



RESEARCH BRIEF

Economics of Grid-Scale Energy Storage in Wholesale Electricity Markets

Ömer Karaduman

The transition to a low-carbon electricity system is likely to require grid-scale energy storage to smooth the variability and intermittency of renewable energy. I investigate whether private incentives for operating and investing in grid-scale energy storage are optimal and the need for policies that complement investments in renewables with encouraging energy storage. In addition to arbitraging inter-temporal electricity price differences, storage induces non-pecuniary externalities due to production efficiency and carbon emissions. In this paper, I build a new dynamic structural equilibrium framework to quantify the effects of grid-scale energy storage and apply it to study the South Australian Electricity Market. My equilibrium framework adds key modeling features to the literature by allowing (1) storage's price impact and (2) incumbents to best response to energy storage's production by using estimated best responses from conventional sources to observed variation in the residual demand volatility.

Energy storage is the capture of energy produced at one time for use at a later time. Without adequate energy storage, maintaining an electric grid's stability requires equating electricity supply and demand at every moment. System Operators that operate deregulated electricity markets call up natural gas or oil-fired generators to balance the grid in case of short-run changes on either side. These peaker units are generally fast and flexible, but due to rapid adjustments in their heat rates, they are inefficient and emit high carbon levels. Production of Variable

Renewable Energy (VRE) resources, such as wind and solar energy, exacerbates the gap between demand and supply due to their short-run variability in output. Energy storage presents a more efficient and environment-friendly alternative.

A grid-scale energy storage firm participates in the wholesale electricity market by buying and selling electricity. Energy storage creates private (profit) and social (consumer surplus, total welfare, carbon emissions) returns. Storage generates revenue by arbitraging inter-temporal electricity price differences.

If storage is small, its production does not affect prices. However, when storage is large enough, it may increase prices when it buys and decrease prices when it sells. The price arbitrage transfers surplus between producers and consumers. The production of storage also shifts the production of electricity from peak periods to off-peak periods. The shift in production between generating units affects production costs and carbon emissions. Moreover, storing energy also allows increased utilization of available capacity for VRE when supply exceeds demand. Without storage, generation from these sources has to be curtailed. This research's focus is also motivated by the rapidly decreasing cost of grid-scale batteries; the last decade saw a 70% reduction in lithium-ion battery packs' price.

In my model, private returns to storage are maximized by trading on intra-day price fluctuations in the wholesale electricity market. In this research, I use South Australia Electricity Market data from 2017. In the observed period, generation in South Australia consists of almost half VRE and half gas-fired generators. This generation mix is the right candidate for an economically optimal low-carbon electricity production portfolio. It also produces some of the high price variability, which creates a favorable environment for energy storage. The high penetration level of VRE also creates a considerable variation in residual demand, which helps my model to recover firms' best responses to storage's production. I evaluate hypothetical energy storage's private and social returns by estimating equilibrium strategies in the electricity market. I allow the decisions of grid-scale energy storage to affect prices.

My results suggest that accounting for the equilibrium effects of storage is important for understanding the market's efficiency. This result holds even for a unit that is only 5% of the average daily capacity. This response occurs because storage activity changes thermal firms' residual demand, and therefore, their market power. In the presence of energy storage, incumbent firms bid more aggressively; in other words, energy storage helps to mitigate market power in electricity markets. Accounting for generators' best responses decreases the storage operator's profit by 10% and increases

consumer welfare by 10%.

Next, I ask whether the absence of grid-scale storage is socially inefficient at current costs. Due to high investment costs, entering the electricity market is not profitable for privately operated storage and won't increase the total welfare. However, the storage-induced consumer surplus change is two times as large as the storage operator's profit, and the combined benefits are higher than the investment cost. This difference in private and social returns makes investing in storage unprofitable but socially desirable, which presents an under-investment problem. Additionally, unlike the previous literature on storage's emissions effect, I find that storage decreases emissions in markets like South Australia.

This under-investment problem suggests a public policy response, including the form of regulation that should be enacted. A hotly debated area is who should be able to own and operate storage units. I consider a load (consumer) owned energy storage. I find that it almost doubles the consumer surplus increase. This difference shows that price signals are not the right incentives to maximize social incentives because of the distortions in the market prices, such as market power.

Finally, I quantify the complementarity between VREs and grid-scale storage. I study the interaction between these technologies by assessing changes in their revenues as renewable generation is increased. At moderate levels of renewable power, when there is almost no curtailment for VREs, I find that introducing grid-scale storage to the system reduces renewable generators' revenue by decreasing average and peak prices. This is the current situation in South Australia, and below that, in most electricity systems worldwide. However, when VRE capacity is doubled from this base, storage increases the return to renewable production and decreases carbon emissions by preventing curtailment. Higher VRE capacity also leads to higher revenue for energy storage due to an increase in price variation. This non-monotonic relation between VRE and energy storage investment returns leads to a need for more carefully designed policies that complement investments in renewables with encouraging energy storage.

About the Center for Energy and Environmental Policy Research (CEEPR)

Since 1977, CEEPR has been a focal point for research on energy and environmental policy at MIT. CEEPR promotes rigorous, objective research for improved decision making in government and the private sector, and secures the relevance of its work through close cooperation with industry partners from around the globe. CEEPR is jointly sponsored at MIT by the MIT Energy Initiative (MITEI), the Department of Economics, and the Sloan School of Management.

References

Ömer Karaduman, "Economics of Grid-Scale Energy Storage in Wholesale Electricity Markets" MIT CEEPR Working Paper 2021-005, March 2021

About the Author



Ömer Karaduman is a Postdoctoral Research Fellow at Stanford University Bits and Watts Institute. His research focuses on the transition of the energy sector towards a decarbonized and sustainable future. In his research, he utilizes large datasets by using game-theoretical modeling to have practical policy suggestions. Prior to coming to Stanford, Omer completed his Ph.D. in Economics at MIT in 2020, and got his bachelor's degree in Economics from Bilkent University in 2014.

About the Center for Energy and Environmental Policy Research (CEEPR)

Since 1977, CEEPR has been a focal point for research on energy and environmental policy at MIT. CEEPR promotes rigorous, objective research for improved decision making in government and the private sector, and secures the relevance of its work through close cooperation with industry partners from around the globe. CEEPR is jointly sponsored at MIT by the MIT Energy Initiative (MITEI), the Department of Economics, and the Sloan School of Management.