The Competitive Space for Thermal Energy Storage on Decarbonizing Grids

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Overview

As the penetration of variable renewable energy (VRE) generation technologies increases, the grid experiences larger and more frequent fluctuation in net load. This creates a role for energy storage. One technology option is thermal energy storage (TES). For example, existing concentrated solar plants employ a two-tank hot-and-cold nitrate heat storage system to extend generation as the sun sets. A similar system is designed into the Natrium nuclear power plant slated for construction in the U.S. state of Wyoming. New heat storage technologies, such as crushed rock, may dramatically lower the capital cost for energy capacity, thereby enabling long duration energy storage (LDES) with thermal storage systems.

There is a need to develop a transparent evaluation of TES for nuclear power plants—whether fission or fusion—and to understand the value drivers and therefore different circumstances under which TES may or may not be a valuable addition to a nuclear power plant. Key drivers are, of course, the technical capabilities and the cost parameters of the thermal storage system. However, the value of TES is also driven by the market context: how the portfolio of generation and storage assets drive price volatility and determine the available competitive space for TES. This market context will vary with assumptions about the costs of generation technologies and with assumptions about decarbonization and other major variables. Understanding the drivers can be vital to optimizing investments across charge and discharge capacity as well as storage capacity, to efficiently targeting technology development across these features, as well as to appreciating the competitive space for TES. This paper aims to leverage the state of the art on TES and capacity expansion modeling to identify whether thermal energy can prove valuable in decarbonizing the grid.

Curiously, we note that contradictory results on the value of thermal energy storage exist in the literature—see Stein et al. (2022), Armstrong et al. (2024), Basnet et al. (2024), and Renteria et al. (2024). These could reflect different assumptions on the costs and performance of the storage technologies, but they may also reflect differences in the modeled decarbonized grids and their price profiles. Unfortunately, the contradictory results have been left unexamined and the drivers unidentified. This study helps to resolve these apparent contradictions and organize these results within the broader results describing the drivers of TES profitability.

Methods

This research uses capacity expansion dispatch modeling to identify the scenarios in which significant investments are made in thermal energy storage and those scenarios in which investments are insignificant. Prior literature in the similar vein include Jenkins and Sepulveda (2021), examining generic long-duration energy storage technologies distinguished by key cost and technology parameters and surveying results across a space of different scenarios. We focus specifically on TES combined with nuclear power plants.

In addition to simply documenting the investment or lack of investment in TES, we use the model outputs to provide a detailed analysis of how TES is operated in different contexts. For example, we document the frequency of cycling—how often does it cycle on a daily or longer basis—and document the profitability of different cycles and events—is it earning the same average level of profits off of many events, or is a large proportion of profits earned on infrequent events? Is it earning profits from arbitraging electricity prices within a usual range, or from supplying electricity in rare scarcity events? The analysis will simultaneously characterize the equilibrium electricity price dynamics in each study's results. What is the profile of the price duration curve? What calendar patterns are evident? What is the frequency and duration of price spikes? What is the persistence of high and low prices? Naturally, these price patterns and the storage utilization and profitability fit together, and the analysis will demonstrate how. In doing this analysis, we expect to be able to shed light on whether the different outcomes of the studies are being produced by the dynamics in the electricity market context in which the storage earns revenue. The alternative will be that it is different input assumptions on the cost of storage or its performance. We will document those different assumptions, and analyze how varying the assumptions would change the results of the studies, keeping the dynamics of each electricity market context fixed.

Results

We find that different markets and their hourly price profiles can be categorized according to the number of available storage cycles—given a particular technology's design and cost structure—and average cycle profitability. For example, some markets are characterized by a diurnal cycle and price discrepancy and necessarily small volumes of stored energy requirements, while others are characterized by seasonal price discrepancies and lasting net load shortfalls demanding large volumes of stored energy requirements. We sort how thermal storage of alternative designs and costs sort onto these different market structures. Current thermal storage designs and cost parameters are suitable for diurnal cycling, but the modeled decarbonized market needs seasonal storage. If future thermal storage designs and cost parameters were more suitable for seasonal storage, penetration would increase significantly.

A key insight we add to the literature is the disadvantage created for traditional thermal storage designs which are coupled to a particular nuclear power plant. In many modeled decarbonized markets where nuclear power plants without storage are included in the cost-efficient portfolio of generation, they are operated at a very high capacity factor. Thus, there is no unused heat capacity available to charge thermal energy storage if it were added to the design. At the same time, other non-thermal storage technologies are utilized, taking excess electricity from the grid in certain hours.

Conclusions

Future-proof energy storage solutions for a net-zero world, such as TES, are expensive to build and should at the same time prove profitable in operations and be upheld by policies. This review highlights the complex equilibrium between technological parameters, economic models and policy support. Sometimes, decarbonization models' hypothesis are bullish and optimistic about the momentum of maturing technologies. At other times, models can hamper the development of decarbonization solutions with conservative assumptions and conclusions. In any case, this article illustrated that storage technologies, either for variable renewable energy or nuclear power plants, may be a pivot solution to reach net-zero goals. Additional technology-specific research will be required to combine the specific needs of power plants, according to their thermal energy flows, and flexibility needs at various timescales (intraday, daily, up to inter-seasonal storage).

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