Associazione Termotecnica Italiana

AIDIC

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Panoramica su turbomacchine per transizione energetica

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Con il contributo di

KSB

MASOL Continental Biofuel

Summary

- ➢Energy Industry macrotrends for Turbomachinery
- ➢Overview of main applications employing axial expanders
- ➢Externally heated sCO_2 power cycles
- ➢Main challenges for sCO_2 Turbomachinery
- ➢Conclusions

Energy Industry Macrotrends (Turbomachinery)

- Hydrogen and other greenfuel (Ammonia and Methanol)
- GT Exhaust Gas Recirculation
- Deflaring emission abatement
- Industrial Carbon Capture
- Energy Storage
- sCO2 cycles for Small Modular Reactors and CSP Generation 3 power conversion plants
- Allam Cycle and other oxycombustion cycle
- Geothermal ORC
- Kalina cycle next generation (high temperature)
- Large Heat Pump systems
- Efficiency optimization of existing assets

The achievements of climate goals is forcing an energy transition era.

A lot of technologies, with different level of maturity, are competing each other: difficult to foresee which are the best positioned to grow at an industrial scale.

There will be market space for some of them but, likely, not for all.

EU, MISE or DOE fundings are are setting the development path for low TRL technologies.

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Applications overview

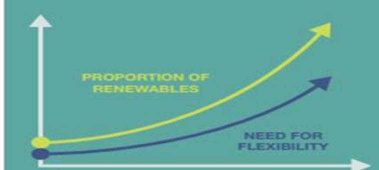
The De-Carbonized Energy Outlook

What is the issue?

To avoid catastrophic climate change, we need to rapidly build a net-zero power sector predominantly powered by renewable energy.

As the proportion of renewables grows, we are presented with 3 challenges; balancing electricity supply and demand; a change in transmission flow patterns; and a decrease in system stability.

LDES can help address these issues by increasing the flexibility of the power system.



Projected installed capacity

How do LDES technologies help?

LDES are a host of different technologies that store and release energy through mechanical, thermal, electrochemical, or chemical means.

Alongside Li-ion battery technology and hydrogen, LDES technologies can play a critical and distinctive role in delivering flexibility on times **ranging from hours to weeks.**

Where are we today and where do we need to get to?

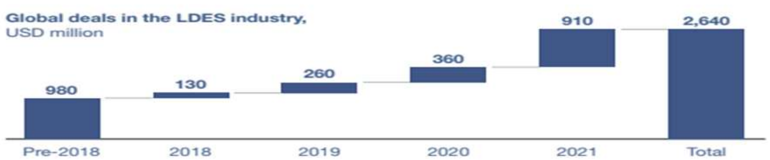
Many LDES technologies currently exist, but they are at different levels of maturity. Some have been deployed commercially, some are still at the pilot phase.

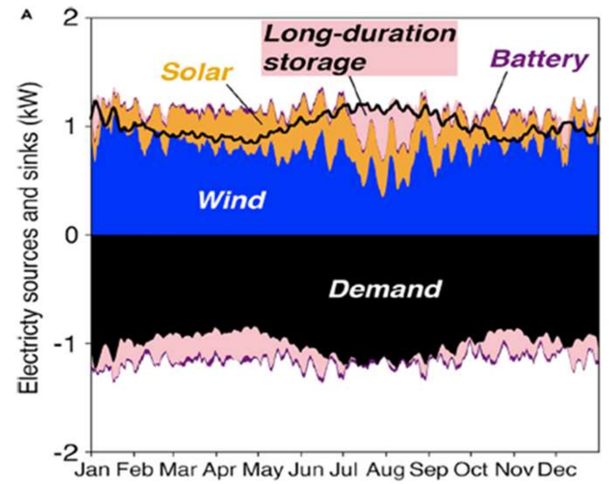
By 2040, LDES need to have scaled up to **~400x present day** levels to **1.5–2.5 TW (85–140 TWh). 10%** of all electricity generated would be stored in LDES at some point.

Our projections show that LDES need to be scaled up dramatically over the **next 20 years** to build a cost-optimal net-zero energy system.

Present-day LDES deployment is low, but momentum in LDES is growing exponentially.

Global deals in the LDES industry,
USD million





https://doi.org/10.1016/j.joule.2020.07.007

LDES value increases with tighter emissions targets: compete with low-cost dispatchable fossil fuels

Sources:
- Net-zero power: Long-duration energy storage for a renewable grid, McKinsey 202

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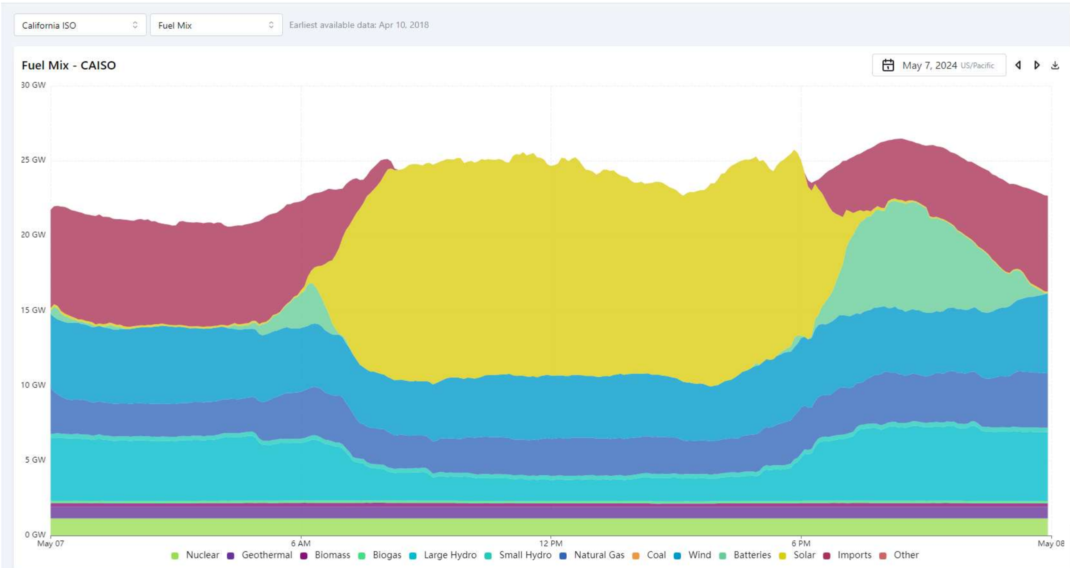
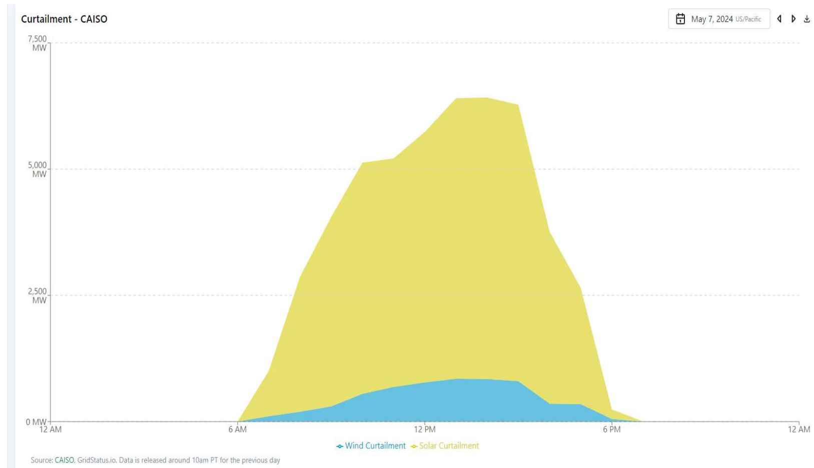
Energy Storage: Long Duration Storage Needed





https://www.gridstatus.io/graph/curtailment?iso=caiso&date=2024-05-07

https://en.wikipedia.org/wiki/California_Independent_System_Operator

Curtailment a short-term strategy not a solution

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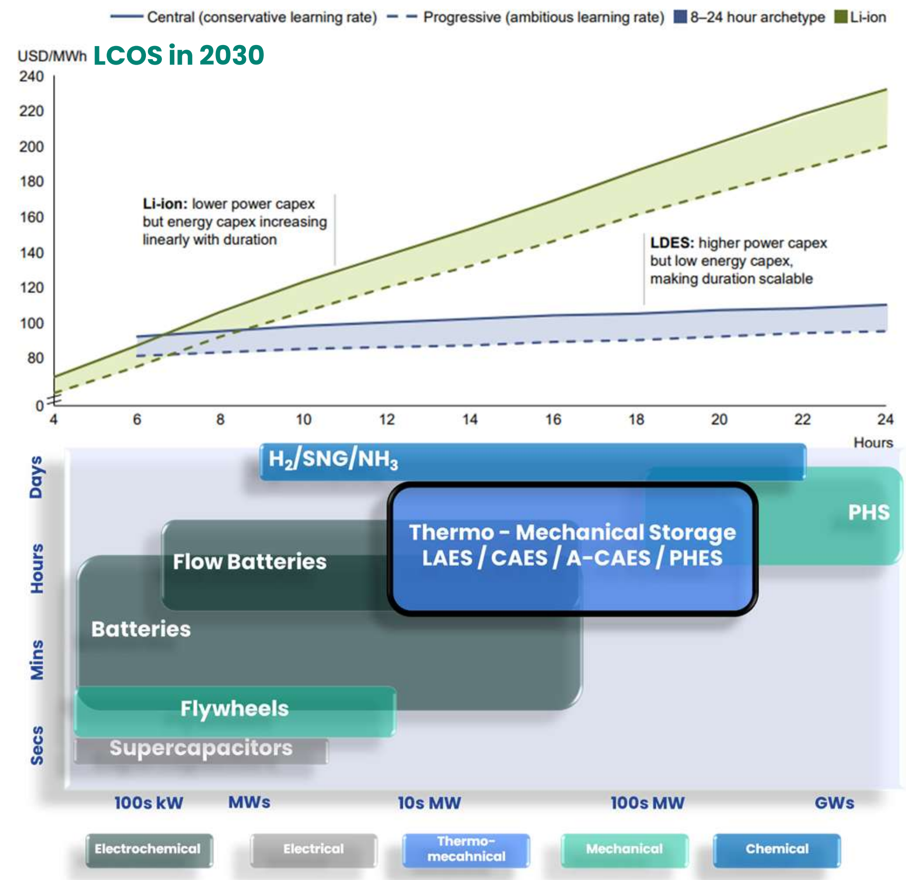
Long Duration Energy Storage Systems



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Energy Storage: CAES

Basic principle

- **Compress AIR storing heat using surplus renewable energy.**
- **Recover energy re-using Air and heat to cover Energy power gap**

Goal

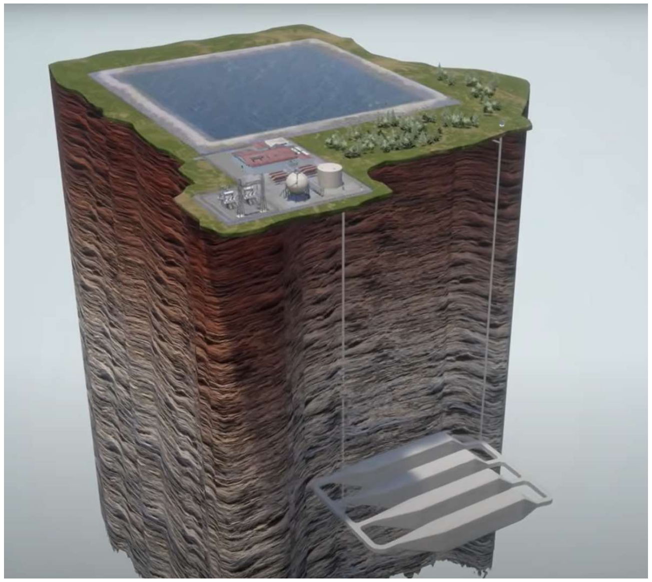
- Use off-peak or excess electricity to store energy that can be reused at a later stage to stabilize grid

Benefits

- Large delivered power up to 100 MW and above
- CO_2 neutral

Application Challenges

- Very quick start up to compete with batteries
- Suitable location for storing air (CAES)



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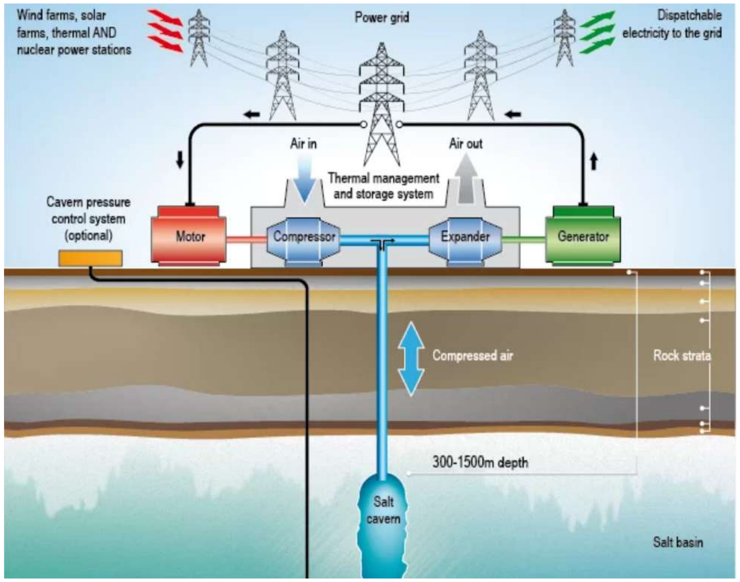
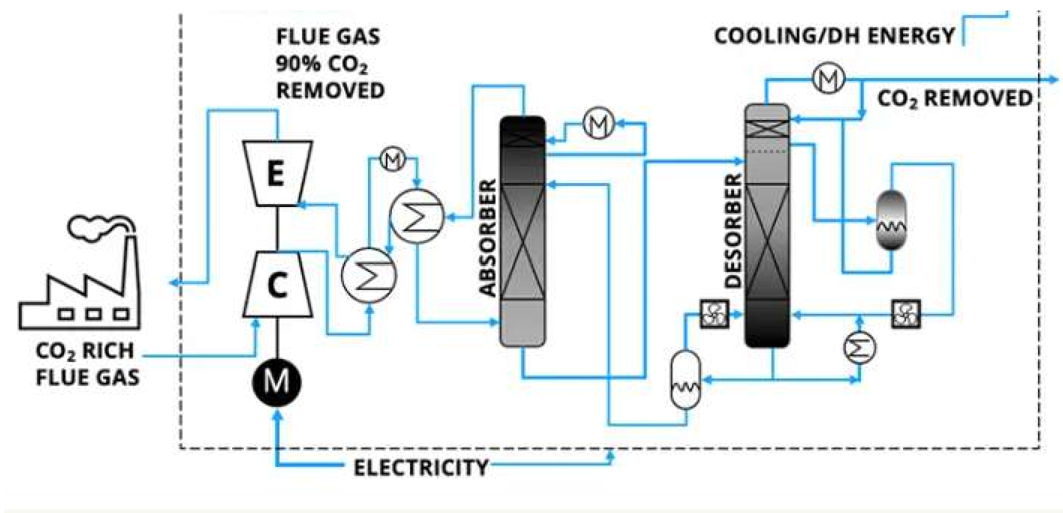


ISOCHORIC

HPC Carbon Capture Process



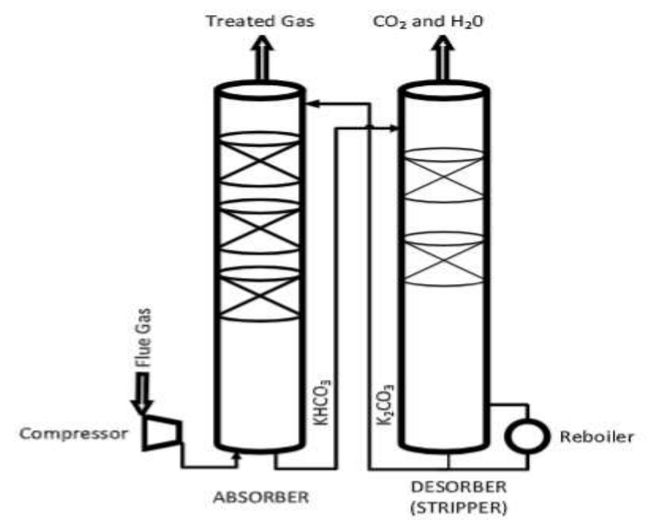


Fig. 2. Schematic of the HPC process.

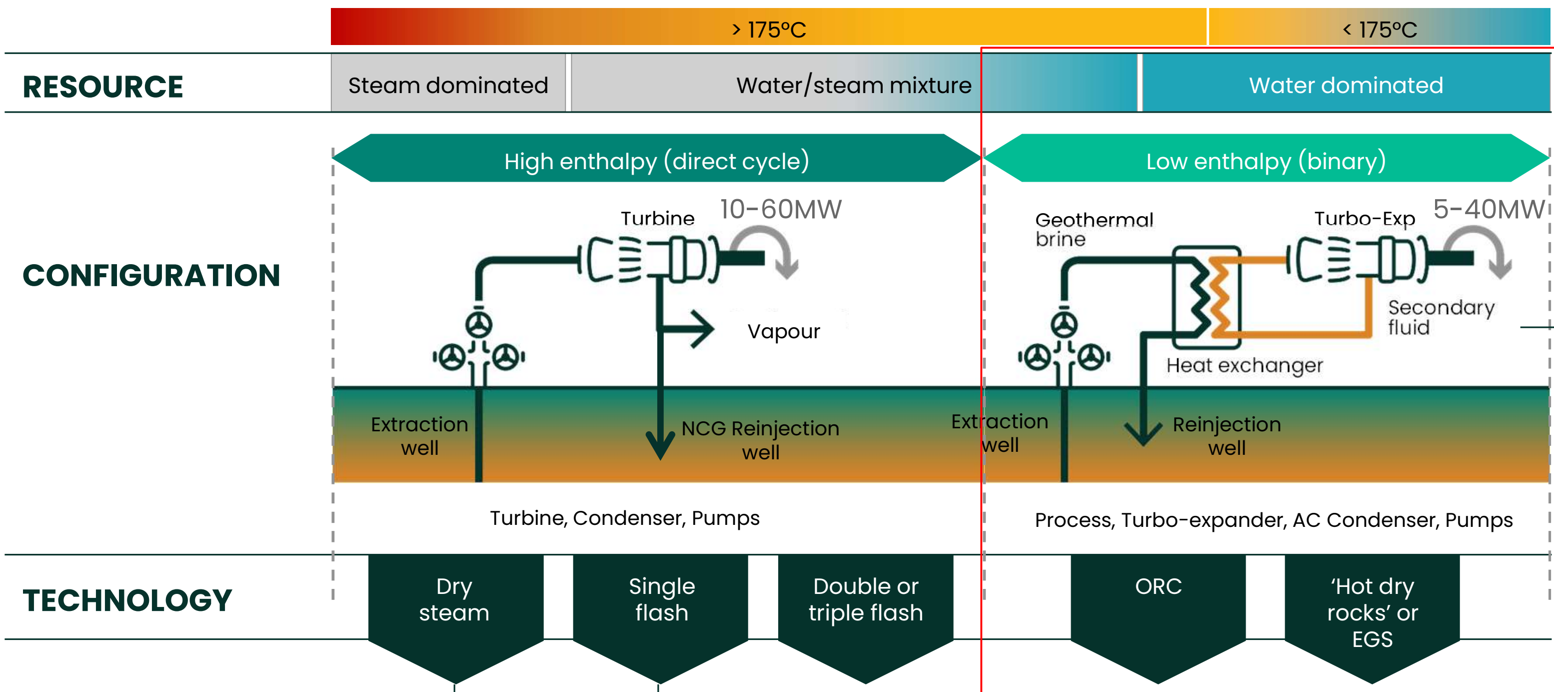
The reactions in the absorber and desorber columns of HPC process are reversible and proceed from left to right in the absorber and from right to left in the desorber:

$$K_2CO_3 + CO_2 + H_2O \Leftrightarrow 2HCO_3^{-1} + 2K^+$$

- Hot Potassium Carbonate used to strip CO2 from flue gas before being released in atmosphere
- Flue gas compressed to 5-7 bar to be treated
- Residual enthalpy of the cleaned gas (5-7bar; ~250°C) recovered by an Expander to reduce Compression work

Geothermal

Thermodynamic cycle adaptation depending on resource conditions

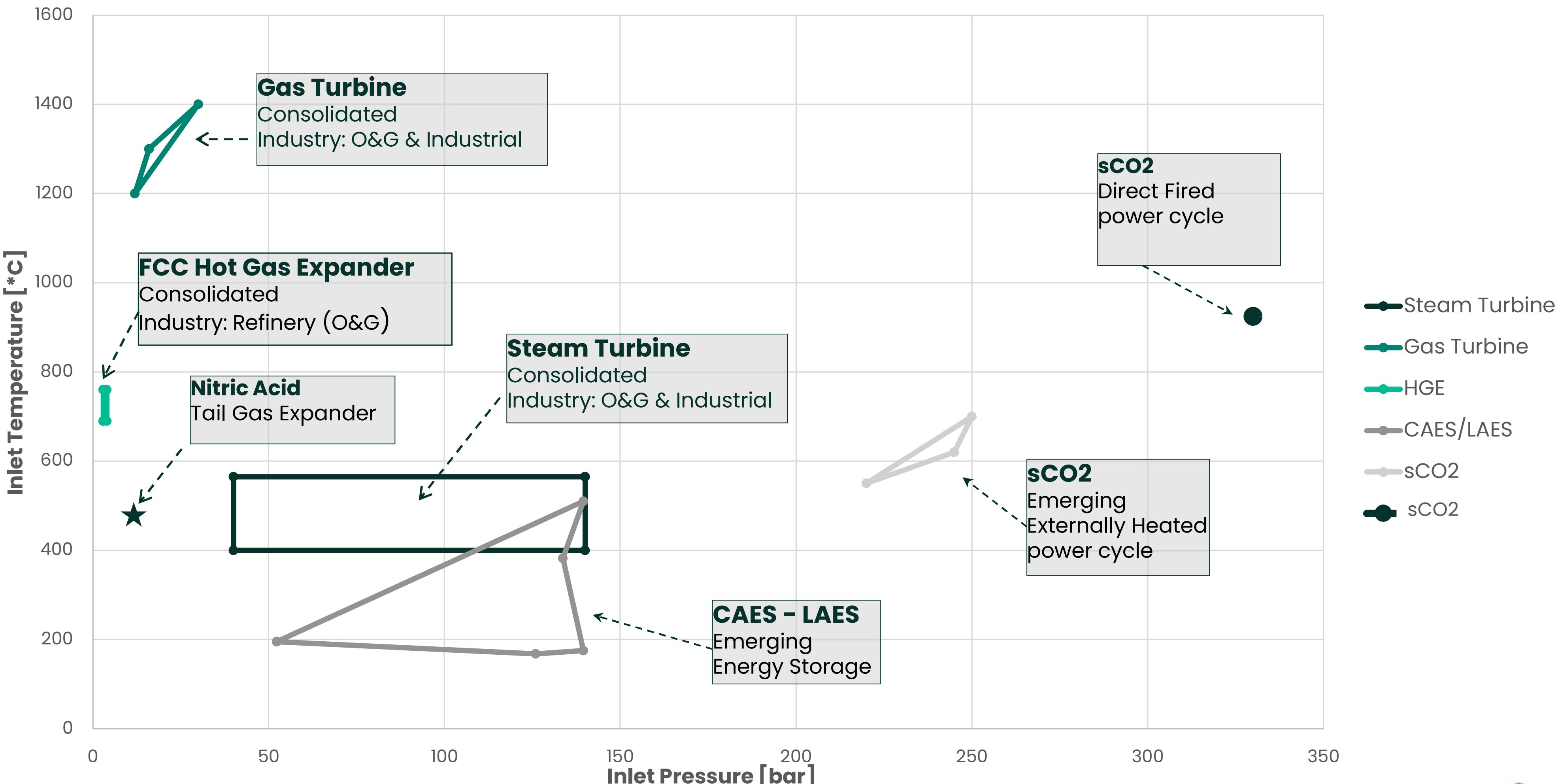


Binary/Organic Rankine Cycle
- Operate at **lower water temperatures: 130-250 °C.**
- The **organic working fluid with a low boiling point** uses the heat from the hot water to boil.

Direct-dry steam power plants
- **High enthalpy vapor-dominated resources**
- **Highest efficiency** among geothermal power plants
- **Simple** to operate
- Relatively **low capital costs**

Single / dual flash power plants
- Most common type of geothermal power plants
- **Medium- to high-enthalpy liquid-dominated resources**

Baker Hughes Axial Expanders design space



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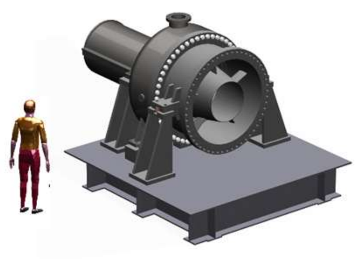
Baker Hughes Axial Expanders architectures

sCO2 Expander
Desolination

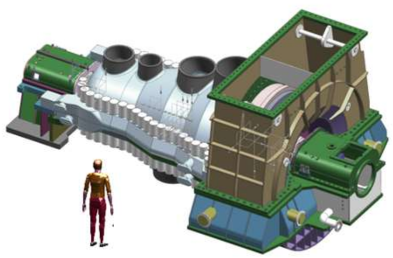
- 2.5 MW
- 550°C-200 bar at inlet
- 93 bar at exhaust
- Mixture CO_2- SO_2
- 17000 rpm, 5 stages
- Transcritical cycle (CSP)
- Unit test

Geothermal ORC Expander



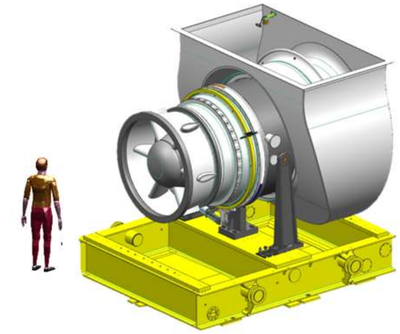
- 6 frames to cover power from 5 to 20 MW
- Customized gas path
- Hydrocarbons or Refrigerant Gas

CAES Expander



- Up to 100 MW
- 195°C-55 bar at inlet
- 1 bar at exhaust
- Customized gas path
- Air
- 3000/3600 rpm

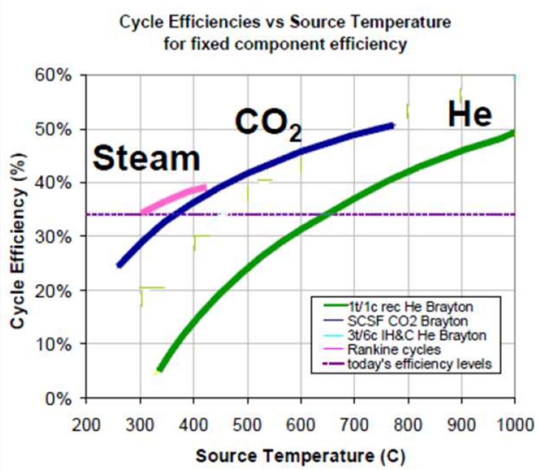
HPC Expander

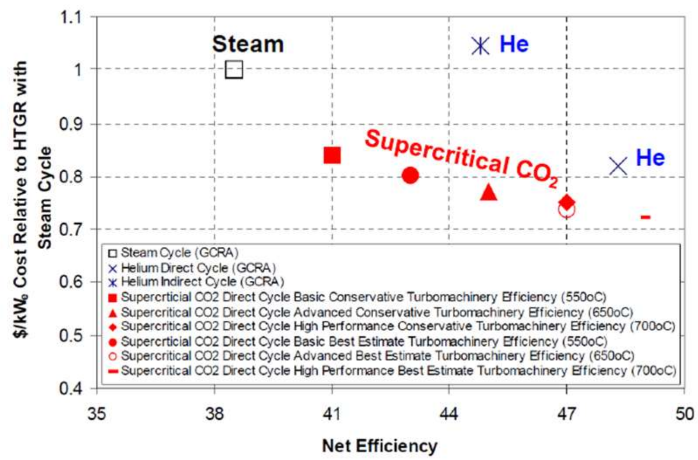


- 4 frames for power up to 20 MW
- 180÷220°C-6÷8 bar at inlet
- 1 bar at exhaust
- Customized gas path
- Nitrogen
- Up to 6500 rpm, 3 stages

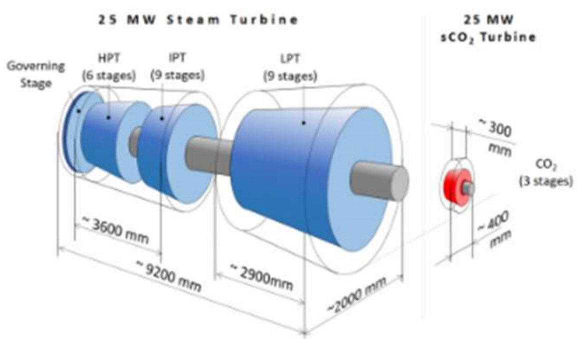
sCO2 Cycles

Why sCO2?

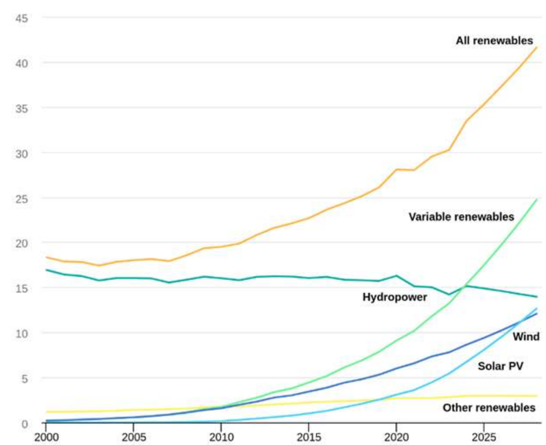




Sources: Wright (2011) and Dostal (2004)



Reproduced by: Scarabeus project website (https://www.scarabeusproject.eu/)



Source: Renewables (analysis and forecast to 2028), IEA (2023)

Main expectations and claims of sCO2 technology are:

- Efficiency improvement.
- Smaller turbomachinery & compact footprint.
- Lower costs.
- Increased operational flexibility (to cope with growth of renewables).

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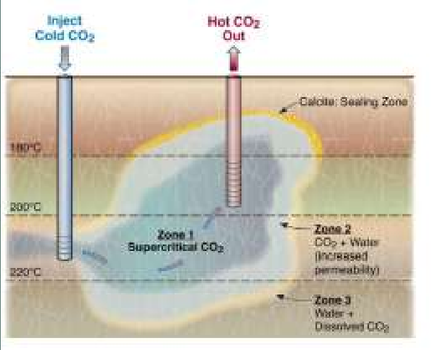
sCO_2 power cycle applications

Concentrated Solar Power

Fossil Fuel



Geothermal

Nuclear

Waste Heat Recovery

Ship-board propulsion

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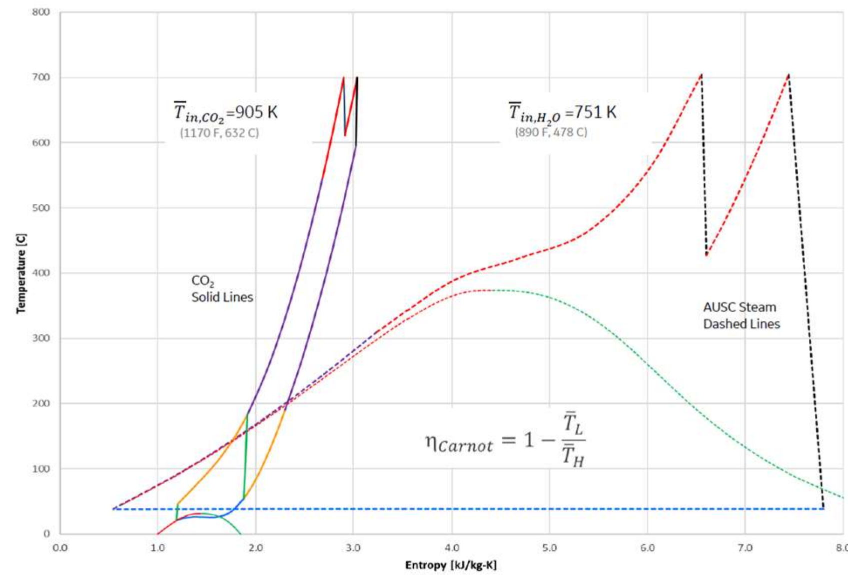
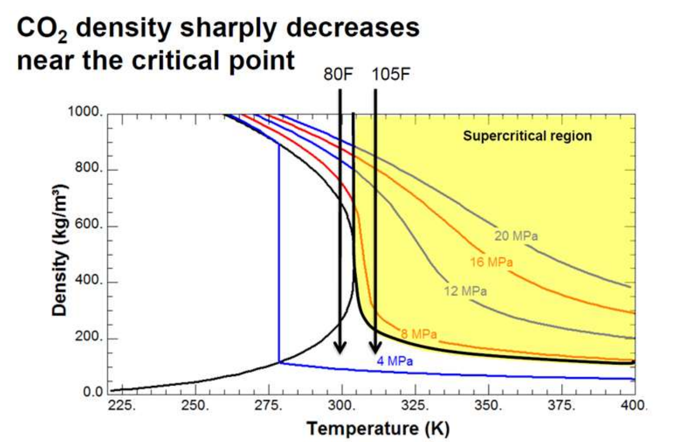
sCO2 Fluid Characteristics

- Critical temperature near ambient temperature
- Enables design of high thermodynamics efficiency cycles
- High density (compared to traditional fluids) => Smaller machinery

	Air	Steam	CO2
Critical Temperature (°C)	-140	374	31
Molar Mass (kg/kmol)	29	18	44
Cp (kJ/kg°K)	1.15	2.73	1.28
Density (kg/m3)	82	60	128
Speed of sound (m/s)	667	731	502

Properties at 700°C and 250 Bara (Cp, Density, Speed of sound)

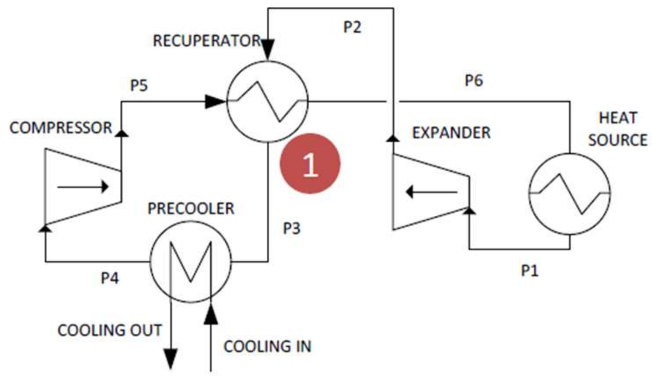


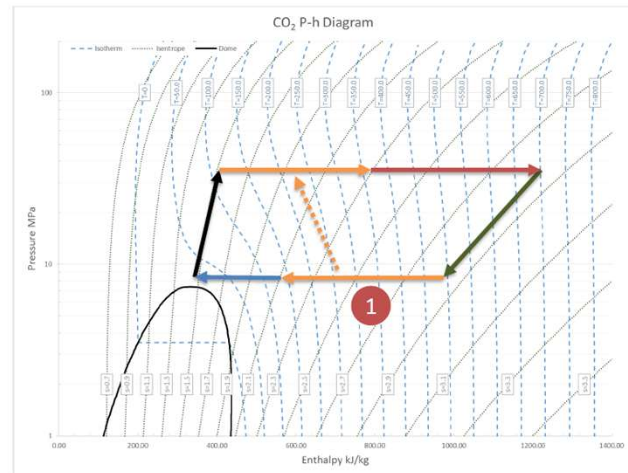


Source:Jason C. Wilkes, Tutorial: Fundamentals of supercritical CO2, Supercritical CO2 power cycle symposium (2024)

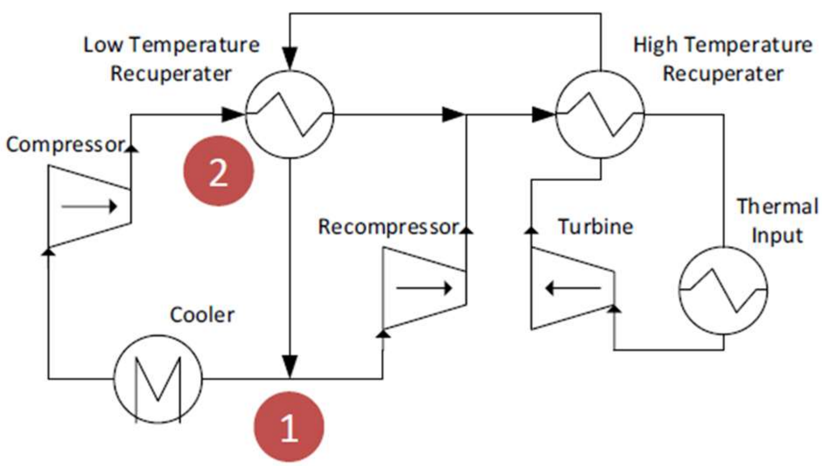
Supercritical sCO_2 cycles typical configurations

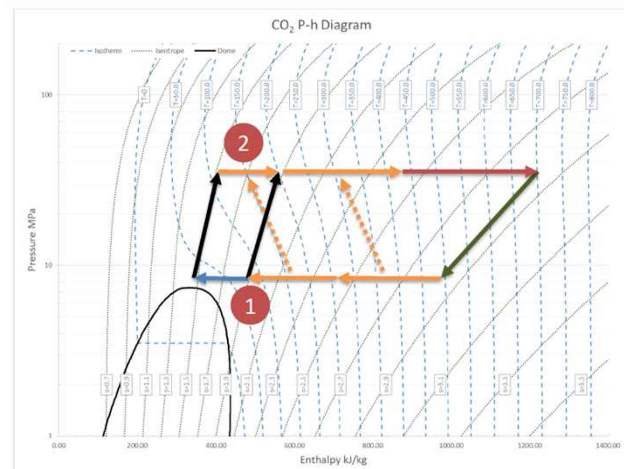
Simple Recuperative



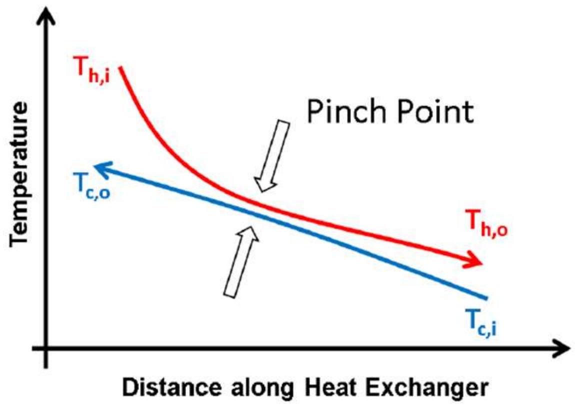


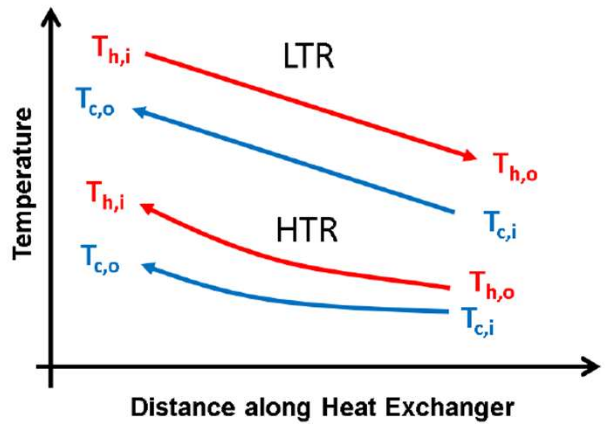
Recompression





Rationale of recompression cycle layout





Reproduced by:Jason C. Wilkes, Tutorial: Fundamentals of supercritical CO2, Supercritical CO2 power cycle symposium (2024)

Recompression cycle layout (heat recovery split into HP and LP recuperator), allows to reduce irreversibilities in the internal heat exchange processes.

The compression work increase (recompressor suction is far away by the critical point) is more than compensated by the irreversibilities decrease.

Minimization of the irreversibilities crucial also for the external heat exchange (primary heat source).

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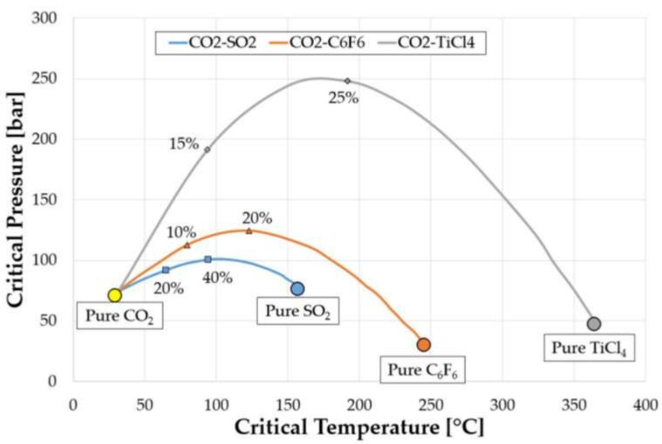
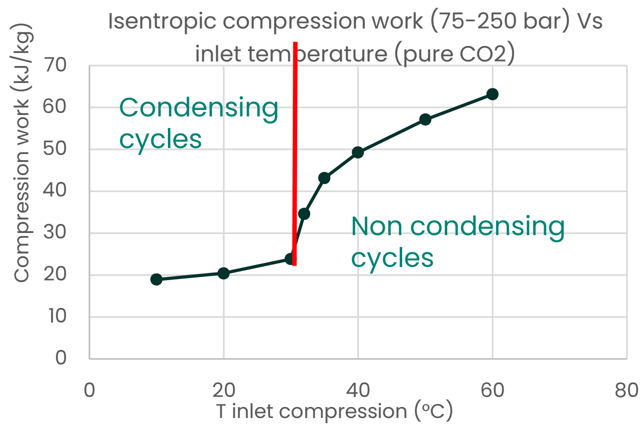
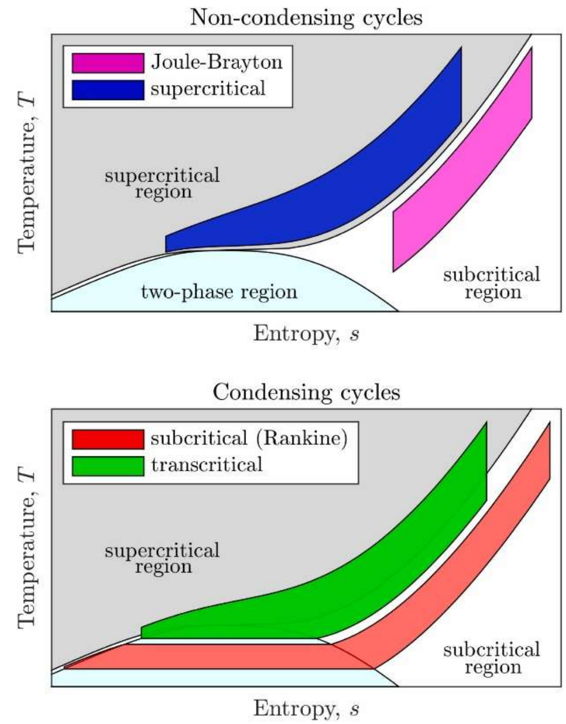
Transcritical Condensing (Rankine) Cycle

- **Transcritical cycles** attractive to **reduce the compression work and enable high ambient temperature** applications (CO_2 critical temperature 31°C)
- **Dopant addition** allows to shift the critical temperature of the mixture with respect to the pure CO_2 case (up to **60-65°C**)







Source: M.T. White, G. Bianchi, L. Chai et al., Review of supercritical CO2 technologies and systems for power generation, Applied Thermal Engineering (2023)

sCO_2 Turbomachinery technical challenges

BH sCO_2 Axial Expanders

sCO2 Axial expanders developed in the framework of **Horizon 2020 (Pictures in scale)**

Desolination

- Started **2021**. Prototype in 2025**.**
- **2.5 MW** (~2MW$_e$).
- **550°C-200 bar** at inlet.
- 93 bar at exhaust.
- Mixture CO_2- SO_2.
- 17000 rpm, 5 stages.
- Transcritical cycle (CSP).

The DESOLINATION project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022686

sCO_2-Flex

- Started **2018**. No prototype built**.**
- **~40 MW** (25 MW$_e$).
- **620°C-245 bar** at inlet.
- 81 bar at exhaust.
- Pure CO_2.
- 9000 rpm, 5 stages.
- Supercritical cycle (coal fueled).

The sCO2-Flex project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement Nº 764690

Scarabeus

- BH joined in **2020**. No prototype built**.**
- **~130 MW** (100 MW$_e$).
- **700°C-240 bar** at inlet.
- 81 bar at exhaust.
- Mixture CO_2- SO_2.
- 3000 rpm, 14 stages.
- Transcritical cycle (CSP).

The SCARABEUS project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 814985

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sCO_2 Expander Main Design Challenges

Dry Gas Seal technology and cooling system: DGS required to minimize shaft end leakage. Existing DGS technology (limited at ~250ºC) not compatible with expander conditions=> dedicated cooling system required.

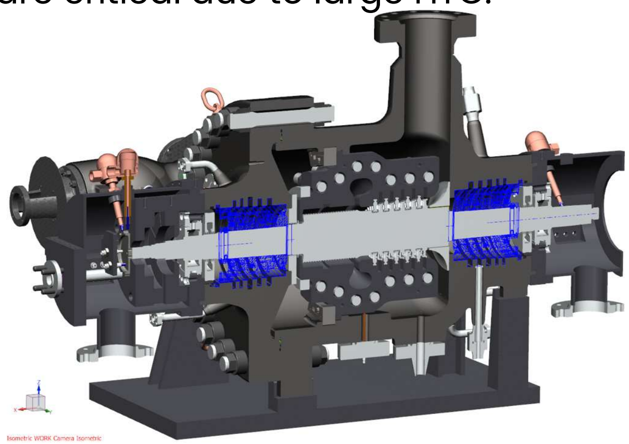
Rotordynamics: high fluid density leads to strong destabilization effects.

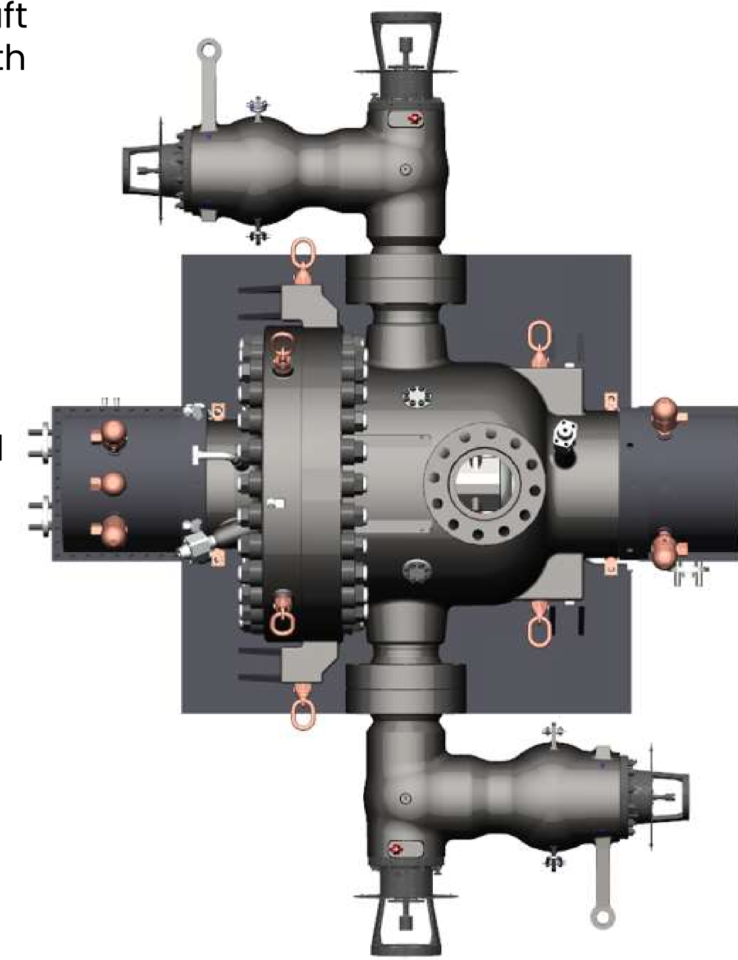
Performance: low volume flow, low aspect ratio blades, low cycle pressure ratio. EOS Modeling in case of CO_2 mixtures.

Materials compatibility: nickel-based alloy required to resist CO_2 corrosion and carburization at high temperature. Possible dopants exacerbates material compatibility.

Manufacturability: required alloys manufacturing process not consolidated for the expander commercial scale size.

Thermal stresses management: despite the advantage of reduced dimensions, thermal stresses are critical due to large HTC.





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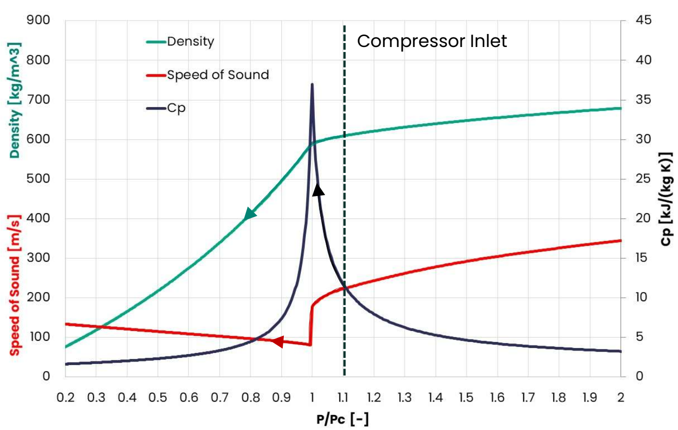
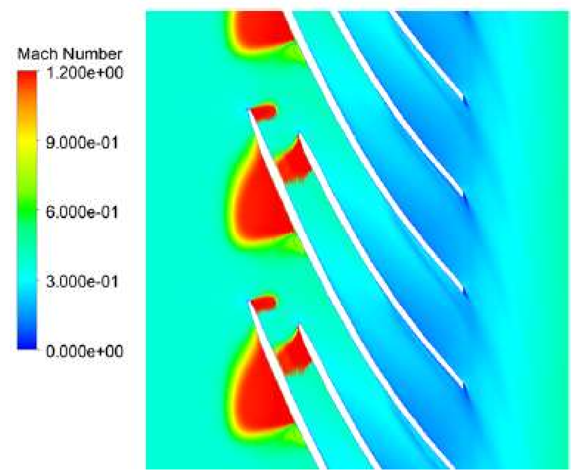
sCO_2 Compressors Main Design Challenges

- Main compressor suction condition close to CO_2 critical point leads to possible uncertainty in performance predictability with strong gradients in thermodynamic properties approaching saturation line
- Close to the critical point local expansions in proximity of the blade surfaces might induce phase transition with abrupt change in speed of sound requiring specific design optimization to reduce two-phase region
- A margin wrt saturation line and critical point is required to preserve performance reliability and compressor controllability
- High power density machine with flexible rotor: mechanical configuration and rotor dynamics





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Dry Gas Seals

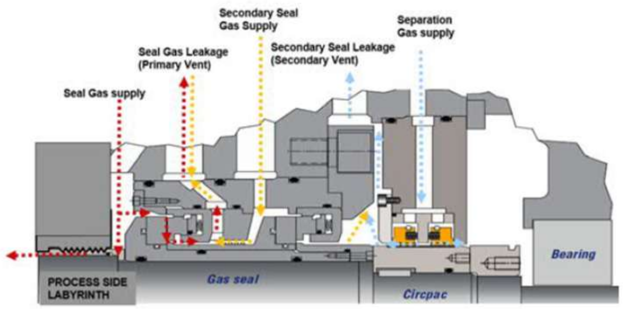
PURE CO_2

- DGS are **essential** to avoid unaffordable quantities of CO_2 released into the atmosphere: gain with respect to labyrinths is some orders of magnitude!
- DGS technology is currently available for low temperatures (**~250°C**): a dedicated **cooling** system is necessary. Tradeoff between cooling effectiveness and thermal stresses minimization in hot components is a tricky task.
- **Primary vent management**

BLENDED CO_2

- Even a minimal release of process mixture into the atmosphere is to be avoided (owing to the nature of all the possible dopants): necessary a **buffer** with **pure CO_2**. To minimize the buffer flow entering the loop (and diluting the mixture), a peculiar (more complex) DGS arrangement is necessary.

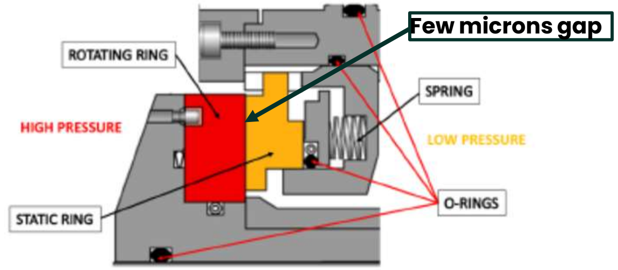
TANDEM DGS ARRANGEMENT



REPRODUCED BY

D. Steinmann et al, «Dry Gas Seals for Centrifugal Compressors in Supercritical CO_2 Application», 7th International sCO_2 Power Cycles Symposium (2022).

SINGLE DGS DETAIL



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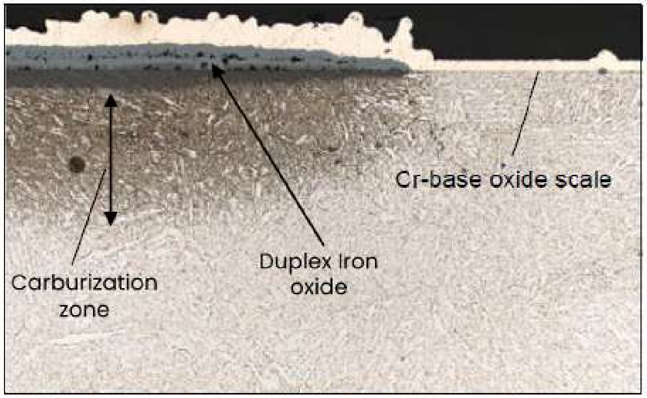
Materials Characterization and Manufacturing Industrialization

Materials Selection and Characterization

- **Carburization** limits application of 12Cr Steel at **400°-500°C.** switch to Ni-based alloys necessary at lower temperatures with respect to steam turbines.
- Nichel-Chromium based alloy required (**bulk or surface protection)**
- Switch to Ni-based alloys necessary at lower temperatures with respect to steam turbines.
- CO_2-SO_2 mixture poses further constraints on material selection
- Environment effect on critical material properties (LCF, FCG) under assessment

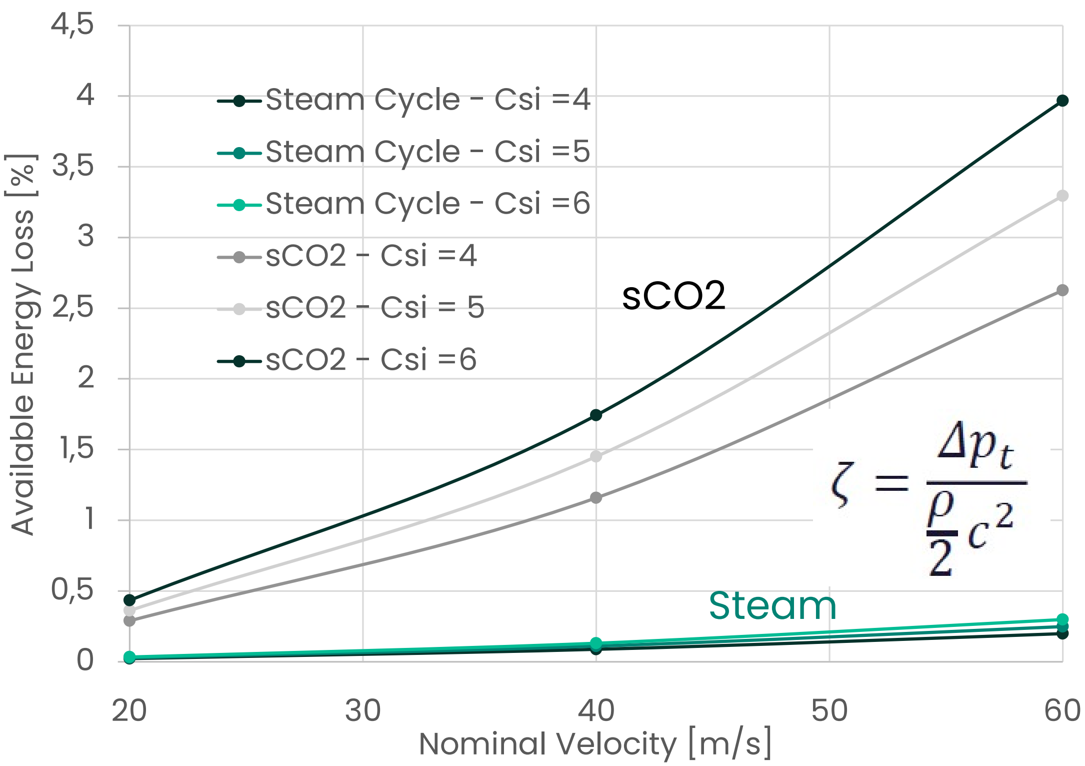


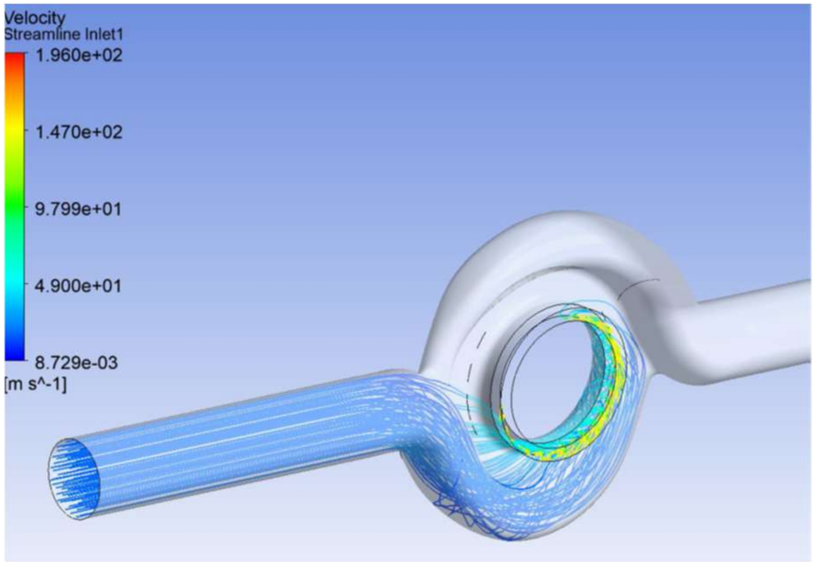
Etched metallographic cross section 12 Cr steel oxidized in Ar/CO_2 for 1000h at 550°C

Manufcaturing Process Industrialization

- Nichel based alloys **large forging and large casting** (commercial scale) size goes beyond existing qualified process
- Procurement of qualification trials started (5 tons shaft forging)
- Main components **manufacturing process optimization** as a function of size (rotor, external casings, blades, valves)

Inlet Pressure losses sensitivity



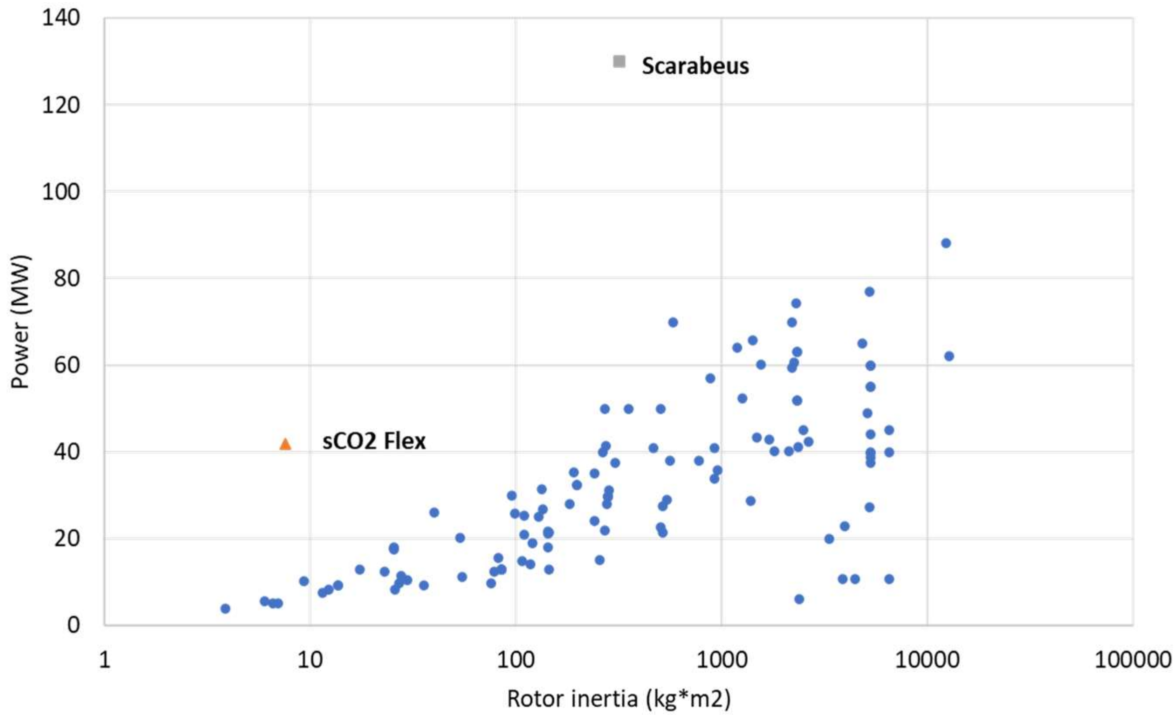


Available Energy:

sCO_2 Cycle = ~ 150 - 200 KJ/kg

Steam Cycle = ~ 1200 – 1400 KJ/kg

Power Density



Large power-to-inertia ratio establishes challenging requirements for **trip system responsiveness** and **rotor overspeed capability.**

Rotor-dynamic stability very much sensitive to **destabilizing** forces triggered by the large power density: **validated models for accurate predictions are crucial.**

Fluid forces drive large airfoil chords => **Low aspect ratio airfoils** => management of secondary secondary flows crucial for flow-path optimization.

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Conclusions

Summary of Turbomachinery for sCO_2

- **Energy transition** is boosting the development of new power conversion/ management solutions.
- **Compressors** primarily critical from an **aerodynamic** standpoint, **expanders** from a **mechanical design** perspective (**materials**, **rotordynamic** and management of **thermal stresses**).
- Turbomachinery design seems able to achieve the claims of sCO2 technology in terms of **efficiency** and **compactness. Cost**, at least with the current manufacturing capabilities, seems less promising than the initial expectation. **Operability** at system level is yet to be assessed in detail.
- **EU and DOE funding** are setting the technology development path in the initial phase then the industry has to continue and bring to commercial.
- Turbomachinery components risks are reduced with detailed analysis and specific component experiments but **system level and cycle operability validation requires demonstrator plants experience.**
- Raw materials and components manufacturing process industrial development crucial for **cost and lead time optimization.**

Current achievements Vs. goals

Efficiency improvement: 👍

Smaller machines & compact footprint: 👍👍

Lower costs: 👎

Increased operational flexibility: ?

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Conclusions

- **Energy transition** is boosting the development of new power conversion/ management solutions

- **EU and DOE funding** are setting the technology development path in the initial phase then the industry has to continue and bring to commercial

- Turbomachinery components risks are reduced with detailed analysis and specific component experiments but **system level and cycle operability validation requires demonstrator plants experience**

- Raw materials and components manufacturing process industrial development crucial for **cost and lead time optimization**

- **Factoring sustainability** into the energy transition equation could influence the development paths

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THANK YOU

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