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Municipal Energy System Optimization with District Heating Expansion and Gravel-Pit Thermal Energy Storage: The case of Lenzburg (CH)

Summary

In this study, we present results from an energy system optimization for the Swiss municipality of Lenzburg. The municipality is planning a substantial expansion of its district heating network (DHN), to be supplied a wood-fired boiler and a waste-heat heat pump located near a retail distribution center. We investigate alternative scenarios for supplying the expanded district heating network, with a particular focus on converting gravel pits situated near the waste heat source into pit thermal energy storage (PTES) systems. These scenarios are integrated into a multi-energy system model, and mixed-integer linear programming (MILP) optimizations are performed to determine the cost-optimal system configuration. We find that the cost-optimal system configurations include PTES, which operates as a seasonal storage device. The simulations are based on projected heat demand for the year 2040 and consider a potential expansion of photovoltaic (PV) generation and battery storage capacity. Through sector coupling, surplus PV electricity is used to charge the PTES, thereby reducing otherwise unavoidable excess PV generation. Our work represents an important first step toward assessing the economic viability of PTES in Lenzburg and other similar municipalities.

Keywords: Municipal energy system planning, thermal energy storage, waste heat usage

Field of application for the findings: Energy planning

Addressed audience: Energy planners, Municipal officials, Researchers

1. Introduction

As the climate crisis intensifies, accelerating the energy transition has become an increasingly urgent challenge. While national and international policies define overarching targets and frameworks, many key implementation decisions must be made at the local level. This study contributes to municipal energy planning with a particular focus on thermal energy storage. Due to its geographical location at higher latitudes, Europe experiences a pronounced seasonal mismatch between solar energy availability and heating demand. Any strategy for an energy supply relying to a large extent on solar energy must address this issue. Seasonal energy storage represents a potential solution to this challenge. However, its typically low annual cycle count makes it economically difficult to justify. In this context, we examine the conversion of existing gravel quarries into pit thermal energy storage systems at a specific location. Owing to their low capital costs, such systems may offer a viable option for the seasonal storage of thermal energy.

2. Model

Our calculations are based on the District Energy Model (DEM) [6, 2, 4, 5]. The DEM is a multi-energy model tailored for applications at the municipal level. It implements an automatic parametrization for all municipalities in Switzerland. Based on publicly available data with building-level precision, the heat and electricity demands of individual buildings are estimated[7]. This enables the evaluation of the aggregated district-wide heat and electricity demand. The model includes detailed information on existing heat generators in buildings, the extent of district heating networks, and installed photovoltaic (PV) systems. Furthermore, it incorporates a building-level assessment of rooftop solar potential [1]. This is particularly important on the Swiss plateau, where extended periods of stratus cloudiness in wintertime affect solar generation profiles. In addition to building-level data, the DEM integrates municipality-wide datasets, such as biomass availability and projected electricity demand from electric vehicles. Based on these inputs, the model first operates as a deterministic energy balance model, enabling simulation of local energy flows.

Secondly, the DEM includes a Calliope[3]-based mixed-integer linear programming (MILP) backend that enables optimization of the multi-energy system. A set of pre-parameterized technologies is available, including techno-economic parameters such as capital cost (CAPEX), operational expenditures (OPEX), and expected lifetimes. The model also accounts for performance characteristics, such as temperature- and building-age-dependent COPs of heat pumps. The MILP backend allows for optimization with respect to total system cost and/or carbon emissions. To represent low-temperature waste heat sources, the model distinguishes between two heat energy carriers: heat and heatlt (low-temperature heat). The latter must be upgraded via a heat pump before it can be used as useful thermal energy. The temporal availability of waste heat can be defined through time series inputs, allowing seasonal variations (e.g., cooling-related waste heat peaks in summer) to be represented.

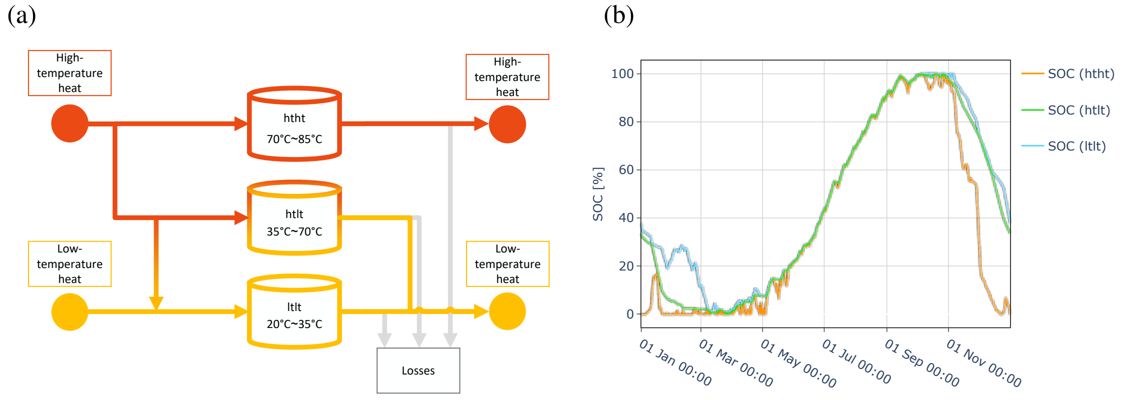

Fig. 1: (a) Representation of thermal energy storage (TES) devices in our model. Three coupled thermal batteries serve to represent the different *temperature* levels of a storage. While the upper storage can be charged and discharged with useful heat, the middle one needs to be charged with useful heat but can only be discharged at a lower temperature level. The lowest temperature range can be charged and discharged at low temperatures. (b) Results of an optimization for the SOC of such a device. The implementation is a Pit-TES.

In the present study, we further employ a module that provides a detailed representation of a thermal energy storage (TES) system. The TES is modeled as three coupled thermal batteries, as illustrated in Fig. 1(a). Each segment represents a distinct temperature range. For example, the lowest-temperature segment may represent the range from 20 to 35°C. A 100% state of charge of this segment implies that the entire storage volume has reached 35°C. Because the three storage segments represent increasing temperature levels, a natural hierarchical constraint is imposed: higher-temperature segments can only be charged once the lower-temperature segments are charged

$$\mathrm{SOC}_{\mathrm{htht}} \leq \mathrm{SOC}_{\mathrm{htlt}} \leq \mathrm{SOC}_{\mathrm{ltlt}}. \tag{1}$$

Our TES model does not account for any intermixing of layers, but instead includes constant storage and charging losses for each segment separately.

3. Simulations and Results

Our simulations consider the combined municipalities of Lenzburg and Staufen in the year 2040. The projected extent of the district heating network (DHN) is determined based on publicly available information, and all buildings within this perimeter are assumed to be connected. The model includes full sector coupling and adopts a local energy community (LEG) perspective, allowing locally generated PV electricity to be freely exchanged. Constant end-user prices are assumed for imported energy carriers. The baseline scenario comprises a full DHN expansion supplied by a wood-fired boiler and waste heat from a nearby distribution center via a heat pump. For remaining buildings, fossil heating systems reaching the end of their service life are required to be replaced by fossil-free solutions. The optimizer can invest in PV and battery storage, with battery costs set at CHF 500/kWh.

As an intervention scenario, we examine the deployment of a PTES in a nearby gravel quarry. The results show annualized cost savings of about 1.5% of total energy system costs (heat and electricity supply, excluding

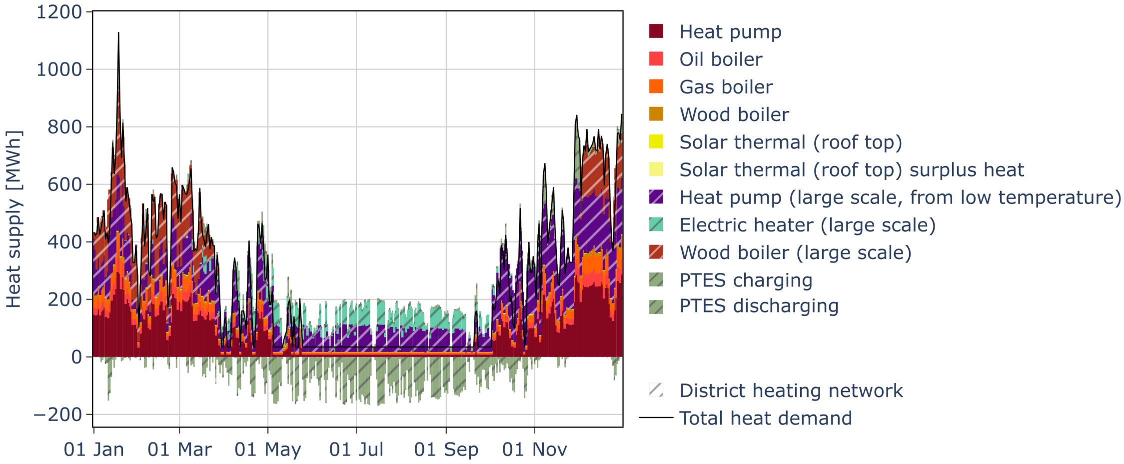

Fig. 2: Heat balance at an hourly resolution for a scenario with a PTES. The charging and discharging of the TES is shown in olive color.

the grid) compared to the baseline. Due to sector coupling, the PTES absorbs most excess PV generation in summer and operates as a seasonal storage device. An hourly heat balance for a representative year is shown in Fig. 2, clearly illustrating the storage operation, whose state-of-charge throughout the year is shown in Fig. 1(b). A large share of winter heat pump operation is supplied by previously stored energy from the PTES; although not directly visible, this accounts for most discharged energy.

4. Conclusion

In this abstract, we present our work on municipal energy system optimization with a focus on thermal energy storage. For the case of Lenzburg, we find that the deployment of a large-scale pit thermal energy storage (PTES) system is economically viable and part of the cost-optimal solution. Our approach, based on an automatically parameterized multi-energy system model with a MILP backend, is transferable and can be applied to other municipalities in Switzerland.

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