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The value of energy storage in decarbonizing the electricity sector

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HIGHLIGHTS

- Energy storage value increases with tighter carbon dioxide (CO_2) emissions limits.
- The marginal value of storage declines as storage penetration increases.
- Large-scale deployment of available battery technologies requires cost reductions.
- Energy storage increases utilization of the cheapest low-CO_2 resources.
- Longer-duration storage increases the share of wind more than solar photovoltaics.

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ABSTRACT

Electrical energy storage could play an important role in decarbonizing the electricity sector by offering a new, carbon-free source of operational flexibility, improving the utilization of generation assets, and facilitating the integration of variable renewable energy sources. Yet, the future cost of energy storage technologies is uncertain, and the value that they can bring to the system depends on multiple factors. Moreover, the marginal value of storage diminishes as more energy storage capacity is deployed. To explore the potential value of energy storage in deep decarbonization of the electricity sector, we assess the impact of increasing levels of energy storage capacity on both power system operations and investments in generation capacity using a generation capacity expansion model with detailed unit commitment constraints. In a case study of a system with load and renewable resource characteristics from the U.S. state of Texas, we find that energy storage delivers value by increasing the cost-effective penetration of renewable energy, reducing total investments in nuclear power and gas-fired peaking units, and improving the utilization of all installed capacity. However, we find that the value delivered by energy storage with a 2-hour storage capacity only exceeds current technology costs under strict emissions limits, implying that substantial cost reductions in battery storage are needed to justify large-scale deployment. In contrast, storage resources with a 10-hour storage capacity deliver value consistent with the current cost of pumped hydroelectric storage. In general, while energy storage appears essential to enable decarbonization strategies dependent on very high shares of wind and solar energy, storage is not a requisite if a diverse mix of flexible, low-carbon power sources is employed, including flexible nuclear power.

1. Introduction

The electric power sector must play a central role in any effort to mitigate the worst impacts of climate change. Most climate stabilization scenarios envision the global power sector emitting very low or zero carbon dioxide (CO_2) by 2050 while also expanding to electrify and decarbonize portions of the industry and transportation sectors [1,2]. Electrical energy storage could play an important role in the deep decarbonization of the power sector by offering a new, carbon-free source of operational flexibility in the power system, improving the utilization of generation assets, and facilitating the integration of variable renewable energy sources (i.e., wind and solar power) [3,4]. Most of the value of energy storage is accrued from its ability to arbitrage wholesale prices during peak and non-peak hours, thereby leveling out the system load [5–8], but also from providing a carbon-free source of operating reserves and flexibility [9–12] that might potentially defer investments in other more expensive generation assets [13,14].

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Abbreviations and nomenclature

AGC	average generation costs in USD/MWh
ASC	average system costs in USD/MWh
C_i^{FIX}	annualized fixed cost of plant i in USD/kW-yr
C_i^{VAR}	variable cost of plant i in USD/MWh
CF_h^{SOLAR}	solar power capacity factor during hour h in per unit
CF_h^{WIND}	wind power capacity factor during hour h in per unit
CCGT	combined cycle gas turbine
D_h	total electricity demand during hour h in MWh
EC	energy contribution of generation technology in %
ERCOT	Electricity Reliability Council of Texas
GW	gigawatts
GWh	gigawatt-hours
h	index for the hours simulated
H	total number of hours simulated
i	index for plants installed
IMRES	Investment Model for Renewable Electricity Systems
kWh	kilowatt-hours
LCOE	levelized cost of energy in USD/MWh
Li-ion	lithium ion
MVS	marginal value of storage in USD/kWh
N	number of generation units installed
n_h	amount of non-served energy in the system during hour h in MW h
NLDC	net load duration curve
OCGT	open cycle gas turbine
p^{SOLAR}	solar power capacity installed in MWs
p^{WIND}	wind power capacity installed in MWs
PV	photovoltaics
RC	rate of renewable curtailment in %
S0	initial storage capacity in kWh
S1	final storage capacity in kWh
t	index for generation technologies
T	set of available generation technologies
TGC	total generation cost in million of USD
TSC	total system cost in million of USD
VOLL	value of lost load in USD/MWh
x_{ih}	output of unit i during hour h in MW
x_h^{SOLAR}	solar generation during hour h in MWs
x_h^{WIND}	wind generation during hour h in MWs
USD	United States Dollars
y	index for years
Y	usable life of the asset in years
Θ	weighing factor to scale up operating costs modeled to one full year

To date, many studies have examined the short-run impact of energy storage on electric power system operations and economics [5–9,14–18]. Some of these studies have focused on the role of energy storage for integrating large amounts of variable renewable energy generation in power system operations [9,15,16], and others have assessed the impact of storage operation on carbon emissions in conventional power systems [17,18]. Studies assessing the short-run value of energy storage in different electricity markets typically employ price-taker arbitrage models (i.e., models that maximize the profits of the storage unit assuming that storage does not impact electricity prices) [5–8,14], while others calculate the short-run price equilibrium minimizing the system operating costs but ignoring long-run capacity expansion decisions [11,12].

The long-run impact of energy storage on renewable energy utilization is explored in [19]. However, this study does not account for economic considerations and maximizes a multi-objective function composed of renewable penetration minus storage and backup requirements, instead of using the standard criterion of maximizing social welfare—or, equivalently, minimizing total generation costs. Conversely, the long-run economic impact of storage is analyzed in [13,20] based on cost minimization, but these studies do not include binding CO_2 emissions limits for the electricity sector. Other studies that consider the long-run market dynamics under stringent CO_2 emissions limits [21,22] do not consider detailed unit-commitment constraints in the operation of the plants, underestimating the flexibility value energy storage technologies bring to power systems.

In contrast to the existing literature discussed above, this paper focuses explicitly on the total generation-system value of energy storage.[1] We explore in detail the impact of energy storage on short-run power systems operations—accounting for detailed unit-commitment decisions, the contribution of storage to system flexibility and operating reserves, and the resulting influence on wholesale electricity prices. We also consider the impact of energy storage on long-run power plant investment decisions, in the context of stringent CO_2 emissions reduction goals. This work therefore adds to the existing literature by providing a more complete assessment of the economic value of energy storage through jointly capturing both the short- and long-run interaction between storage, renewable energy, and other zero-carbon electricity sources and their relative contributions to meet demands for energy and operating reserves along with emissions reduction objectives. The novel analytical framework used in this work can be applied to more accurately value energy storage in indicative planning [23] for future low-carbon power systems, where the CO_2 emissions and flexibility attributes of the different generation technologies play a critical role in determining the minimum cost generation fleet that is operationally feasible and complies with a given carbon emissions limit.

In our analysis we made extensions to the Investment Model for Renewable Electricity Systems (IMRES) [24], an advanced generation capacity expansion model that considers unit commitment constraints for individual power plants, system-wide reliability requirements, and individual power plant investment decisions. The model selects the cost-minimizing set of investments in electricity generation capacity to reliably meet the electricity demand in a future year, subject to a CO_2 emissions limit.[2] We model a power system with electricity demand and wind and solar resource data from the Electricity Reliability Council of Texas (ERCOT) grid. To explore the impacts of storage on the long-run portfolio of power generation capacity, we increase demand consistent with 2035 projections in Texas and employ the model in a "greenfield" configuration—i.e., selecting the entire generation mix from scratch. Eligible technologies include pulverized coal, combined cycle gas turbines (CCGTs), open cycle gas turbines (OCGTs), wind turbines, solar photovoltaics (PV), and nuclear power. The nuclear power plants are modeled as capable of flexible operation consistent with reactors in France, Germany and other locations [25–27] as well as modern

[1] By generation-system value we refer to the full value of generation, including capital and operating costs for meeting energy and ancillary services needs, but without accounting for transmission or distribution costs, which are very much contingent on the particular power system analyzed.

[2] The CO_2 emissions limit applies only to emissions from power plants during operations and does not include emissions associated with construction, decommissioning or other lifecycle related emissions.