The Role of Thermal Storage Power Plants in Germany's Energy Transition: A Temporal and Regional Analysis

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Abstract:

The transition to a carbon-neutral energy system requires innovative solutions to address the challenges posed by intermittent renewable energy sources and the phase-out of fossil-based power plants. This study explores whether Thermal Energy Storage Power Plants (TESPs) could be a viable solution. TESPs are using the infrastructure of decommissioned fossil-fueled power plants which are repurposed with a thermal energy storage to supply both electricity and heat on demand while enhancing system flexibility. Using the Energy System Optimization Framework REMix, we developed a TESP module and integrated it into a high-resolution energy system model for Germany, divided in 9 regions, and including its neighboring countries. Scenarios for 2030, 2040, and 2050 were analyzed to assess TESPs' economic viability and regional suitability. Results indicate that TESPs could be part of a future energy system in central and southern Germany, where sustainable energy production is abundant and a significant demand for renewable process and district heat exists. This study provides a comprehensive analysis of TESPs' potential, offering insights on how to integrate TESPs effectively into carbon-free future energy systems.

Keywords: Energy Transition, Energy System Optimization Model, Thermal Energy Storage Power Plants, System Flexibility

1 Introduction

The energy sector is a major contributor to greenhouse gas emissions, with coal power plants historically playing a significant role in electricity and heat supply [1]. However, the decarbonization of the energy sector has accelerated and the German energy transition ("Energiewende") aims for a carbon-neutral energy sector by 2045, relying heavily on renewable energy sources such as wind and solar power [2].

While renewable energy is crucial for reducing emissions, its intermittent and weather-dependent nature introduces new challenges for ensuring a stable and reliable energy supply. To address this variability, the future energy system must incorporate flexible technologies capable of balancing supply and demand, ensuring grid stability, and supporting industrial processes that depend on consistent heat supply [3].

As Germany phases out coal power plants [2], one challenge emerges: replacing the simultaneous provision of electricity and heat, a role that combined heat and power (CHP) systems have traditionally fulfilled. Thermal (Energy) Storage Power Plants (TESPs) offer a promising solution to this problem. By integrating heat storage and utilizing green electricity to charge the system, TESPs can supply both electricity and district and process heat on demand without greenhouse gas emission. This hybrid concept positions TESPs as a flexible option for decarbonizing the energy sector while filling critical gaps left by the coal phase-out [4].

Despite their potential, TESPs are not yet deployed. Questions remain about their competitiveness compared to other flexibility options and the conditions under which they can be successfully integrated into the energy system.

This paper explores the potential role of TESPs in an optimized energy system, focusing on their economic competitiveness, regional suitability, and contribution to Germany's decarbonization goals. By examining TESPs within a model of a future energy system, this study provides insights into their feasibility and the conditions under which they can effectively support the energy transition.

2 Background and Context

Energy storage technologies play a crucial role in addressing the challenges created by the energy transition by balancing supply and demand, ensuring reliability, and secure energy supply [5]. A variety of storage solutions are already established, including battery storage systems, gas storage caverns, pumped hydro storages, or thermal energy storage systems.

One novel energy storage technology is the Carnot Battery (CB). Based on the Carnot Cycle, a theoretical thermodynamic concept, a CB is a thermal energy storage system that converts electricity into heat, stores it in high-temperature materials like molten salts, and later reconverts it back into electricity using a heat engine [6]. Carnot Batteries can achieve efficiencies of 50–70%. They provide a cost-effective and scalable solution for long-duration energy storage, particularly for integrating renewable energy into the system.

An earlier study analyses the potential of CBs as electricity storage in the German energy system [7]. Nitsch et al. are using an energy system optimization model and an agent-based electricity market model to determine the viability of this storage technology in the future energy system. They conclude that Carnot Batteries are currently too expensive to be considered in the cost-minimized model.

The concept of TESPs [4] builds on this concept of a Carnot Battery. It expands this idea by addressing not only power generation and storage but also direct heat supply, which is particularly relevant for Germany's industrial processes and district heating networks.

The core of a TESP is its heat storage, charged via an electric heater that converts electricity into heat. During discharge, the repurposed steam turbine of a decommissioned fossil power plant converts stored heat back into electricity (Figure 1). Additionally, heat can be supplied directly to industrial processes or district heating. To enhance system reliability, TESPs can integrate backup gas turbines, biomass heaters, and on-site renewables such as photovoltaics [4].

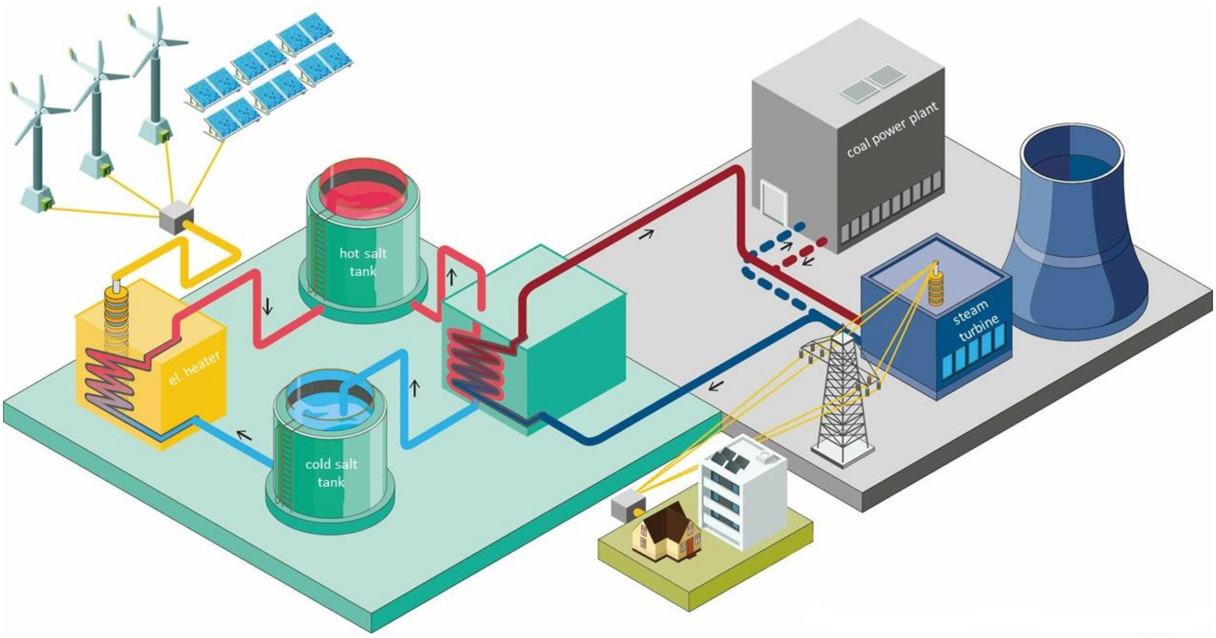

Figure 1: Structure of a Thermal Energy Storage Power Plant [8].

Recent projects like StoreToPower in Germany [9] and the Cerro Dominador solar thermal plant in Chile [10] highlight both the potential and challenges of large-scale thermal storage power plants. The StoreToPower project focuses on electricity storage in power plants. It aims to explore how supply security can be ensured without coal-fired power plants and how existing infrastructure can be repurposed post-coal phase-out. Initial results indicate that while thermal storage power plants can provide flexible and reliable energy supply, their economic viability depends on factors such as storage efficiency, system costs, and market conditions. The result from this project is that at that specific power plant site, a TESP is not the best economic decision. The Cerro Dominador project is a combined concentrated solar power and photovoltaic plant located in the Atacama Desert. The plant utilizes molten salts to store heat, allowing it to generate electricity for up to 17.5 hours without direct solar radiation. However, open questions remain regarding the optimization of materials for storage tanks and the long-term stability of molten salts. Further research is needed to evaluate the economic viability and market regulation of such systems.

In general, TESPs face several challenges, including high investment costs for the electric heating system and thermal storage units, as well as competition from other technologies like batteries and hydrogen systems. Their economic viability depends on factors such as investment costs, efficiency, and available infrastructure, while technical and regulatory challenges still need to be addressed. A key question remains open: Under which economic and technical conditions can TESPs become a viable and competitive solution within a decarbonized energy system?

3 Methodology

This study addresses the viability of TESPs by modeling them within Germany's energy system using the REMix framework [11]. By situating TESPs within the broader context of energy storage technologies and Germany's energy transition strategy, this work provides insights into their potential role in the future energy system.

3.1 Modeling Framework

This study uses the Energy System Optimization Framework REMix (Renewable Energy Mix), a tool designed for high-resolution modeling of integrated energy systems [11]. REMix can capture the interactions between multiple energy sectors, including electricity, heat, hydrogen, and gas, and can evaluate the potential of various technologies, from renewable energy sources to conventional power plants and storage systems.

The REMix-MuSeKo model [12, 13] used for this work divides Germany into 9 distinct regions, each characterized by specific energy demands, renewable resource availability, and infrastructure, while also accounting for cross-border energy exchanges with 12 neighboring countries. By integrating regional weather data, this model can simulate energy system evolution with high spatial and temporal resolution, providing insights into the future energy system of Germany and its neighboring countries up to 2050. This regional granularity allows the identification of localized opportunities and challenges for technology deployment, including the potential integration of TESPs.

3.2 Model Adjustments

Some changes are necessary to allow the implementation of TESPs. In this work we use one commodity each for industry, local, and district heat. Since we want to identify which power plants are best suited for conversion into TESPs, it is important to map industry and district heat commodities in a way that allows the power plant to supply them.

Another important change is a data update based on Germany's national power plant strategy including greater hydrogen production capacities by 2030. Furthermore, we update fuel prices and installed power generation capacities according to the most recent energy scenarios published by the German Ministry of Economic Affairs and Climate action [14].

3.3 TESP Module Development

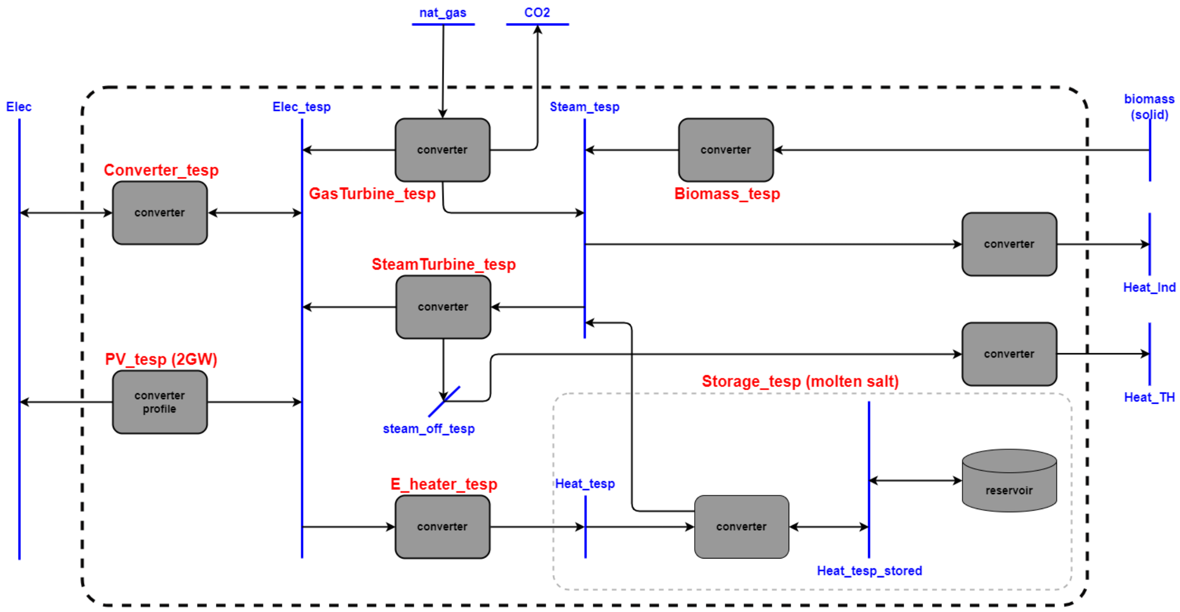

Figure 2: Thermal Storage Power Plant Module for REMix.

To explore the role of TESPs, we developed a dedicated software module within the REMix framework. This module incorporates the already mentioned hybrid concept:

- **Electricity Storage**: TESPs can store surplus renewable energy as heat, which later can be converted back into electricity if needed, which enhances system flexibility.
- **Heat Provision**: The stored thermal energy can be used directly as process or district heat using the grid connection of the old power plant.

The TESP module (Figure 2) is designed to assess the flexibility and economic performance of TESPs. It is then integrated into the larger REMix model to simulate TESPs' contribution to Germany's energy system. Hereby the upper limit for installed TESP capacity is the installed capacity for fossil-based CHP plants, which could be redeployed as TESPs.

We use the following investment costs and efficiencies for the components of our TESP module.

Component	Investment costs	Efficiency
Heat Storage	25 €/kWh	99.5%
Electric Heater	189 €/kW	98%
Steam Turbine	no investment due to reutilization	electricity 32% heat 59%
Gas Turbine	850 €/kW	electricity 27% heat 64%
Biomass Backup Heater	500 €/kW	60%

Table 1: Investment costs and efficiencies of TESP components.

3.4 Flexibility Options

Various flexibility providers, including TESPs, are subject to optimization. Starting from the existing grid, electricity and gas transfer capacities between regions can be expanded as needed.

Storage options also vary in their constraints. Pumped hydro storage, hydro reservoirs, and methane gas caverns have fixed capacities, reflecting already installed infrastructure in each region. In contrast, hydrogen caverns have no pre-existing capacity but are subject to upper expansion limits based on potential sites. Other storage technologies, such as hydrogen tanks, lithium-ion batteries, and thermal energy storage have no predefined limits, allowing the optimizer to determine their required capacities [13].

An exception applies to peak-load boilers, as well as thermal energy storage for CHP plants. These technologies can only be expanded if the corresponding plant is first constructed, ensuring a structured deployment of additional storage and peak boilers.

3.5 Analyses

We perform two different analyses in order to assess the regional and temporal deployment of TESPs. For the first, the TESP module was implemented in every German region and the energy system is optimized for the target year 2030 to examine if the model considers TESPs for capacity expansion in its cost-optimal solution. There, we determine which regions are beneficial by looking at the installed capacities in the regions and look for correlations to other factors, to search for the optimal conditions for TESP utilization.

The second analysis is to determine the best temporal scope to start building TESPs, so we did model runs with different target years, namely 2030, 2040, and 2050.

Due to uncertainties in future prices for TESP components and hydrogen production, a parameter study is conducted on the investment costs of the electric heater and heat storage of the TESP and of the electrolyzers. The basic cost assumptions for TESP components are listed in Table 1. Electrolyzer capital expenditure (CAPEX) is set at 550 €/kW, with stack replacements accounted for in operation and maintenance costs of 9%. To assess the impact of cost variations, we calculate model runs for 2030 with investment and operation and maintenance costs of TESPs and electrolyzers at 50% and 200% of the current assumptions.

4 Results

The results show that TESPs are considered in the cost-optimized solution of the model and are utilized in every German state.

4.1 Optimal TESP Capacities

The analysis shows that the earlier stages of the energy transition are more beneficial for the implementation of TESPs. In the 2030 model run 82 GWh of TESP thermal storage capacity is utilized, compared to only 37 GWh in the run for 2050. This means that the energy system in 2030 will profit more from the transition to TESPs than the system in 2050. A possible reason for this could be that the energy system in 2050 has higher capacities of electrified heat production. Furthermore, since the future energy system is expected to rely more on storage solutions overall, the increasing storage capacities will likely reduce the dependence on TESPs.

4.2 Regional Distribution of TESPs

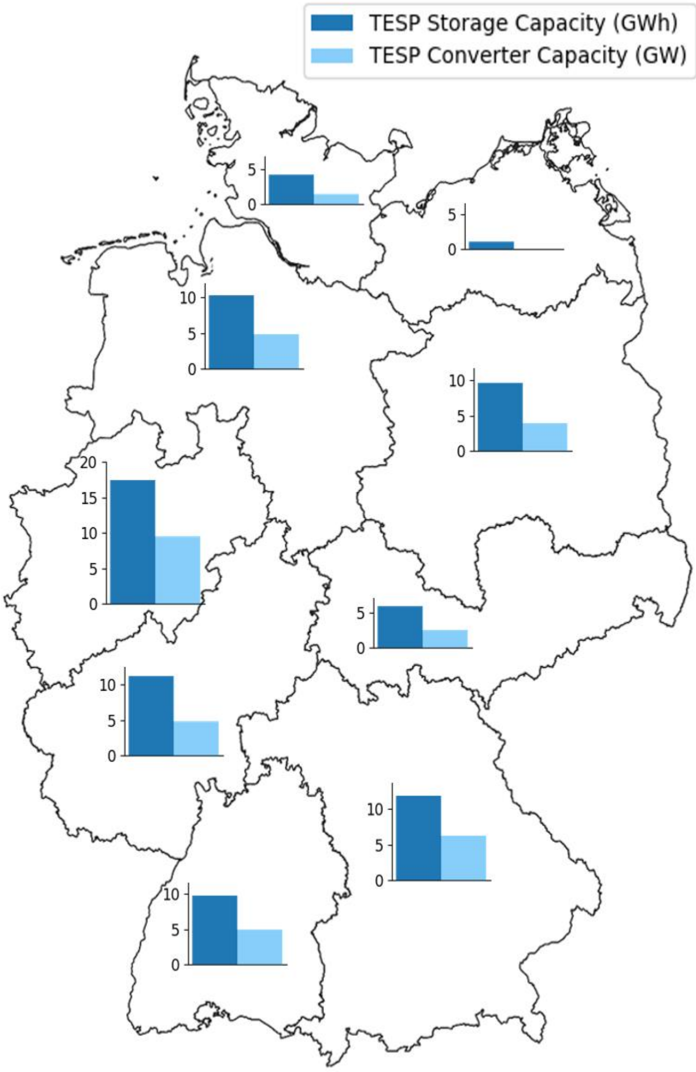

Figure 4: Distribution of installed TESP storage capacity in Germany for 2030.

One of the key findings of the simulations is the identification of regional deployment patterns for TESPs in Germany. Initial results show that higher capacities of TESPs are deployed in the central and southern regions of Germany (Figure 4).

With the correlation between installed renewable capacities or heat demand and TESP capacities (Figure 5), one can see that the availability of renewable electricity production, especially from solar sources and a high heat demand favor TESP expansion.

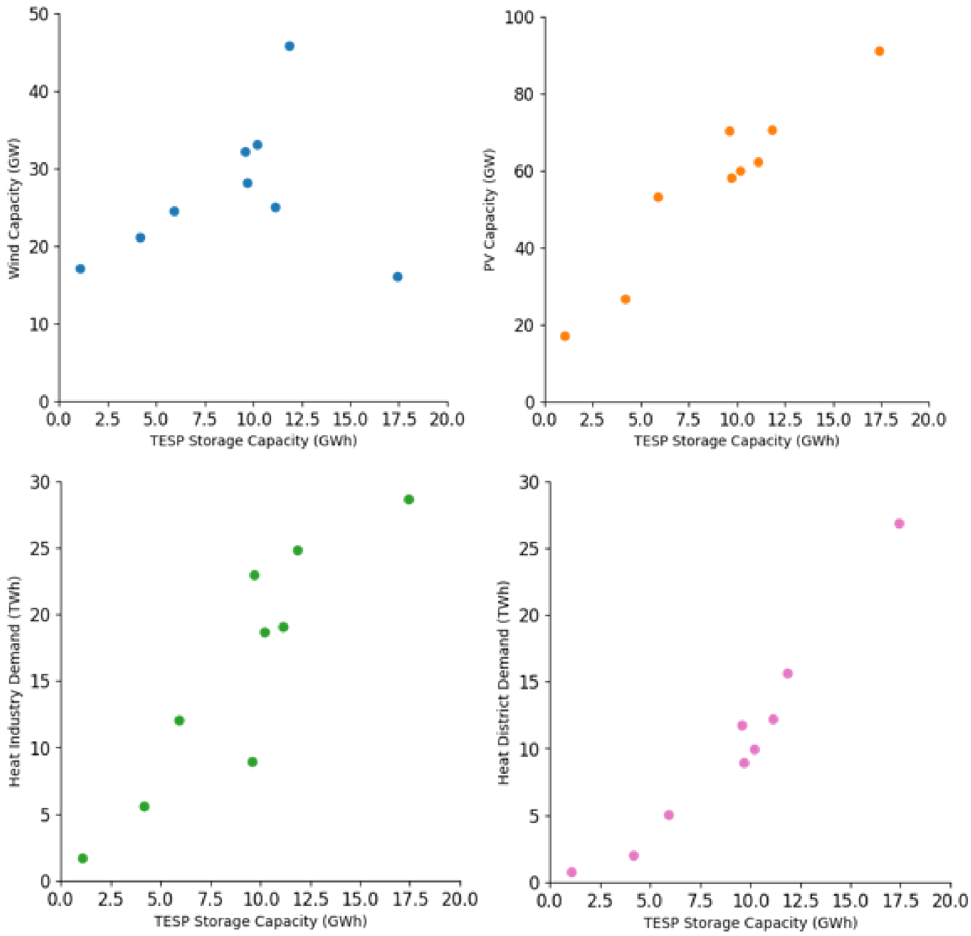

Figure 5: Correlation of TESP capacity compared to renewable capacities and district and industry heat demand in Germany.

These regional differences highlight the importance of considering local renewable energy potential, heat demand, and existing infrastructure when planning the deployment of TESPs. Since the capacities for TESPs is higher there, the study shows that certain existing conventional power plants, particularly those in North Rhine-Westphalia, could be repurposed to operate as TESPs.

4.3 CAPEX Sensitivity

The parameter study shows that variations in electrolyzer costs do not impact the use of flexibility options. However, when TESP investment costs are doubled, the storage capacities of TESPs, other thermal energy storages, and hydrogen caverns decrease, while the use of lithium-ion batteries increases. Additionally, hydrogen transfer is reduced. Transport of power and methane is not affected by any of these CAPEX variations.

5 Discussion

Our analysis shows that there are multiple favorable conditions for TESP deployment. There is a correlation of TESP capacity and renewable energy generation. For regions with high shares of green energy, the deployment of TESPs is comparable high. This is due to the provision of flexibility by TESPs. A high industrial or district heat demand is a favorable condition for TESP utilization too. This can be explained by the fact that TESPs are used to decarbonize the heat production. Of course, also the availability of old decommissioned plants in the next few years is an important factor. Since TESPs can be only built in regions with capacities for fossil-based power plants, this could also influence the deployment pattern of TESPs.

In comparison to the Carnot Battery study [7], where similar investment costs were used, the additional heat supply functionality makes the TESP more valuable for the overall system, compared to the Carnot Battery used as electricity storage.

While this study provides valuable insights, there are several limitations that must be addressed in future work. The model does not currently account for certain factors, such as the role of TESPs in backup power provision, resilience to grid disruptions, or their reliance on critical materials compared to batteries. Moreover, the inclusion of backup power provision and grid resilience modeling will help provide a more comprehensive assessment of TESPs' long-term viability.

Additionally, the current cost assumptions for TESP conversion may be optimistic, as the generator is assumed to be available for free, with only the costs for the storage and heat generator considered. However, converting a plant to an efficient TESP likely involves additional expenses beyond those considered in this study, which will need to be incorporated in future models for a more realistic economic assessment.

6 Conclusion and Outlook

This study investigates the potential of Thermal Energy Storage Power Plants as a flexible solution for Germany’s future energy system. By integrating TESPs into the energy grid, it is possible to store surplus renewable energy as heat and convert it into both electricity and process heat when needed, thus supporting the decarbonization of the energy sector. The hybrid functionality of TESPs offers a potential solution to address challenges such as renewable energy variability and the increasing demand for carbon-free process heat, particularly in industrial sectors. Additionally, the potential for cost reduction through the repurposing of existing coal power plants into TESPs could lower initial capital expenditures and help accelerate the transition to a decarbonized energy system.

While this study identifies mid-western and southern Germany as a key area for TESP deployment, it also highlights the importance of considering regional variability in future research. Differences in renewable energy potential, industrial and district heat demand, and the existing energy infrastructure will all influence the optimal locations for TESPs. Further research should focus more on the last aspect and determine the best CHP types to be transformed first and the regions with a predicted high availability of decommissioned power plants.

Looking ahead, the integration of TESPs into Germany's energy transition strategy shows potential, as indicated by our model results. TESPs could play a role in regions with high renewable energy availability and industrial heat demand, such as central and southern Germany. However, several challenges remain. Key areas for future research include improving the economic viability of TESPs by reducing costs for electric heating systems and thermal storage units, as well as enhancing the efficiency of reconversion into electricity.

Furthermore, additional studies need to provide insights into how the electricity storage function of TESPs can be seen compared to other storage technologies, addressed with a multi-criterial optimization looking at cost minimization and low dependence on critical materials.

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