Energy Conversion and Management 87 (2014) 885–894

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Review

Grid-scale energy storage applications in renewable energy integration: A survey

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ARTICLE INFO

Article history:
Received 17 April 2014
Accepted 22 July 2014
Available online 20 August 2014

Keywords:
Energy storage
Renewable energy
Power systems
Energy markets
Energy policy

ABSTRACT

This paper examines both the potential of and barriers to grid-scale energy storage playing a substantive role in transitioning to an efficient, reliable and cost-effective power system with a high penetration of renewable energy sources. Grid-scale storage is a term that describes a number of different technologies with a wide range of characteristics. This versatility leads to the use of storage to perform a number of grid-services. We first enumerate these services, with an emphasize on those that are best suited to mitigate the effects of uncertainty and variability associated with intermittent, non-dispatchable renewable energy sources. We then provide an overview of the current methods to evaluate grid-integrated storage, summarize key findings, and highlight ongoing challenges to large-scale adoption of grid-scale energy storage. We focus on one particular area that is critical to both the efficient use of energy storage in the power grid and its long-term economic viability: the conflict between the technical benefits of this resource, which can provide both power and energy related grid-services (in some cases simultaneously), and the economic challenges of compensating these services within the current market structures. We then examine recent progress in addressing these issues through regulatory changes and other initiatives designed to mitigate previous market failures. This discussion is followed by some remarks about ongoing regulatory and market design challenges. The paper closes with a summary of the ideas presented and a discussion of critical research needs.

Contents

1. Introduction

The power system is undergoing rapid changes. On the generation side, renewable energy mandates, see e.g. [1], are accelerating the replacement of large-scale, slow-ramping, dispatchable power plants with smaller non-dispatchable renewable energy resources such as solar and wind power plants. Similarly, electric vehicles, demand response and advanced metering systems are altering usage patterns. Both the supply- and demand-side changes are introducing uncertainty regarding the resource requirements for maintaining power balance on the electricity grid. For example, the inherent variability and intermittency[1] of many popular renew-

[1] Although the terms intermittency and variability are often used interchangeably in the literature, we adhere to the definition by the US Energy Information Administration, which defines intermittency as resulting from direct, non-stored conversion of naturally occurring energy fluxes whereas variability is by nature in the energy source controlling the generating plant [2].

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http://dx.doi.org/10.1016/j.enconman.2014.07.063

able sources can result in fluctuating generation patterns [3] along with sudden or unexpected changes in the availability of power. On the demand-side, large numbers of electric vehicles can suddenly increase or decrease grid loads. Traditionally, such added risk is managed through operating reserves or other ancillary services that can immediately address short-term imbalances. However, as the grid changes the size and capacity requirements for dealing with the new challenges are also uncertain and can vary dramatically with regional, seasonal and real-time weather patterns; hence it is difficult to accurately estimate or even define resource adequacy [3]. Current renewable integration studies indicate that the power grid can accommodate up to 20% of energy production from wind without energy storage [4]. However, even this level of penetration requires modifications to grid operating paradigms and market designs [4]. Current grid infrastructure and operational strategies will be unable to maintain reliable function as the system incorporates an even larger number of non-dispatchable renewable energy resources and encounters less predictable, rapidly changing load patterns [5–7]. Accommodating these new resources will thus require new tools, technologies and additional grid services to provide the required level of system resiliency, see e.g. [7–9].

Technologies that help to increase power system flexibility are critical to reaching renewable energy integration targets without compromising efficient, reliable and cost effective operation of the grid [8,9]. Grid-scale energy storage is widely believed to have the potential to provide this added flexibility, see e.g. [8,10–13]. This perceived promise has led to great deal of research investigating both the technical and economic issues surrounding its use. This paper presents an overview of the current literature in this area, specifically highlighting the complicated interplay between the technical capabilities of grid-scale energy storage and the market structures that determine its economic outlook.

There are a broad range of grid-scale energy storage technologies that operate on a variety of time-scales ranging from seconds to hours. There are complementary grid-related operations that function at similar time-scales as well as different markets and regulatory structures that determine how the corresponding resources are dispatched. We begin this survey in Section 2, which introduces a number of common storage technologies for grid applications. We then outline the range of technical services that these various types of storage can provide and classify them into two broad categories (power and energy services) based on the time-scale of interest. We include a broad range of storage applications but focus on those that are associated with large-scale integration of non-dispatchable, intermittent resources such as wind and solar energy systems. At the end of Section 2 we discuss how the versatility of certain technologies complicates both technical and economic assessments of grid-scale storage. Section 3 continues this theme of evaluating storage for different applications by providing both an overview and a critical assessment of the current literature analyzing a variety of storage integration issues. We first identify important technical considerations for storage system design, operation and integration with the grid. We focus on studies that address questions such as storage capacity requirements, portfolio selection, siting and the role of storage in renewable energy applications. The discussion at the end of this section highlights some of the gaps in the current literature. In particular, the missing connections between technical, economic, market and regulatory issues that need to be addressed in order to reach the full potential of grid-scale energy storage. Current regulatory efforts aimed at filling these gaps are discussed in Section 4. We then remark on some on ongoing challenges for current market design and regulatory rule-making in the distinct but related areas of compensating storage and integrating renewable energy sources. The paper concludes with some remarks on-going challenges and important directions for future work.

2. The many roles of grid-scale energy storage

The term grid-scale storage encompasses a number of different technologies, such as pumped hydroelectric storage (PHS), compressed air energy storage (CAES), batteries, flywheels, superconducting magnetic energy storage (SMES), and super-capacitors, see e.g. [14–19] for a full list along with descriptions and analyses of these technologies for various applications. The essential characteristics of typical grid-scale energy storage mediums can be described in terms of the following metrics.

- **Energy storage capacity (kW h)**: the amount of energy that can be stored.
- **Energy density (Wh/L)**: the nominal storage energy per unit volume, i.e. the volumetric energy density.
- **Power density (W/L)**: the maximum available power per unit volume.
- **Charge/discharge duration**: the time needed for the storage to fully charge or discharge.
- **Typical power output (MW)**: the amount of power that can be discharged within the typical discharge duration.
- **Response time**: the time needed for the storage to start providing power output.
- **Lifetime (years or cycles)**: the number of cycles and/or years that a storage technology will continue to operate, the rating in terms of years versus cycles depends on the specific storage technology.
- **Roundtrip efficiency (%)**: the ratio of energy discharged by the system to the energy required (including losses) to charge the system over each cycle.
- **Capital cost ($/kW or $/kW h)**: the upfront investment costs of a storage technology per unit of power discharge ($/kW) or energy storage capacity ($/kW h).
Other storage characteristics that are often considered include: the footprint of the equipment, the cost of the technology, the associated balance-of-plant costs, and environmental factors [20]. Table 1 provides a summary of these performance characteristics for lead acid (L/A) batteries, lithium ion (Li-Ion) batteries, sodium sulfur (NaS) batteries, vanadium redox (VRB) flow batteries, super capacitors, SMES, high-powered flywheels, PHS and CAES based on information obtained from Refs. [21–24]. These examples highlight the wide range of different grid-scale storage technologies. The breath of available resources enables energy storage to provide a number of grid-services, which can be broadly classified based on their time-scale as power (short duration) or energy (long duration) services. The following list describes a number of common grid-services provided by energy storage, which are classified into power or energy related applications in Table 1.

- **Power quality services** support utilization of electric energy without interference or interruption. Generally power quality refers to maintaining voltage levels within bounds.
- **Transient stability services** help to maintain synchronous operation of the grid when the system is subject to sudden (potentially large) disturbances.
- **Regulation services** correct short-term power imbalances that might affect system stability (generally frequency synchronization).
- **Spinning reserves** provide on-line reserve capacity that is ready to meet electric demand within 10 min.
- **Voltage control** provides the ability to produce or absorb reactive power, and the ability to maintain a specific voltage level.
- **(Energy) Arbitrage** refers to using power that is produced during off-peak hours to serve peak loads, i.e. energy storage