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Emissions impacts of using energy storage for power system reserves

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HIGHLIGHTS

- We evaluate the emissions impacts of energy storage-based reserves.
- Using energy storage for reserves can cause system dispatch to change.
- System-wide emissions impacts are case-dependent.
- Emissions changes are a function of a variety of factors including system costs.
- We analyze cost/emissions trade-offs by reformulating the dispatch algorithm.

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ABSTRACT

Energy storage devices, such as batteries and flywheels, are promising options for providing operating reserves due to their fast response and low emissions during operation. However, because of the complex nature of power systems, adding energy storage-based reserves to the power system may not necessarily benefit the environment. In this paper, we analyze these impacts in a test system and identify important drivers that affect the environmental outcomes. Dispatch results are obtained by solving an optimal power flow (OPF) problem and are used to determine emissions. We find that the impacts of adding energy storage are highly case-dependent. In systems with high renewable penetration levels and significant renewable curtailment, adding energy storage reduces emissions; in other systems, the impacts on emissions could be positive, neutral, or negative. The analyses presented in this paper show that policies to procure energy storage as a means to reduce emissions may actually lead to increased system-wide emissions if current dispatch algorithms are used. We also explore the impacts of modifying the dispatch algorithm to ensure system emissions with energy storage are no worse than system emissions without energy storage.

1. Introduction

As more renewable energy sources are integrated into the power system, additional operating reserves are required to ensure the functionality and reliability of the system [1–4]. Conventional generators provide reserves by holding back some capacity so that they can ramp up or down to balance supply and demand. However, this can result in less efficient generator operation and increased air pollution [5,6]. Energy storage devices are promising alternatives to generators for providing reserves because, in general, these resources are more responsive than conventional power plants, output no emissions during operation, and their costs are increasingly competitive [7,8].

Recent regulatory developments are creating more favorable conditions for large-scale deployment of grid-connected energy storage. For example, the Federal Energy Regulatory Commission (FERC) Order No. 755 [9] requires Independent System Operators (ISOs) to take performance, i.e., both response speed and accuracy, into account when compensating ancillary services. Though this is a policy that is equally applied to all service providers, it benefits energy storage more than traditional generators because energy storage usually has shorter response times and better accuracy. FERC Order No. 784 [10] requires utilities to better account for transactions related to energy storage resources. At the state level, California is leading the way in energy storage policy by mandating procurement requirement of 1325 MW for energy storage by 2020 from its three investor-owned utilities [11].

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Nomenclature

β	energy storage round trip efficiency
γ	traditional generator reserve emissions coefficient
Θ	bus voltage angle
a^e, b^e, c^e	fuel combustion emissions coefficients
a^g, b^g, c^g	generation cost coefficients
B_{bus}	power injection susceptance matrix
B_f	power flow susceptance matrix
C^g, C^d, C^{ES}	grid topology matrices
d	total demand in the Q_2 example
E^g	emissions from power generation
E_{orig}	system emissions without energy storage
E^r	emissions from reserves
F	fuel consumed by generator
f^{ES}	energy storage reserve cost
f^g	generation cost
f^r	reserve cost
H	average heat rate
k_c	fuel price
k_e	emission factor
k^{ES}	energy injected into energy storage per unit of reserve procurement
L	energy storage round trip losses
P_{bus}	bus power injection
P^d	load
$P^{d,ES}$	load due to energy storage round trip losses
P_f	transmission line power flow
P^g	power generation
r_{CO_2}	emission rate from traditional generator reserves
R^{ES}	reserves from energy storage
R^g	reserves from traditional generators
r_{req}	reserve requirement
W^{ES}	energy injected into energy storage due to reserves

With low or no direct emissions during operation, having energy storage-based reserves in power systems is often assumed to reduce pollutant emissions to the environment [12,13]. Some policy makers also consider emissions reduction as a motivation for encouraging energy storage installation; see, for example, the California's energy storage procurement mandate [11]. However, due to the complex nature of power systems and their operational strategies, the validity of this assumption is not clear. The objective of this paper is to investigate the range of emissions impacts resulting from use of energy storage-based reserves in the current power system. We find that energy storage-based reserves may lead to negative impacts under certain dispatch algorithms, system configurations, generation mixes, and reserve requirements.

In a power system, generation and reserve dispatch schedules are determined by solving the unit commitment problem and the economic dispatch problem [14]. The unit commitment problem determines which units will be committed during which hours, but does not specify their production levels. The economic dispatch problem, which is solved after the unit commitment problem, is usually posed as an optimal power flow (OPF) problem [15] and determines the most cost-efficient production levels and reserve capacities across the committed units. In current U.S. electricity markets, only the energy and reserve costs of the system are minimized, while the emissions impacts are not explicitly considered within these problems (though some emissions are indirectly limited/priced, for example, SO_x is limited through a cap and trade program and CO_2 is priced through voluntary carbon markets). A number of dispatch algorithms that consider environmental impacts have been proposed; for example, including emissions costs [16–18] or constraints [19]. However, these algorithms have not yet been adopted. As a result, although adding energy storage to the system could reduce the cost of the system, the environmental outcome may not necessarily improve.

In this paper, we focus on the economic dispatch problem and adopt a single-period deterministic OPF formulation. This formulation models the current practice, which suits our objective of investigating the emissions impacts of adding energy storage-based reserves to the current power system. The state of charge (SOC) of the energy storage affects its ability to continuously provide reserves. ISOs have proposed to use the real time energy market to manage the SOC of storage devices, so that they can bid their full capacity without considering their current SOC [20,21]. This decouples the time periods of the OPF problem and justifies the use of a single-period formulation. Stochastic formulations have been proposed [22,23]; however, they are not yet adopted in practice.

The OPF problem is solved to obtain the dispatch result, which is used for evaluating the CO_2 emissions. We first analyze a standard IEEE 9-bus test system [24], which is modified to include a renewable energy source, energy storage, and congestion, and is simple enough for analysis. We then test a more realistic IEEE 30-bus system [24,25]. Though the test systems do not capture all the complexities in a real power system, the similar trends between the 30-bus system and 9-bus system indicate that the overarching trends we find are generalizable to real systems.

Many researchers and practitioners have studied energy storage in power systems. However, the emissions impacts of energy storage-based reserves are usually studied for a particular power system or under a newly-proposed dispatch algorithm. How the impacts vary under different grid configurations given current dispatch practices have not been thoroughly investigated. In this paper, we analyze the emissions impacts of energy storage-based reserves under different grid configurations and identify important factors that affect these impacts. A few examples of dispatch strategies for power systems with energy storage include [26–32]. The economic potential of energy storage is studied in [8,33,34]. Researchers have also included energy storage-based reserves in large-scale simulations; see, for example, [5]. In [12,13], the authors discover that utilizing electric vehicle batteries to provide ancillary service could reduce emissions in simulations of a model of Electricity Reliability Council of Texas (ERCOT) electric power system. In [30], a hierarchical dispatch algorithm is proposed to include responsive loads as energy storage for spinning reserves; reduction in operating costs and emissions are observed in tests on a modified IEEE 14-bus system. Although in [12,13,30], positive environmental impacts are reported in their particular test systems ([30] also includes carbon tax), our paper finds that emissions results are a function of the grid configuration and could decrease *or increase* with energy storage.

Our contributions are threefold. First, we develop methods to evaluate the emissions impacts of adding energy storage-based reserves to a physically constrained power system. Second, we find that the emissions impacts of adding energy storage-based reserves are case-dependent and may not always be positive, depending on the system configuration. Third, our results inform energy policy. Energy storage policies are still in their infancy, but as interest in these technologies grows, one may expect an increase in such policies. Our results will help policy makers understand the potential environmental outcomes resulting from use of energy storage-based reserves, allowing for better design of incentives and dispatch algorithms that achieve the over-arching environmental and economic goals.