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Parameters driving environmental performance of energy storage systems across grid applications

Maryam Arbabzadeh*, Jeremiah X. Johnson, Gregory A. Keoleian

Center for Sustainable Systems, School of Natural Resources & Environment, University of Michigan, 440 Church St., Ann Arbor, MI 48109, United States

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ABSTRACT

Large-scale energy storage may effectively meet the needs of several grid applications. However, understanding the environmental impact of energy storage for these grid applications is challenging due to diversity in loads, grid mixes, and energy storage systems. Comprehensive sustainability assessments are necessary to yield the best environmental outcomes for grid-scale energy storage systems. To achieve this, we first developed fundamental principles for green energy storage, addressing key issues such as material sustainability, round-trip efficiency, service life, and degradation. In the current study, we couple the principles with a sustainability assessment model to investigate the impact of design and operational parameters on environmental outcomes of utilizing energy storage for grid applications. This model takes into account the service that the energy storage would provide (e.g., bulk energy time-shifting) as well as the energy storage parameters and grid application parameters that influence environmental outcomes. Parameters examined include energy storage round-trip efficiency, degradation, service life, upstream production burden, and heat rates of charging and displaced generation technologies. Environmental sustainability performance is evaluated using a universal set of equations that incorporates all the mentioned parameters. The relationships between these parameters are investigated to determine their influence on environmental performance of energy storage for three grid applications: energy time-shifting, frequency regulation, and power reliability. This model guides the design and operation of new and existing technologies, targeting audiences from energy storage designers to energy storage operators and power utilities.

1. Introduction

The integration of energy storage systems into the power grid may lead to a wide range of environmental impacts [1,2]. Environmental sustainability assessments can guide both development and deployment of energy storage technologies to achieve better environmental outcomes. Many existing environmental assessments, however, have not systematically evaluated the influence of various parameters on these environmental impacts across grid applications. In this study, we address this gap by developing model equations to explore the key parameters that influence environmental outcomes of integrating energy storage systems. This parametric model shows how environmental impact of energy storage integration may be influenced by energy storage parameters and grid application parameters. Across the full range of parameters, environmental outcomes could be positive or negative. It can be used as a guideline to determine, systematically, when and how to choose storage systems to achieve positive environmental outcomes.

Several studies have analyzed the environmental implications of energy storage systems [3,4]. Argonne National Laboratory conducted life cycle assessments of different battery technologies, examining emissions, energy requirements, water, and solid waste indicators [5]. Their results indicated that lead-acid batteries had the lowest production burden compared to other battery technologies. Chul et al. conducted life cycle analysis of lithium-ion battery electric vehicles from cradle-to-gate [6]. Their results demonstrated that cell manufacturing was the main contribution in upstream greenhouse gas emissions. In a life cycle analysis of batteries, Bossche et al. concluded that the environmental impacts

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* Corresponding author.
E-mail address: marbab@umich.edu (M. Arbabzadeh).

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Nomenclature

η	Energy storage round-trip efficiency
n	Energy storage service life
deg	Annual degradation in energy storage round-trip efficiency and capacity
$ESBurden_s$	Energy storage production burden (storage dependent)
$ESBurden_p$	Energy storage production burden (power rating dependent)
E_{uch}	Charging technology upstream emissions factor
E_{Cch}	Charging technology combustion emissions factor
E_{udis}	Displaced technology upstream emissions factor
E_{Cdis}	Displaced technology combustion emissions factor
HR_{ch}	Charging technology heat rate
HR_{dis}	Displaced technology heat rate
P	Energy storage power rating (MW)
S	Energy storage size (MWh)
$cycle$	Number of cycles
T	Study lifetime

of assembly and production stages could be offset significantly when the collection and recycling of batteries was efficient and performed on a large scale [7]. Hou et al. and Larcher and Tarascon emphasized that the advancements for sustainable energy storage systems depended on the discovery of less expensive and environmentally benign materials [8,9]. In a life cycle assessment of compressed air energy storage (CAES), Bouman et al. concluded that the design and processing of underground air storage had a large contribution in environmental impacts [10].

Other studies have explored the integration of storage systems and the associated environmental outcomes. Arbabzadeh et al. showed that in an off-grid system, increasing vanadium redox flow battery capacity would have environmental benefits when reducing high wind curtailment [11]. Hiremath et al. showed that it would be misleading to exclude the use stage impacts and neglect the stationary application of battery technologies in an evaluation of their environmental performance, especially when they had different characteristic parameters [12]. They also demonstrated that increasing round-trip efficiency of batteries reduced their life cycle greenhouse gas (GHG) emissions significantly. Poizet and Dolhem emphasized that, besides reducing the consumption of non-renewable materials in rechargeable batteries, managing the batteries during their lifetime would influence their sustainability performance [13].

Other studies have demonstrated the importance of the grid mix [1,14,15], presence of renewables [16–18], and off-peak marginal generation [19] on environmental outcomes from integrating energy storage. Across all of these examples, we see that production, operation, and deployment of energy storage systems within a grid application can impact the environmental outcomes. Although these studies provide valuable insights into the environmental impacts of integrating energy storage systems, they do not systematically examine the role of energy storage parameters and grid application parameters in affecting these impacts. Our parametric analysis allows us to provide concrete recommendations which can be tailored to different grid applications and storage technologies to influence the environmental impacts of integrating energy storage systems.

Each energy storage technology differs in operational parameters, longevity, and materials requirements. Several studies have identified and compared the characteristics of various energy storage systems that need to be evaluated when considering energy storage on the utility scale. These studies demonstrated that key energy storage parameters such as service life, efficiency, capacity, and number of cycles, among others, differed greatly across technologies [8,20–24].

Energy storage systems can be utilized for several distinct grid applications such as ancillary services and bulk storage for renewable integration [25,26]. Each grid application has specific performance requirements that determine which energy storage technologies are suitable to meet the application's performance requirements. Several studies have reviewed technical characteristics of energy storage technologies and identified their potential grid applications, including reports by the Department of Energy and the Sandia National Laboratory [27–31], and the Electric Power Research Institute [25,32]. These and other studies [33–38] show that the fit of an energy storage system to a specific grid application depends on its match with the performance requirements of the desired application.

Understanding the interaction between energy storage parameters (e.g., round-trip efficiency, degradation, service life, and production burden) and grid application parameters (e.g., generators' heat rates) can inform the relative importance of each parameter in determining the environmental performance of utilizing energy storage, which is the focus of this study. In 2012, Hittinger et al. evaluated the impact of energy storage parameters on the economic cost of providing energy service across grid applications [39]. The study presented here is novel, however, because it identifies how these parameters drive environmental outcomes in grid applications, providing new insights for energy storage designers, operators, and utilities.

This analysis is informed by the twelve principles for green energy storage systems (see Appendix C), which detail key drivers for improving environmental performance when integrating energy storage systems in grid applications [2]. The principles address the importance of the operational parameters of energy storage such as service life, round-trip efficiency, and degradation but do not address how to deal with trade-offs and competing objectives. Motivated and guided by this framework, we have developed universal equations to address the conflicts among the principles. In this model, the viable energy storage technologies for the given application are determined based on the required performance characteristics. The influence of parameters on the environmental outcomes is investigated using the universal equations, providing insights into the design and deployment of new technologies and the modification and improvement of existing ones. Three examples of energy storage applications—energy time-shifting, frequency regulation, and power reliability applications—are selected to demonstrate the impact of parameters on the results. These grid applications were chosen to illustrate a wide range of performance requirements such as required energy storage power rating, capacity, and number of cycles.

2. Case studies: energy time-shifting, frequency regulation, and power reliability

The first case study examined is the application of energy storage for bulk energy time-shifting. The minimum and maximum size range studied for energy storage in this application is 1 MW to 3 GW, with discharge duration between 2 and 10 h, operated at 300 to 400 cycles per year [25,28,40]. For the electric energy time-shifting application, several energy storage technologies offer the most suitable characteristics: pumped-hydro storage,