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SYSTEM-LEVEL OPTIMIZATION OF POWER-TO-HEAT CONVERSION WITH MOLTEN-SALT THERMAL STORAGE AND STEAM GENERATION FOR INDUSTRIAL PROCESS HEAT

Summary

Electrifying process steam generation with power-to-heat (P2H) conversion and molten-salt thermal energy storage (TES) must be cost-competitive under real tariffs. We simulate and co-optimize the sizing and operation of a P2H-TES unit and a steam generator, including a hybrid gas boiler. Historical day-ahead prices (2023–2025) and future projections (2028–2044) are used. Electricity and gas grid fees with energy and capacity components are explicitly modeled. The objective function minimizes LCOH, and we report OPEX, NPV and ROI; dispatch uses rolling horizons versus full-year planning. In the years 2023 to 2025, industrial grid charges make pure P2H-TES rarely economical. A gas backup improves near-term economics but increases energy losses. Future prices and rising CO_2 costs shift competitiveness toward P2H-TES with optimized sizing and operation. Sensitivity analyses reveal the impact of tariffs. The findings also provide insights into the required tariff structure to encourage the growth of these systems, to enable climate-neutral solution with predictable, competitive costs for steam in the range of approximately180–250 °C.

Keywords: power-to-heat, molten salt, thermal energy storage, process steam, LCOH, grid fees, rolling horizon, hybrid systems

Field of application for the findings: Industrial medium-temperature process heat; thermal storage; hybrid P2H/gas steam supply

Addressed audience: Energy system modellers, industrial heat engineers, project developers, utilities, and policy analysts

1. Introduction

Decarbonizing industrial process steam at 180–250 °C requires high-efficiency conversion and market-aware operation. Power-to-heat conversion coupled with two-tank molten-salt thermal energy storage (P2H-TES) can shift electricity use to low-price hours and deliver dispatchable steam, but industrial grid fees—especially capacity charges—and gas network tariffs significantly influence the levelized cost of heat. Building on prior assessments of molten-salt P2H-TES for steam (e.g., Trevisan et al.), we quantify when and how P2H-TES becomes competitive with gas-only and hybrid configurations by co-optimizing sizing and dispatch under historical day-ahead prices and future projections, with explicit electricity and gas tariff models.

2. Methods

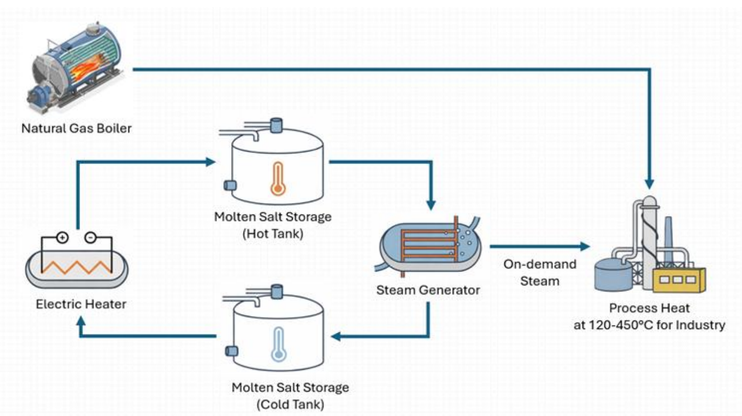

Fig. 1: Schematic of overall system (standalone P2H-TES system without gas boiler or hybrid system)

We model a standalone P2H-TES-steam-generator system and a hybrid system with a gas boiler. The TES is a two-tank molten-salt storage (sensible heat), charged via an electric heater and discharged through a steam generator as shown in Fig. 1.

We develop a tariff-aware optimization framework that ingests hourly German day-ahead electricity prices for 2023–2025 and future projections for 2028–2044 (based on Thelen et al.), together with electricity taxes/levies, grid fees split into energy and capacity components with usage-hour thresholds, gas prices including CO_2 pricing and gas network tariffs defined by energy and capacity ranges. The model reports levelized cost of heat (LCOH), operating expenses (OPEX), net present value (NPV) and return on investment (ROI). and tracks CO_2 emissions in hybrid operation. Component sizing (electric-heater power, TES capacity, and optionally gas-boiler size) is solved via mixed-integer optimization, while dispatch is linear; planning strategies compare full-year optimization to rolling horizons of three and seven days and to day-by-day control. Electricity tariffs are applied through explicit logic for energy- and capacity-based charges conditional on annual usage hours, and gas tariffs through range selection with base amounts and per-unit adders. Sensitivity analyses toggle capacity fees, vary the capital expenditure (CAPEX) financing factor, switch the sizing criterion between minimum LCOH and maximum NPV, and treat gas-boiler power as a decision variable to quantify impacts on economics and emissions.

3. Results

3.1 Historical prices (2023–2025)

Across 2023–2025, the standalone P2H-TES configuration is rarely economical when industrial electricity grid charges—especially capacity-based fees—are included. Optimizations that ignore these fees systematically oversize the electric heater and understate true costs, producing deceptively low LCOH during design while yielding higher realized LCOH once fees are applied. In hybrid layouts, the gas boiler tends to dominate dispatch under these market conditions, reflecting the combined effect of price levels and tariff structures.

3.2 Future projections (2028–2044)

Under forward-looking price and policy scenarios with higher CO_2 costs and evolving electricity price structures, competitiveness shifts toward P2H-TES. Both standalone and hybrid systems achieve lower LCOH than gas-only from the early- to mid-2030s when optimally sized and dispatched. In hybrids, the gas boiler mitigates exposure to capacity charges while enabling greater use of low/negative-price hours. Minimizing the gas-boiler size further reduces LCOH and improves NPV by reallocating energy toward electrification and lowering emissions. A representative CAPEX/OPEX breakdown is shown in Fig. 2. The impact of including versus excluding grid fees on LCOH for a medium load profile is shown in Fig. 3.

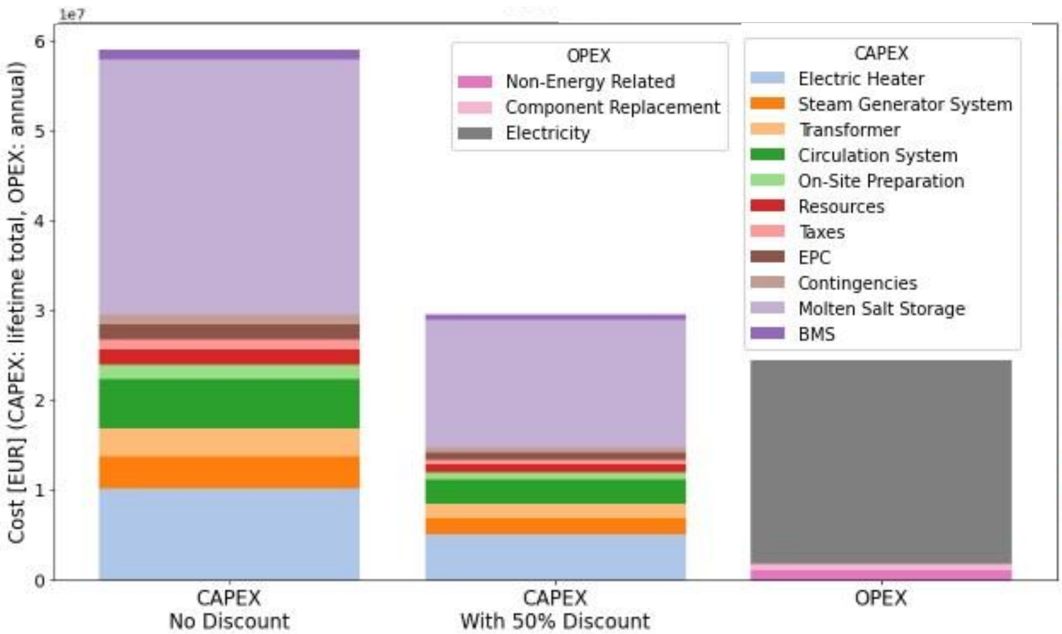

Fig. 2: CAPEX and OPEX breakdown for medium load profile, standalone P2H-TES system (2028)

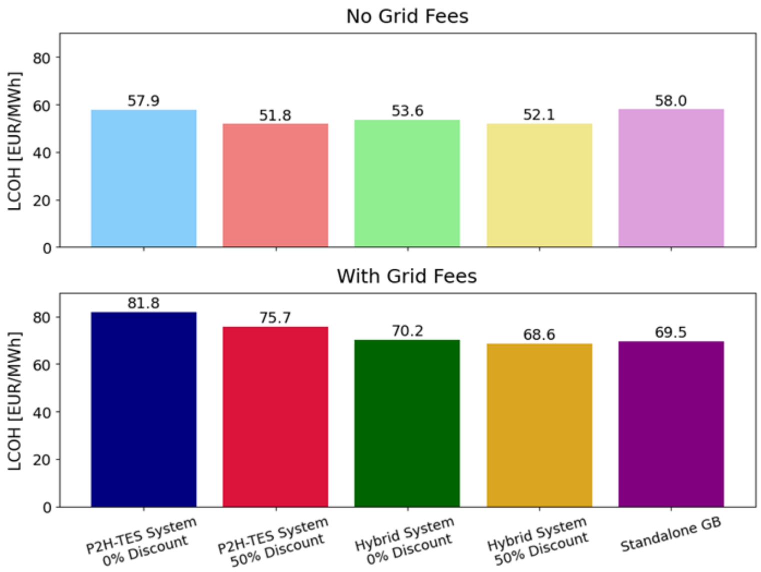

Fig. 3: LCOH by system for medium load profile, with and without grid fees (2028)

3.3 Dispatch strategy

When comparing dispatch schemes, a seven-day rolling horizon achieved near-optimal annual costs relative to full-year planning, while three-day horizons remained close (+0.2 % difference); day-by-day control underutilized storage and increased costs (+11.4 % difference) by missing opportunities to shift across multi-day price patterns. For hybrids with modest TES, the choice of strategy has a negligible impact because the gas boiler buffers high-price periods, keeping cost differentials between planning horizons narrow and reducing reliance on long forecast windows.

4. Discussion

Grid fees (energy and capacity) largely determine near-term economics; tariff reform (e.g., capacity-fee design and usage-hour rules) can unlock electrification. Future markets with frequent low/negative prices and higher CO_2 costs favor P2H-TES. Because low-price periods coincide with high shares of renewable generation, electricity consumed during these hours carries a lower CO_2 intensity, reinforcing the decarbonization benefit of P2H-TES beyond pure cost savings. Practically, 7-day rolling horizons suffice for near-optimal dispatch, reducing forecasting burdens. Optimizing gas-boiler size is key in hybrids, preventing overinvestment and lowering LCOH.

5. Conclusions and Outlook

P2H-TES with steam generation becomes cost-competitive under future price/tariff conditions when sized and dispatched optimally. Near-term competitiveness is constrained by industrial grid charges; hybrids bridge the transition at the expense of higher losses. Priorities include (i) tariff-aware sizing that limits capacity-fee exposure, (ii) rolling-horizon control for robust scheduling, and (iii) optimizing backup capacity. Future work will extend cross-market comparisons, intraday markets, uncertainty handling, and policy scenarios on tariff reform.

6. References

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