THERMODYNAMIC AND MARKET-ORIENTED OPTIMIZATION OF A BIDIRECTIONAL SCO2 BRAYTON HEAT PUMP/HEAT ENGINE SYSTEM FOR WASTE-HEAT-ASSISTED POWER-TO-HEAT-TO-POWER

Summary

This work investigates a bidirectional supercritical CO2 (sCO2) Brayton concept for power-to-heat-to-power operation with thermal energy storage (TES). In charging mode, a closed Brayton heat pump upgrades waste heat and charges the TES; in discharging mode, a Brayton heat engine reconverts the stored heat into electricity. The system is assessed for a representative 10 MW_{th} waste heat source at 300–350 °C, motivated by a data center case in which a solid oxide fuel cell (SOFC) afterburner provides the thermal input. The methodology combines a large static design-space screening with dynamic annual simulations and market-based dispatch optimization. A key finding is that optimizing only for design electric round-trip efficiency does not necessarily lead to the most economic system design, as it may result in only a small temperature lift that does not justify the investment of TES. The study further shows that charging and discharging favor different cycle architectures and operating conditions: a simple Brayton heat pump is preferred for charging, whereas a recuperated Brayton heat engine is favored for discharging. Annual simulation results indicate that local electricity-price spreads dominate profitability, while ambient effects are of secondary importance.

Keywords: sCO2 Brayton cycle, heat pump, heat engine, Carnot battery, thermal energy storage, power-to-heat, waste heat valorization, electrification

Field of application for the findings: Sustainable Energy Infrastructure and Electrification; Thermal Energy Storage; Sustainable Heat for Industrial Process; Power-to-X, Thermal Energy Storage (Carnot Battery)

Addressed audience: Researchers and engineers in thermal energy storage, heat pumps, Brayton cycles, waste-heat recovery, system simulation, and energy-system electrification

1. Introduction

Supercritical CO2 Brayton systems are promising for compact heat pumps, heat engines, and Brayton-based Carnot batteries because CO2 above the critical point combines high density with favorable expansion and heat-transfer behavior. These characteristics are attractive for waste-heat utilization and thermal storage applications in the moderate-to-high temperature range. In the present work, a bidirectional sCO2 Brayton cycle is studied in which charging is performed by a closed heat pump and discharging by a heat engine coupled via a single-tank stratified TES. The intended application is a data center partly supplied by an SOFC, whose afterburner and several pre-heaters in series provide flue gas at 300–350 °C. The charging cycle recovers this waste heat and raises it to a storage-suitable temperature, while the discharging cycle can later supply electricity during high-price periods (Figure 1).

A central aspect of the study is that charging and discharging are first optimized as separate cycles with separate turbomachinery. This avoids constraining both modes to a common machine set before their thermodynamic optima are understood. Only after this first screening, overlap in pressure ratio, mass-flow range, and operating range can be evaluated for a possible future reversible or shared machine concept.

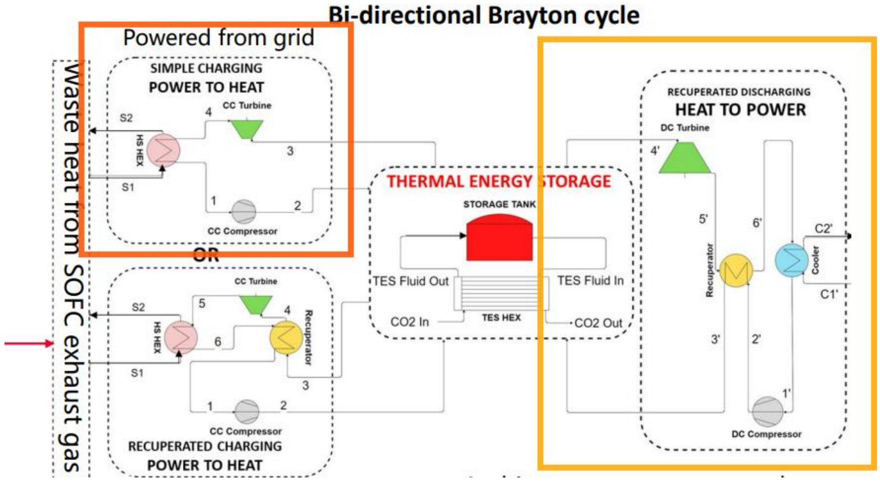

Figure 1: Reference Pumped Thermal Energy Storage (PTES) configuration: simple charging recuperated discharging (Shamsi et al. 2024)

2. Methods

The assessment is performed in two stages. First, static cycle models are used for thermodynamic screening and pre-sizing. The design space includes charging and discharging pressure ratios, CO2 mass flow rate, TES hot and cold temperatures, and compressor inlet pressure. For the representative 10 MWth waste-heat source, a total of 511,875 configurations are evaluated. In this stage, the key performance indicator (KPI) is the design electric round-trip efficiency, defined as the ratio of net electric power generated during discharge to electric power consumed during charging. However, this KPI is interpreted in conjunction with TES temperature limits, achievable temperature rise, waste-heat boundary conditions, heat-exchanger implications, and compatibility of heat-pump and heat-engine operating points.

In the second stage, selected candidate cycles are transferred to a dynamic system model in ColSim, Fraunhofer ISE’s in-house simulation environment. The dynamic model includes map-based compressor and turbine models with real-gas corrections, discretized heat-exchanger models, and thermocline TES models. Annual simulations are then used to optimize operation with respect to local electricity-market conditions. At this stage, the optimization target is no longer design-point round-trip efficiency, but annual net cash flow, reflecting electricity purchase during charging and electricity sales or avoided grid consumption during discharge.

3. Results

The thermodynamic screening reveals a clear asymmetry between charging and discharging layouts. Recuperation is beneficial in discharging mode because it reduces external heat demand from the TES and improves electrical efficiency. In charging mode, by contrast, recuperation is disadvantageous because it reduces the useful heat transferred to storage. The preferred unconstrained architecture is therefore a simple Brayton heat pump for charging and a recuperated Brayton heat engine for discharging.

The results also show that charging and discharging generally favor different pressure ratios and different CO2 mass-flow ranges. This means that enforcing a single shared compressor–turbine set too early in the simulation-assissted design process would often move at least one operating mode far away from its efficient region. With respect to design-point KPIs, the highest electric round-trip efficiencies are typically obtained at low charging pressure ratios and high discharging pressure ratios. However, these cases often yield only a small rise in temperature. This is one of the main findings of the study: maximizing design electric round-trip efficiency alone does not necessarily lead to the most economic system design. A small storage temperature lift reduces stored exergy and thus weaken the system value of TES.

When practical constraints are introduced, the preferred design space shifts towards the mid-efficiency configurations. Realistic TES temperature limits, waste-heat-source temperature, required temperature lift, waste-heat return temperature, and heat-exchanger implications significantly narrow the technically feasible region. Under realistic molten-salt TES constraints, moderate charging pressure ratios (resulting in storage temperature of about 400 °C) and moderate-to-high discharging pressure ratios become more attractive than the unconstrained round-trip-efficiency optimum (Figure 2). Dynamic annual simulations further show that the decisive external factor is the local electricity market. For an investigated low electricity-price spread case in Dublin, the selected exemplary configuration does not reach positive annual cash flow, whereas two investigated Chinese market cases provide more favorable operating conditions because of larger price spreads. Ambient effects such as TES heat loss and cooling penalties are comparatively minor.

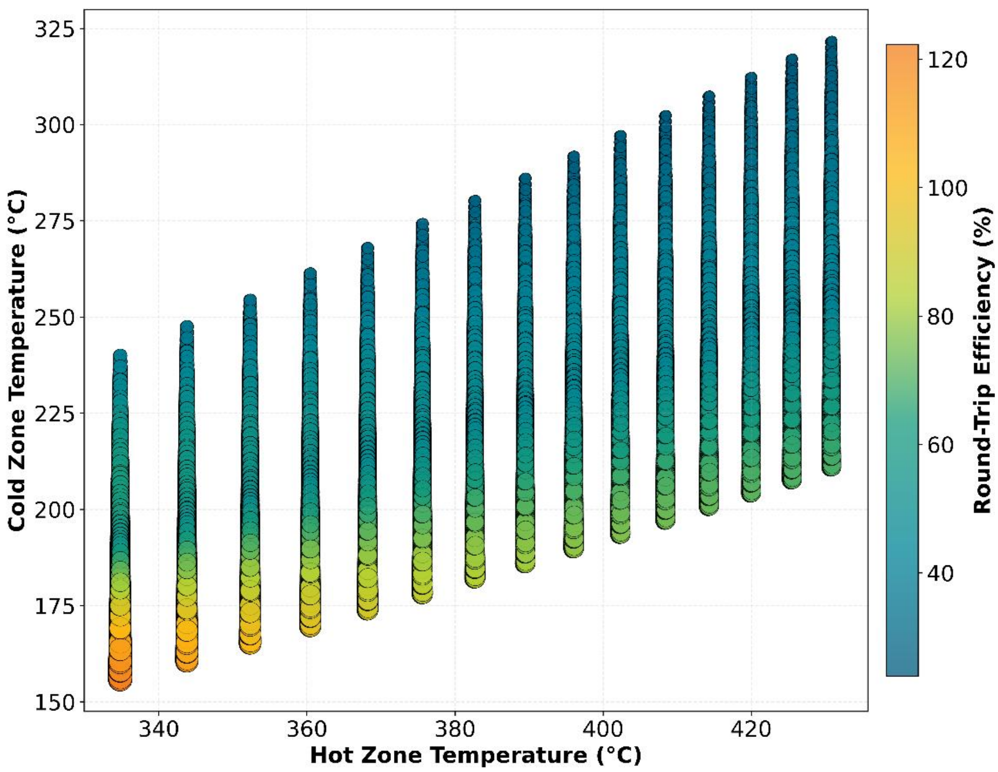

Figure 2: Influence of storage zone temperatures on electrical round-trip efficiency.

4. Conclusions and outlook

A bidirectional sCO2 Brayton PTES system can be a promising concept for waste-heat-assisted power-to-heat-to-power applications, especially when charging and discharging can be decoupled in time. The study shows that charging and discharging should first be optimized separately, and that the preferred baseline architecture is a simple charging heat pump combined with a recuperated discharging heat engine. It also shows that design electric round-trip efficiency is an important but insufficient selection criterion, since high efficiencies are associated with low storage temperature lift and lower economical benefits. Annual optimization demonstrates that market conditions, particularly electricity-price spreads, are more influential - for economic operation - than any other variable such as ambient temperature. Future work will focus on screening for operating-point overlap that may enable a reversible or shared-machine concept and comparison with a typical recuperated sCO2 Brayton cycle for waste heat recovery.

Publication bibliography

Shamsi, Syed Safeer Mehdi; Barberis, Stefano; Maccarini, Simone; Traverso, Alberto (2024): Thermo-economic performance evaluation of thermally integrated Carnot battery(TI-PTES) for freely available heat sources. In *Journal of Energy Storage* 97, p. 112979. DOI: 10.1016/j.est.2024.112979.