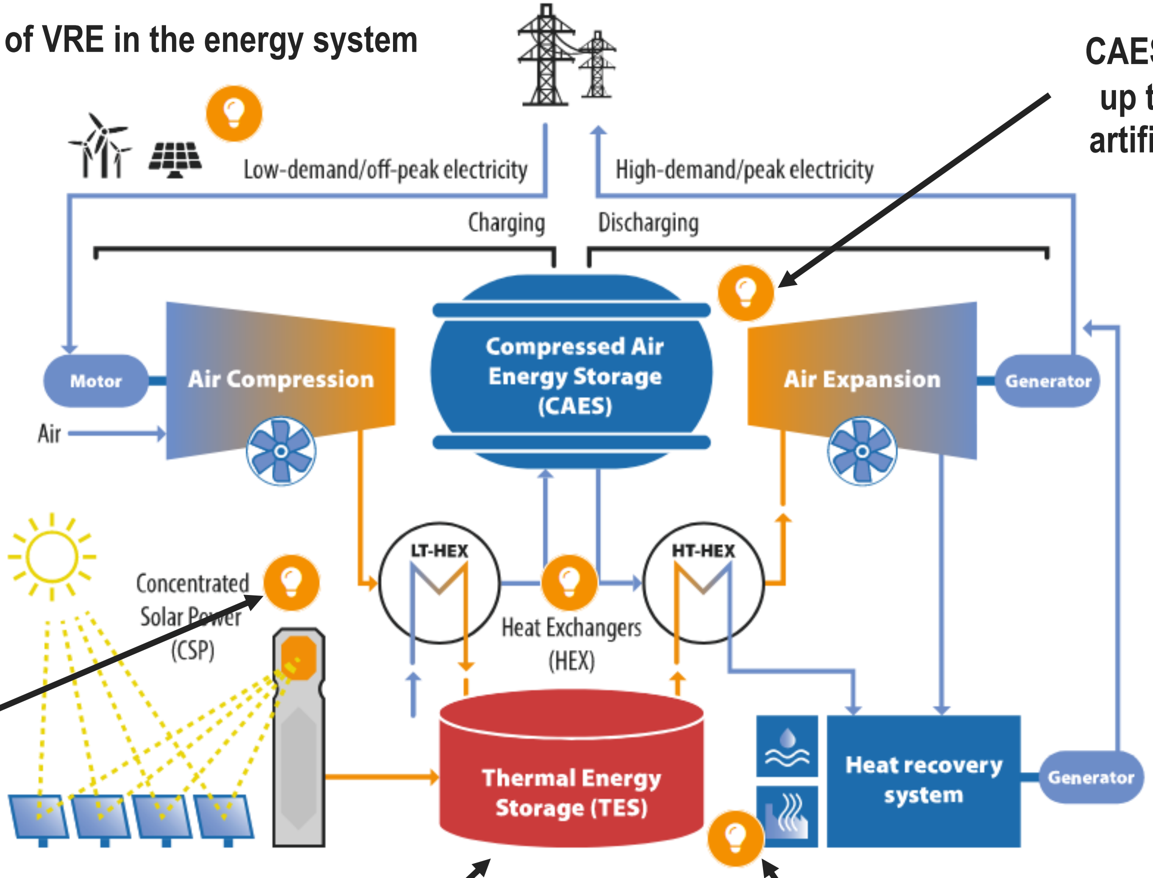
ASTERIx-CAESar: Overview & Consortium

- 480 kWt prototype (Target TLR: 6-7)
- Solar-to-electric efficiency: 40%
- Scale: 1 to 150 MWe

Higher share of VRE in the energy system

CAES with round trip efficiency up to 65-75% and economical artificial above-ground storage



Disruptive, highly efficient Open Volumetric Air Receiver (OVAR) AI-based heliostat tracking system

Packed-bed thermocline and efficient air-air low and high-temperature heat exchangers

Desalination through: Reverse Osmosis (RO) + Air-Water pressure exchanger (ERD) + Thermal Vapour Compression (TVC)

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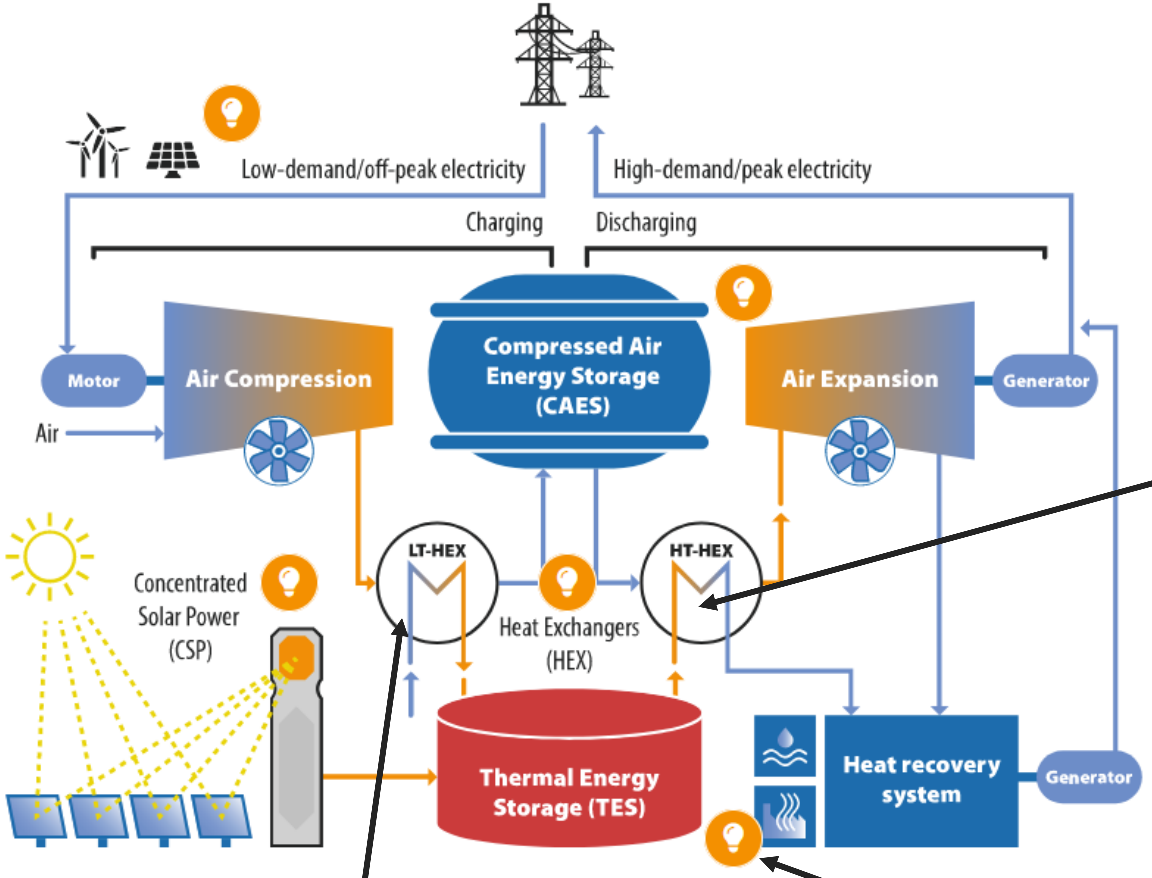
ASTERIx-CAESar: Overview & Consortium

- Hybrid (adiabatic + diabatic)
- Charge: adiabatic
  - Intercooled compression
  - Low-T TES
- Discharge: diabatic
  - Solar heat (high-T TES)
  - Reheat expansion
  - Bottoming power system



HT-HEX: provide heat from solar field (D-CAES)

LT-HEX: stores heat from compression (A-CAES)

Bottoming Cycle: Rankine, ORC

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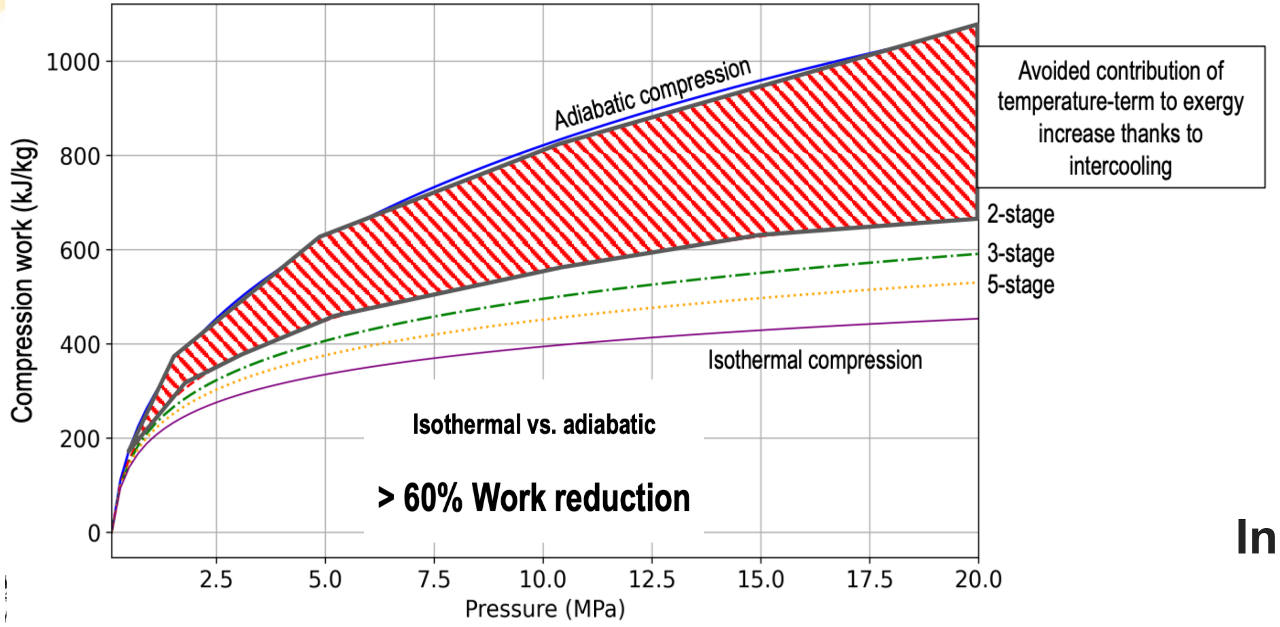
CAES charging: Compression Train

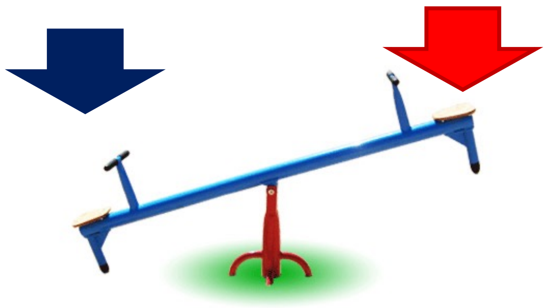


$$\Delta\dot{E}_{air}(T,P) = \dot{m} \cdot \Big[\underbrace{T_0 \cdot C_p \cdot \left(\frac{T}{T_0} - 1 - \ln\left(\frac{T}{T_0}\right)\right)}_{\text{Temperature-term}} + \underbrace{T_0 \cdot R_g \cdot \ln\left(\frac{P}{P_0}\right)}_{\text{Pressure-term}}\Big]$$

Compr. Work ↓

LT-TES ↓

Increasing nº stages →



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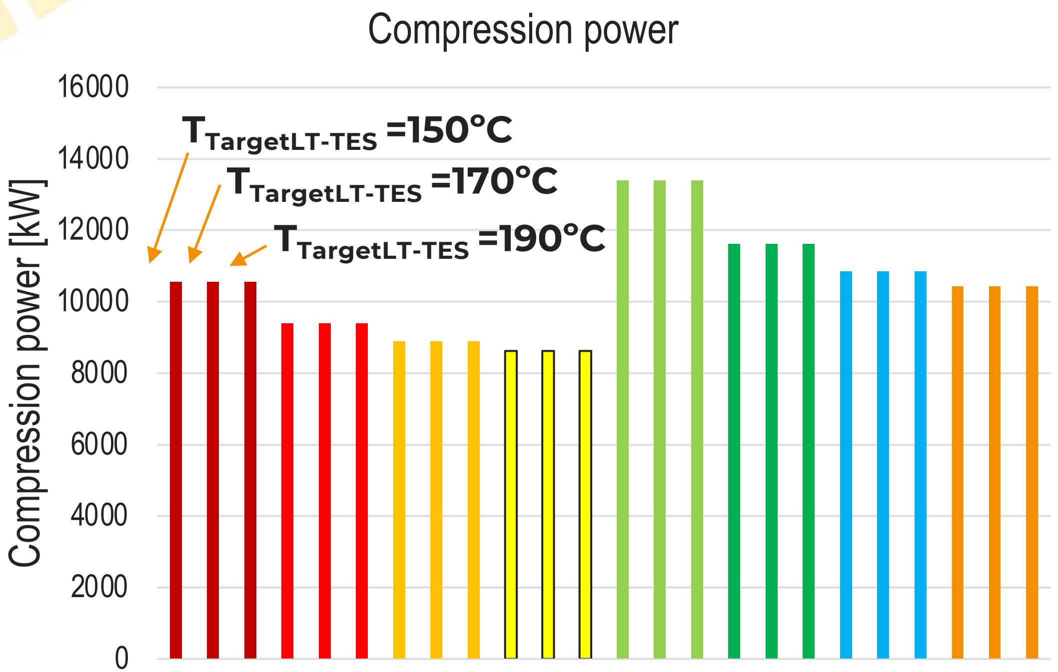
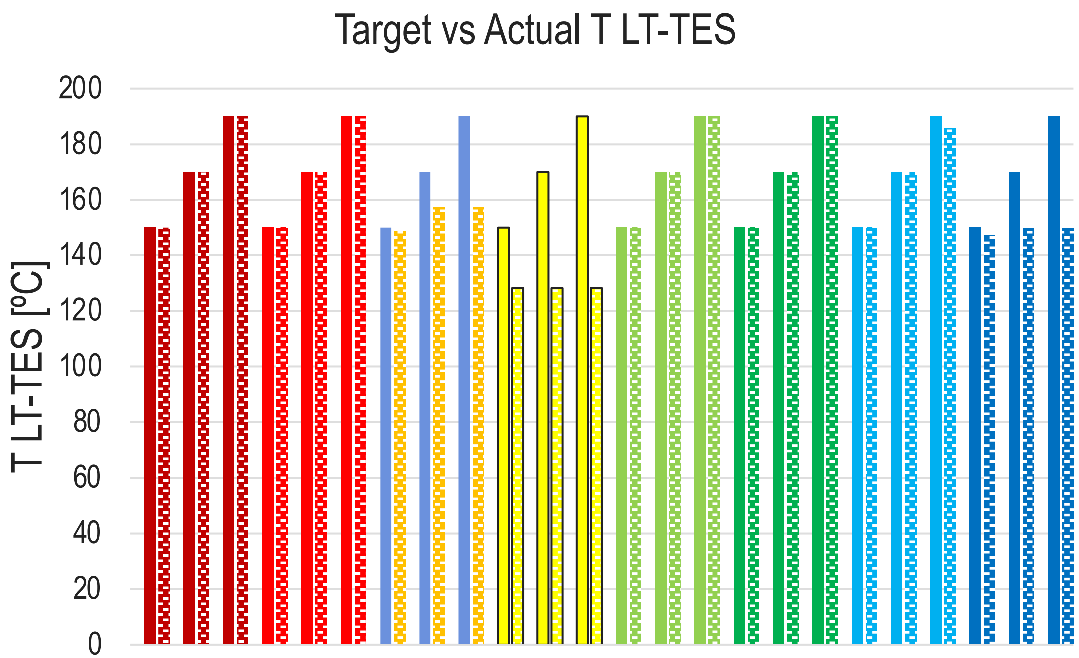
CAES charging: Compression Train





2 stages, P_{CAES}=70 bar | 3 stages, P_{CAES}=70 bar | 4 stages, P_{CAES}=70 bar | 5 stages, P_{CAES}=70 bar

2 stages, P_{CAES}=150 bar | 3 stages, P_{CAES}=150 bar | 4 stages, P_{CAES}=150 bar | 5 stages, P_{CAES}=150 bar

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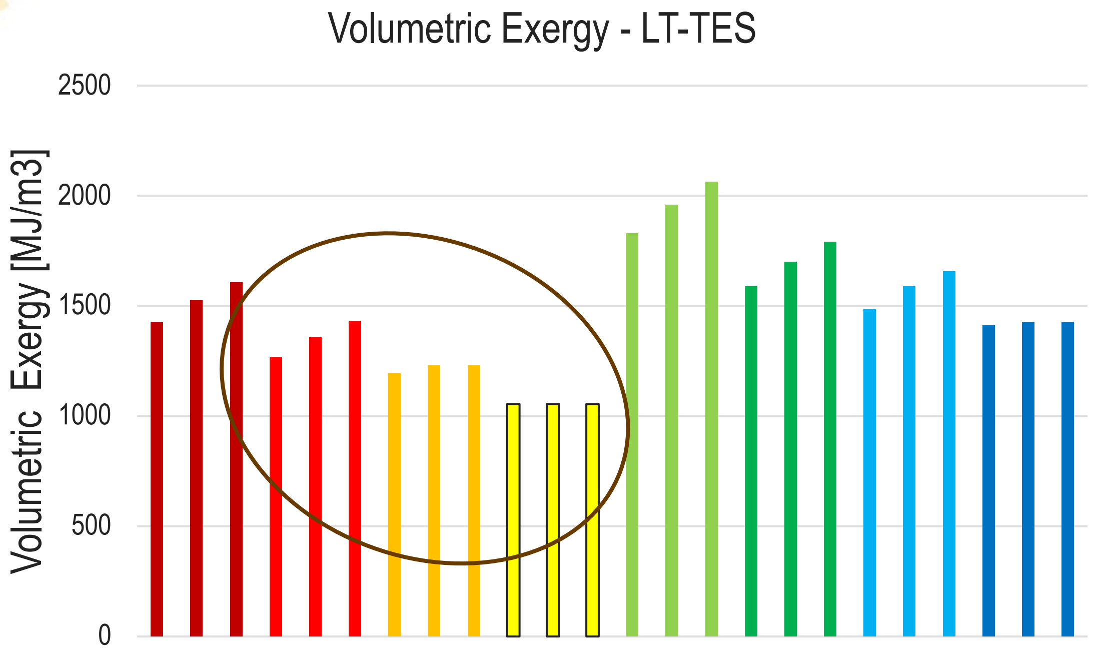
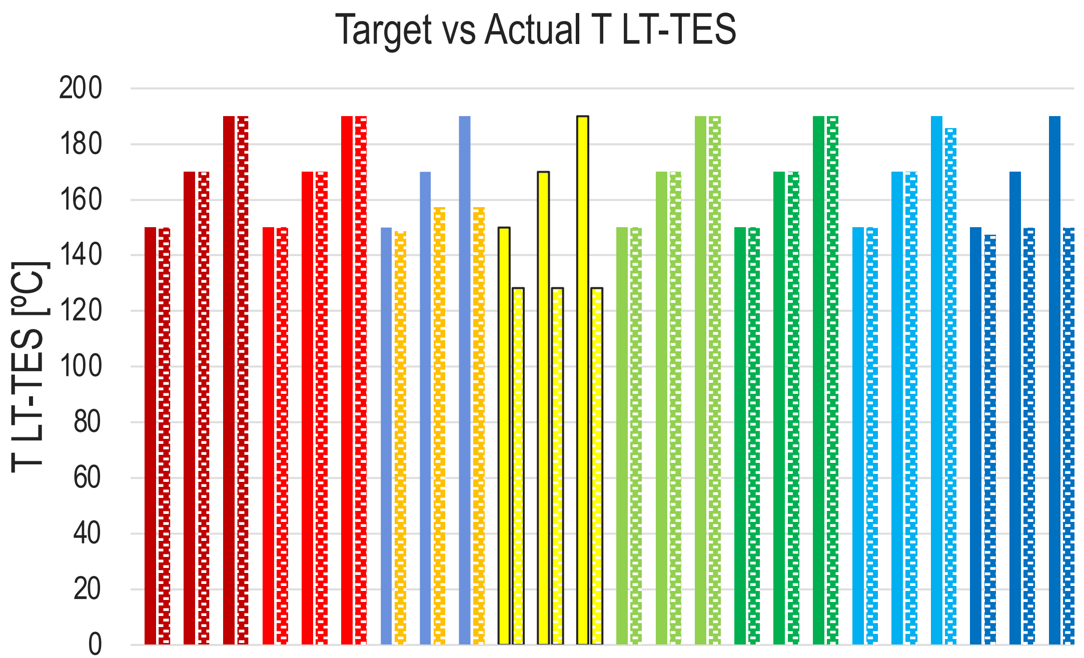
CAES charging: Compression Train





2 stages, P_{CAES}=70 bar
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4 stages, P_{CAES}=70 bar
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2 stages, P_{CAES}=150 bar
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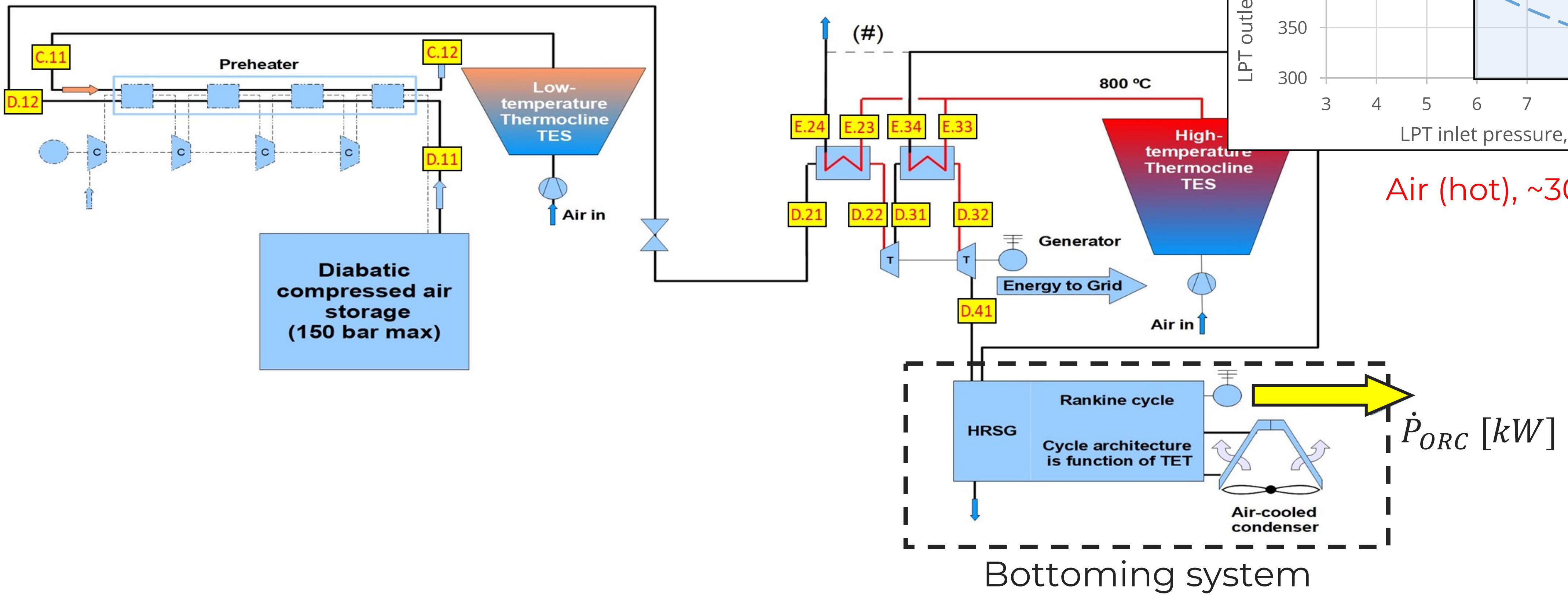
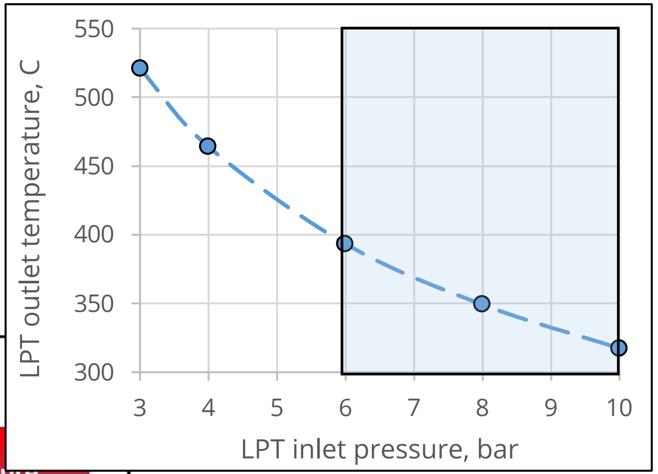
Bottoming cycle optimisation





Air (hot), ~300-400°C

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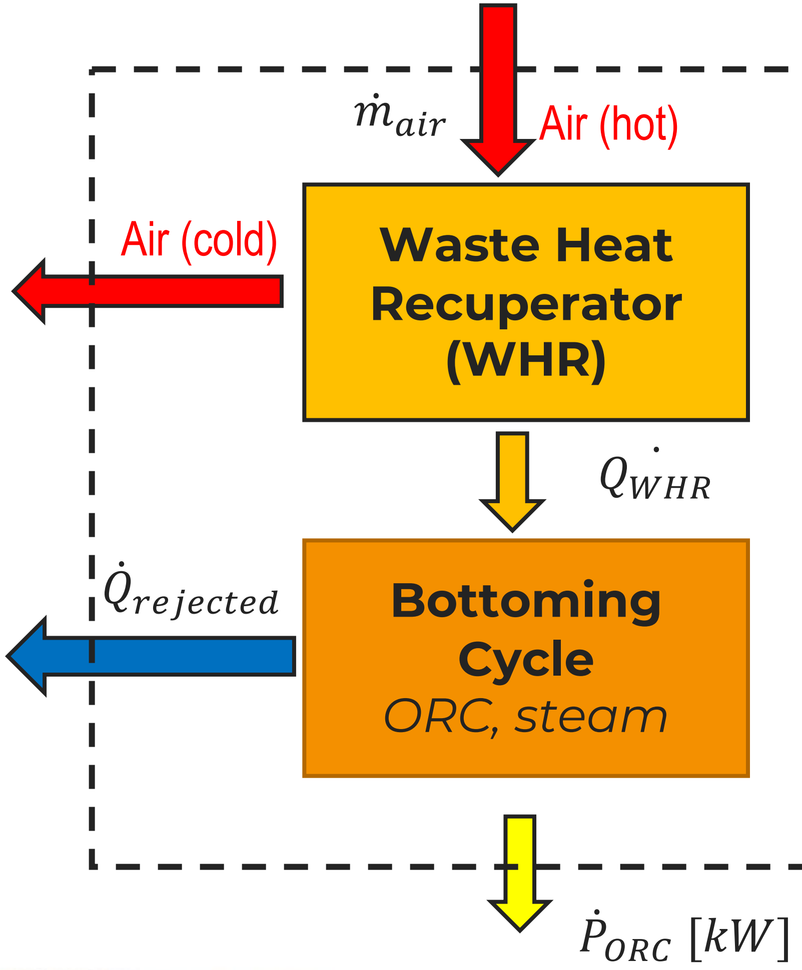
Bottoming cycle optimisation

Bottoming system



$$\eta_{WHR} = \frac{\dot{Q}_{WHR}}{\dot{Q}_{max}}$$

$$\eta_{ORC} = \frac{\dot{P}_{ORC}}{\dot{Q}_{WHR}}$$

Objective function for opt.

$$\boxed{\boldsymbol{\eta_{WHR-ORC} = \eta_{WHR} \cdot \eta_{ORC}}}$$

$$\boldsymbol{\eta_{WHR-ORC} = \frac{\dot{P}_{ORC}}{\dot{Q}_{max}}}$$

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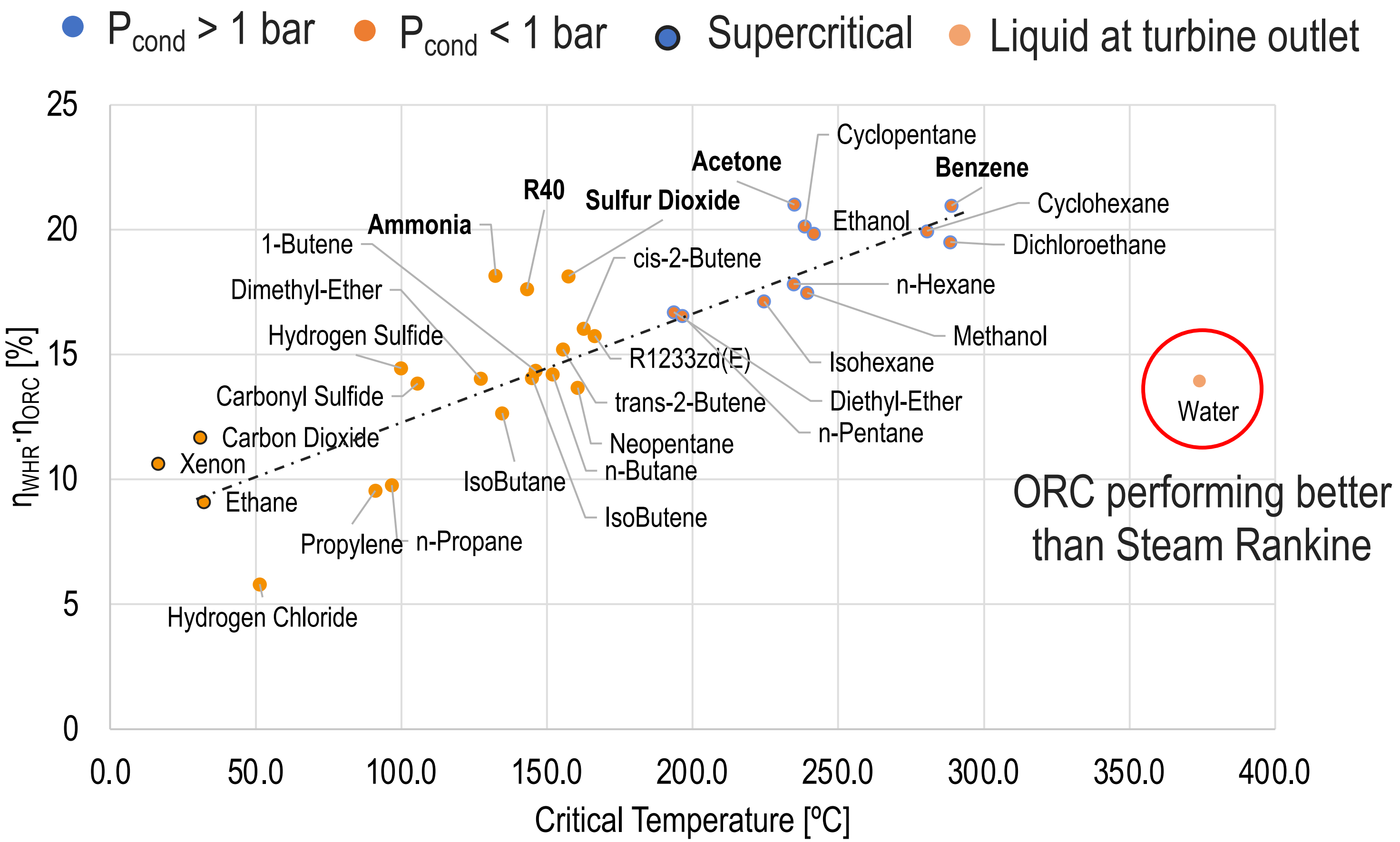
Bottoming cycle optimisation – fluid selection

Selection of working fluid:

- $P_{cond} < P_{atm}$
- Thermal degradation
- Critical temperature
- Molecular complexity
- Low ODP and GWP
- Safety



Link between critical temperature and cycle performance

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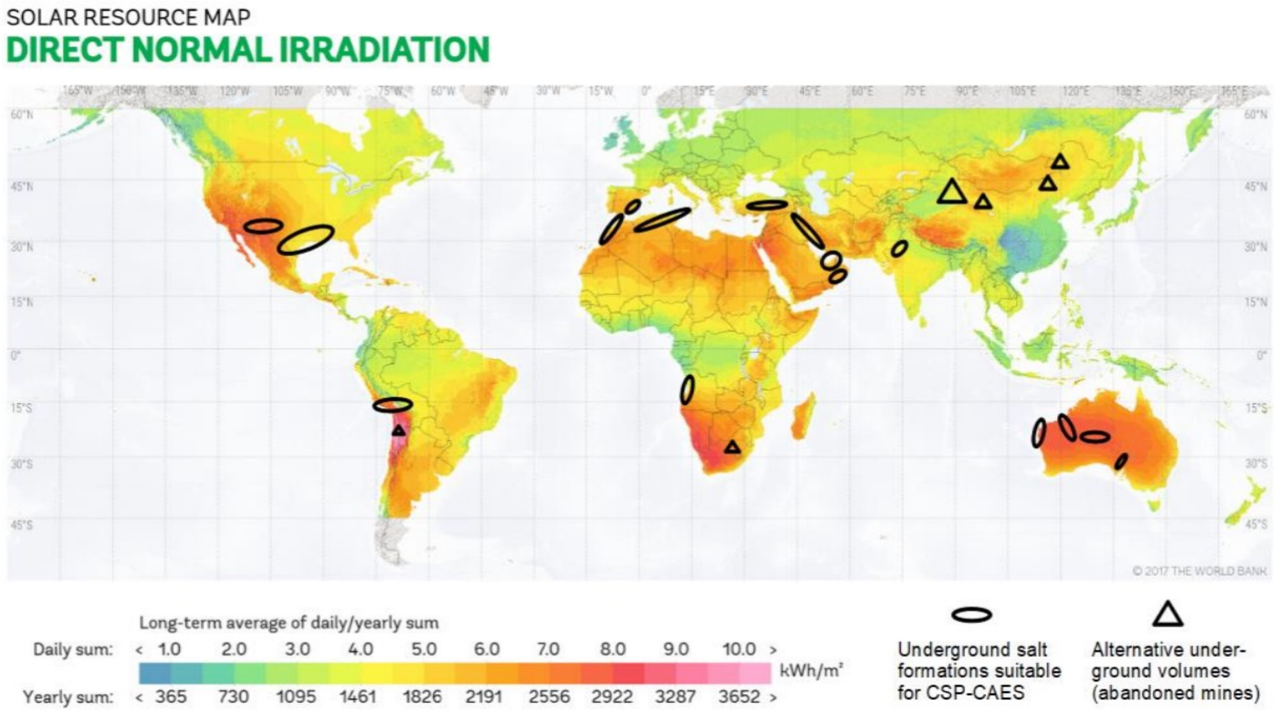
Two options for compressed air storage volumes

- **Evaluation** of different **compressed air storage solutions** (aboveground and underground)
  - **Artificial vessels for small scale** (cost effective pressure vessels – e.g. array of connected pipes)
  - **Conventional underground caverns** in salt formations or adapted closed mines within high DNI resource areas (a must for CSP) – large scale application



Information about suitable locations for compressed air underground storage as well as solar resources has been obtained from references listed under this link.

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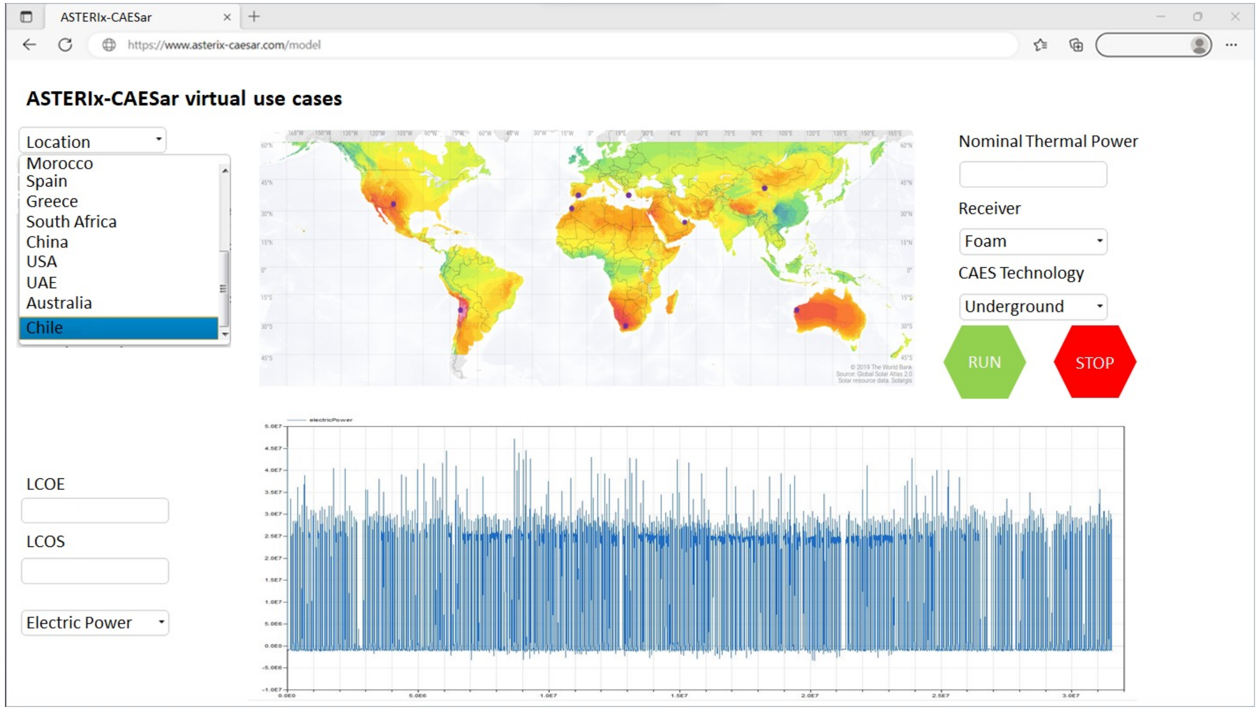
Modelica library allows for techno-economic optimisation

Techno-economic optimisation of the ASTERIx-CAESar concept **considers use-cases worldwide**

- 11 use-case locations worldwide
- Integration with desalination
- Integration with process heat
- Open-source public Modelica library
- Online simulation of use-cases will be available on project website in the final phase of the project



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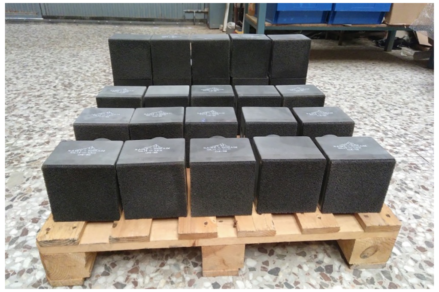
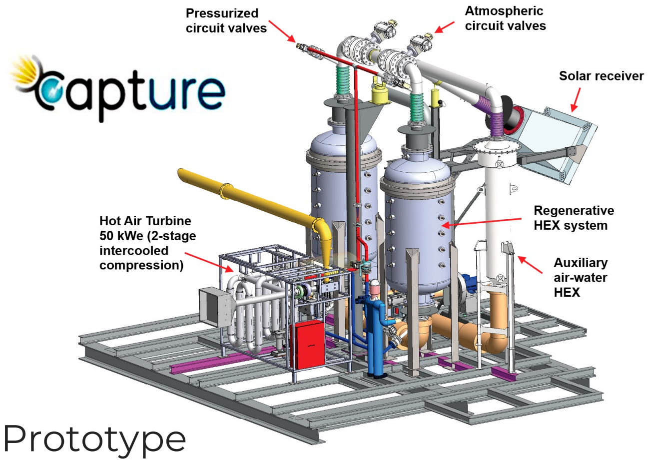
The project builds upon past successful developments

Development of optical fiber solar flux meters

CAPTURE Prototype in operation



Pressureless sintered silicon carbide foam ceramic (SSiC)



CAPTURE Prototype

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Questions? Let us know!

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