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A novel hybrid system for medium-temperature industrial steam: Techno-economic performance across European climates

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Abstract

Decarbonising industrial steam generation is critical for meeting climate targets and reducing exposure to volatile fossil fuel prices. However, standalone high-temperature heat pumps may be constrained by the limited availability of sufficiently hot and continuous waste heat sources, while solar thermal systems face economic barriers due to the lack of cost-effective large-scale steam storage.
To address these limitations, this study investigates a novel hybrid energy system that combines flat-plate solar collectors (FPC), pit thermal energy storage (PTES), and a high-temperature heat pump (HTHP) for the continuous supply of industrial steam at 150 °C.
The system concept relies on solar collectors charging PTES, which subsequently provides a stable, low-to-medium temperature heat source to the HTHP evaporator. This source-side integration reduces the required temperature lift, improves heat pump efficiency and enables near-complete decarbonisation even in the absence of industrial waste heat.
A three-step methodology was applied:

i. Derivation of two representative industrial load profiles from 22 real facilities using k-means clustering.
ii. Python-based stochastic co-optimisation of solar field area, storage volume, and HTHP capacity across more than one million configurations.
iii. Detailed TRNSYS simulations of near-optimal designs under three European climate locations (Würzburg, Davos, Seville).

Results show that the hybrid system can meet between 83% and 99% of the annual steam demand. The lowest levelized cost of heat (LCOH) was achieved in Seville (Spain) at 71 €/MWh (at a 5% discount rate and 15-year lifetime), corresponding to a discounted payback period of 7.5 years compared to a natural gas baseline of 70 €/MWh. In Davos (Switzerland) and Würzburg (Germany), competitive payback periods (<10 years) are achievable only when electricity prices fall below 100 €/MWh and 60 €/MWh, respectively. CO_2 emission reductions range from 40% (Würzburg) to over 90% (Davos), depending strongly on the grid's carbon intensity. These findings demonstrate that coupling FPC, PTES, and HTHP offers a scalable and replicable pathway to high-renewable-fraction steam generation across diverse industrial contexts.