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Fundamental Thermodynamic Insights on Compressor Train Design for Indirect-Heated Solar D-CAES

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Why CAES?

- **Decarbonizing the energy sector** requires phasing out fossil fuels and massively deploying renewables.
- Wind and PV are abundant but non-dispatchable, compromising grid stability.
- **Long-Duration Energy Storage (LDES) is instrumental** to reduce curtailment and ensure reliable, low-carbon electricity.
- Compressed Air Energy Storage (CAES) offers a unique balance of technical performance and economic viability over other LDES (**Table 1**).
- This study explores a **solar D-CAES concept** using indirect air heating – unlike conventional fired-CAES systems which burn natural gas.

Table 1. Key advantages of CAES

Other LDES	Solar D-CAES
PHES	Not geographically restricted (storage vessels)
Batteries	Lower LCOS, inertia
PTES	Higher RTE
Hydrogen (P2H2P)	Higher RTE and lower LCOS

Exergy-Based Framework

- The objective is to quantify how key design specifications impact system-wide performance.
- Flow Exergy: $\dot{E}_{flow} = \dot{m}[(H - H_0) - T_0 \cdot (S - S_0)]$
- Exergy balance (system / component) [1]:

$$\dot{E}_D = \dot{E}^{mech}_{Fuel} + \dot{E}^{th}_{Fuel} - \dot{E}^{mech}_{Product} - \dot{E}^{th}_{Losses}$$

- Key Performance Indicators (KPI):

$$RTE = \frac{\dot{E}^{mech}_{Product}}{\dot{E}^{mech}_{Fuel} + \dot{E}^{th}_{Fuel}} \qquad P2P = \frac{\dot{E}^{mech}_{Product}}{\dot{E}^{mech}_{Fuel}}$$

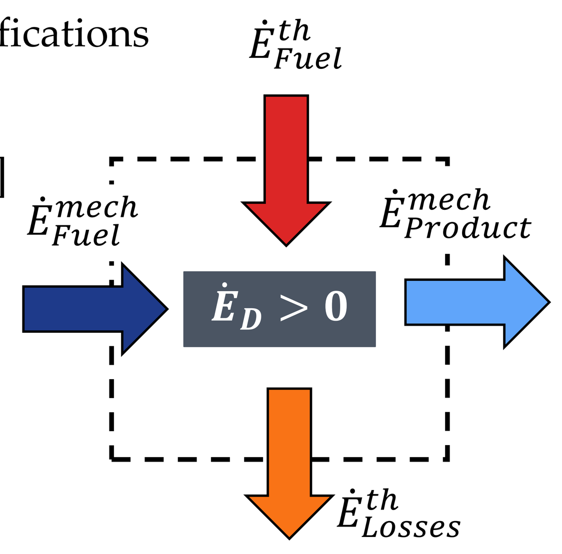


Figure 1. Exergy Balance

Exergy-Informed Design Guidelines

1. Number of Compression Stages (Figure 2):

- Mechanical fuel exergy demand decreases as the process become more isothermal.
- Reducing the number of stages from 4 to 3 significantly lowers thermal fuel exergy — but requires higher TES temperatures to efficiently recover compression heat.
- Larger compression trains also increase operating complexity and cost

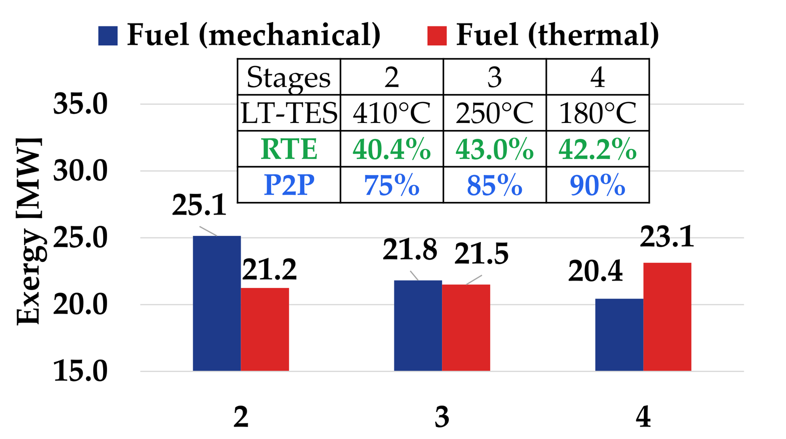


Figure 2. Number of compression stages

3. Organic Rankine Cycle [2]:

- Exergy losses can be partially recovered and converted into mechanical exergy (**Figure 4**).
  - LPT & HT-HEX Exhausts: increase product exergy
  - LT-HEX Exhaust: reduces mechanical fuel input.
- RTE and P2P improved by 12.1 p.p. and 29.8 p.p.

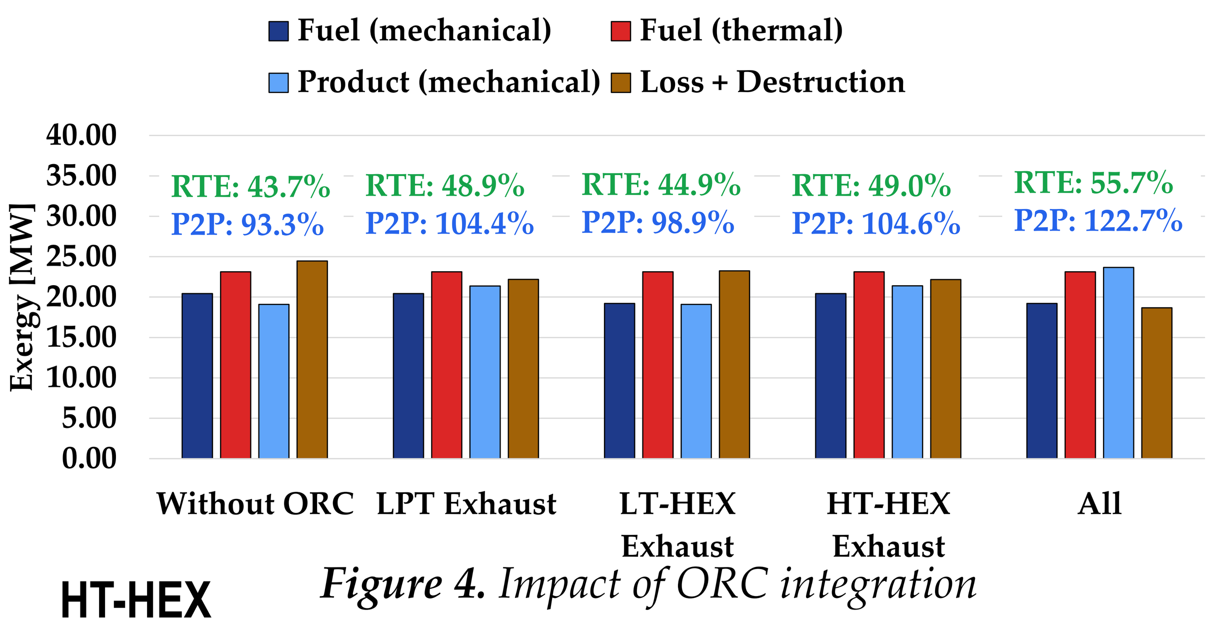
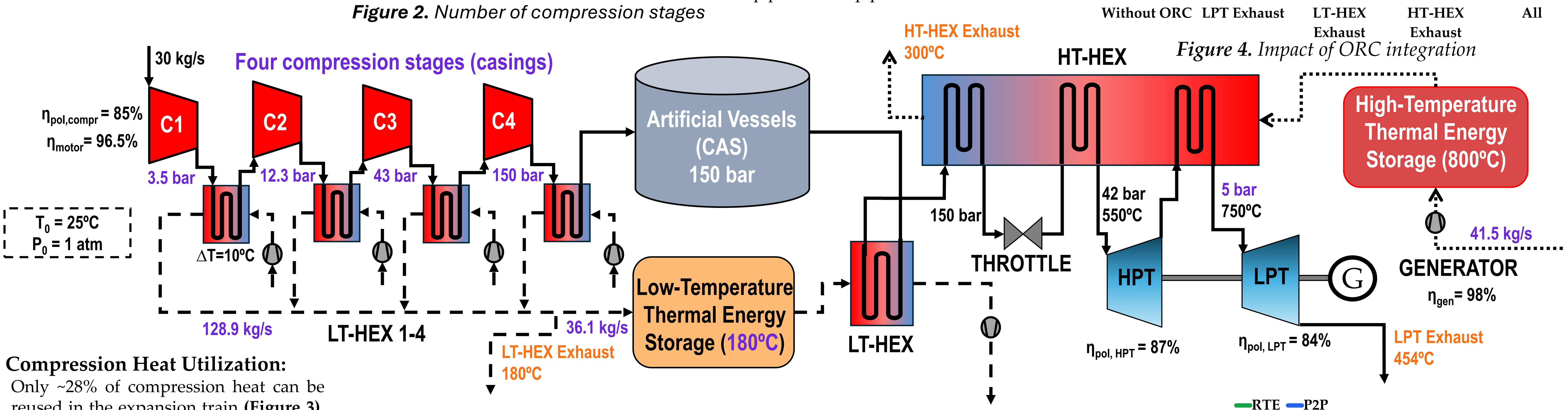


Figure 4. Impact of ORC integration



2. Compression Heat Utilization:

- Only ~28% of compression heat can be reused in the expansion train (**Figure 3**), roughly equivalent to the heat generated in one compression stage.
- This is due to the unbalanced number of LT-HEX units between compression (4) and expansion (1) trains.
- Storing more heat leads to an unnecessary oversizing of the LT-TES (higher cost) and increased parasitic consumption in blowers (lower product exergy).

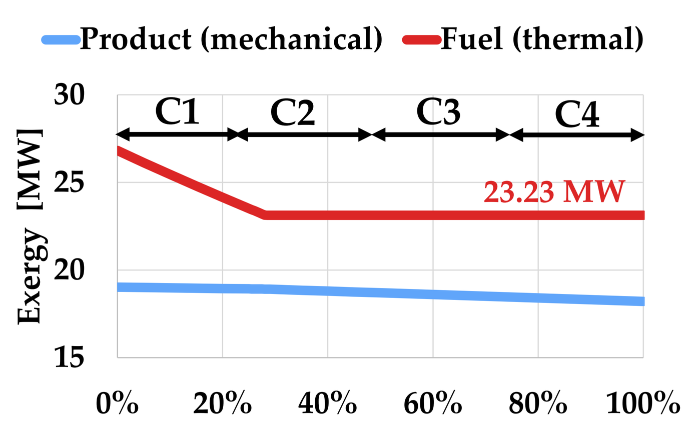


Figure 3. Fraction of compression thermal exergy stored in LT-TES

4. Expansion Train Optimization:

- Adjusting LPT inlet pressure allows optimizing the balance between higher P2P and higher RTE (**Figure 5**).
  - Max P2P: 122.7% (5 bar)
  - Max RTE: 58.2% (17 bar)

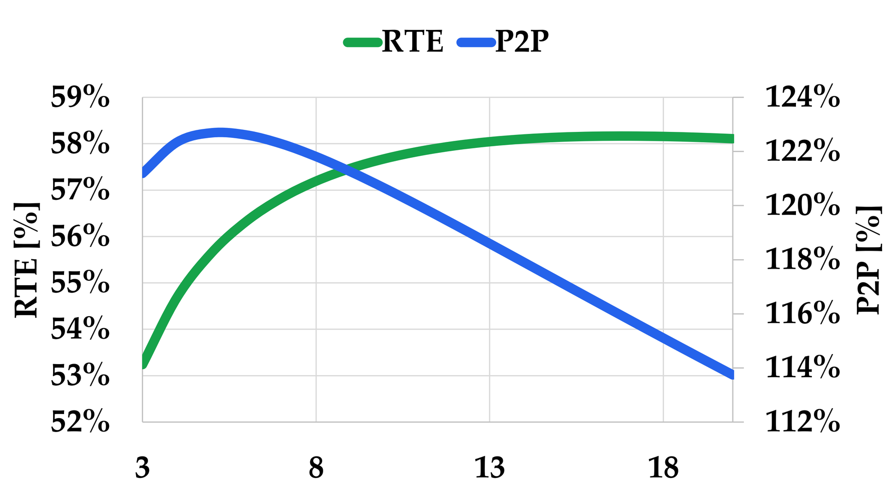


Figure 5. Low-Pressure Turbine Inlet Pressure [bar]

Sankey Diagram

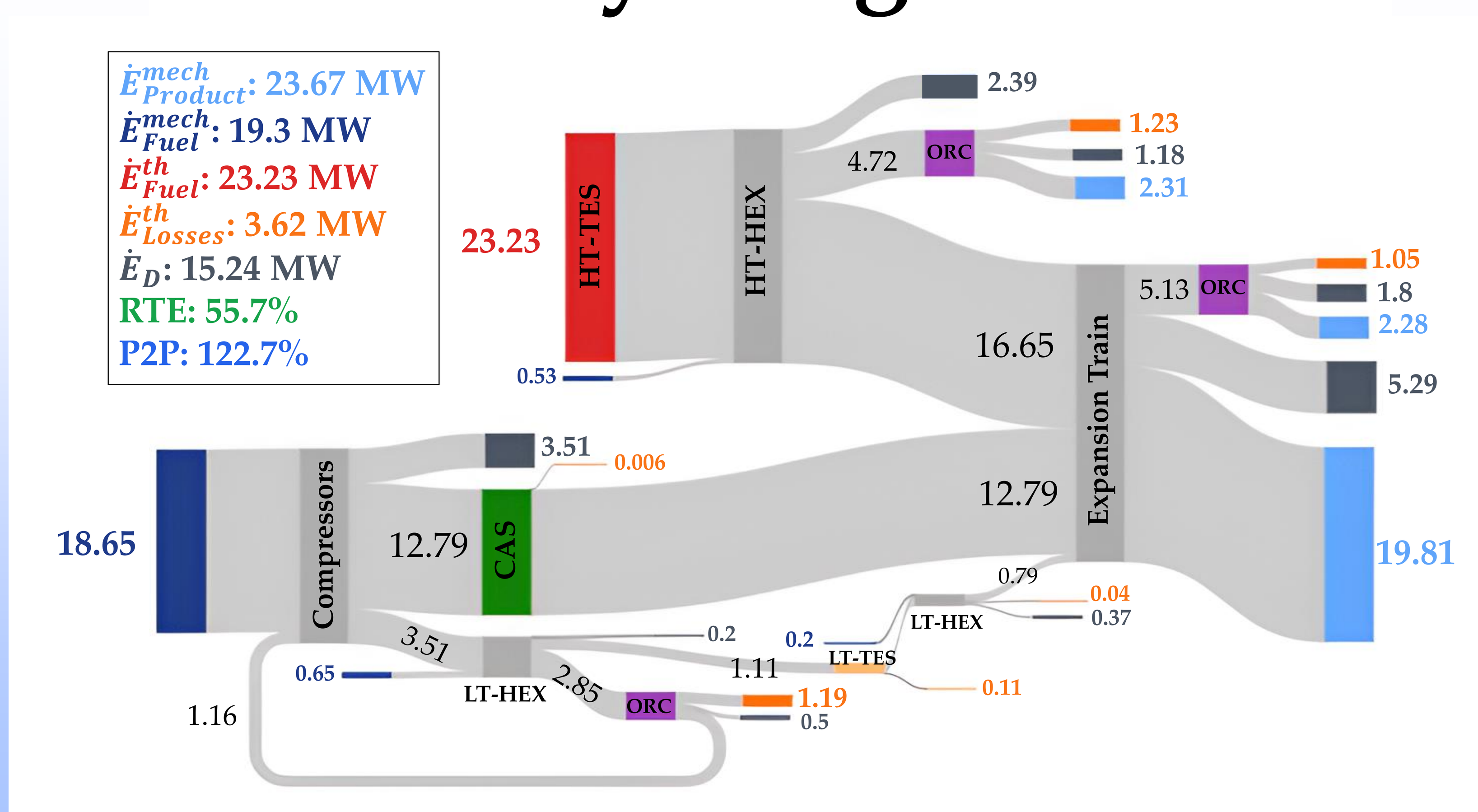


Figure 6. Sankey Diagram. Values in MW.

Conclusions

This study identifies key design trade-offs and performance drivers in Solar-Heated D-CAES system:

- Increasing the number of compression stages improves CAES performance but increases system complexity and cost.
- Most compression heat cannot be reused during expansion → LT-TES sizing must align with the actual thermal exergy demand on the expansion train.
- ORC integration effectively recovers exergy losses, boosting both Power-to-Power and Round-Trip efficiencies.
- LPT inlet pressure is a key optimisation variable, enabling a trade-off between P2P and RTE.

References

[1] Tsatsaronis, G. (2007). Definitions and nomenclature in exergy analysis and exergoeconomics. *Energy*, *32*(4), 249-253.

[2] Rodríguez-deArriba, P. et al. (2025). Multi-objective optimisation of expansion trains in CAES: Incorporating Organic Rankine Cycles for improved Efficiency, in: ASME Turbo Expo: Turbomachinery Technical Conference and Exposition 2025.