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Energy storage for grid services and applications: Classification, market review, metrics, and methodology for evaluation of deployment cases

Niklas Günter[a,b], Antonios Marinopoulos[c,*]

[a] Instituto Superior Técnico, Universidade de Lisboa, 1049-001, Lisbon, Portugal
[b] Karlsruhe Institute of Technology, 76131, Karlsruhe, Germany
[c] ABB AB, Corporate Research, Västerås, Sweden

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ABSTRACT

Electric energy storage can provide several important services and is used in a variety of applications. New and improved technologies and decreasing costs of batteries make energy storage competitive in certain applications.

This paper presents services that can be provided by grid connected energy storage systems (ESSs) as well as applications in which these services can be deployed. A review of current and potential future markets has been conducted and metrics for measuring the monetary benefits of ESSs are presented.

Deployment cases are defined for frequency regulation in the eastern United States and peak limiting in California and examined in cost-benefit and sensitivity analyses. The results show that energy storage is cost-efficient in these cases even if frequency regulation market prices and subsidies drop below today's level.

From the analyses conducted in this paper it can be concluded that energy storage offers valuable alternatives to current grid resources and can help integrate fluctuating generation and demand, if market structures that recognize the value of energy storage and the services it can provide are in place.

1. Introduction

The need for electric energy storage has been in existence since the start of the first locally isolated grids more than a century ago until today's interconnected grids [1]. This need is a result of variable demand from the consumer side in the electrical grid as well as of increasing deployment of fluctuating renewable energy sources (RES) adding variability at the generation side. Energy storage systems (ESSs) are capable of providing several valuable services in different applications that address this need for flexible grid resources.

This paper attempts to make a contribution to the evaluation of the economics of energy storage systems, by providing a comprehensive analysis of services, a review of markets for ESSs, and a detailed development of metrics for the evaluation of benefits. Furthermore, it provides a methodology for the definition of deployment cases and analyzes two cases in detail.

In this paper these services and applications are analyzed in Section 2 along with a review of current and potential future markets for energy storage. Metrics that measure the various financial benefits of ESSs have been developed and are introduced in Section 3. In Section 4 a methodology for the evaluation of deployment cases of ESS is presented, which is then applied in Section 5 where results of the analysis of two deployment cases are discussed. Finally, the conclusions are given in Section 6.

2. Background

There is a great variety of services provided by ESSs in a wide range of applications. In this context it is important to note that the definitions of the terms "service" and "application" vary among the reviewed literature and are sometimes used interchangeably. Within this paper the term "service" describes the electrical operation that is fulfilled by the energy storage system including its power conversion system [2]. The term "application" describes the location within the grid and the connection and functionality of the ESS in relation to its surrounding infrastructure as well as its technical characteristics [3]. The term "benefit", which in the literature also often describes a service, is used in this paper exclusively for financial benefits [4]. Here, we focus on grid

* Corresponding author.
E-mail addresses: niklas.guenter@gmail.com (N. Günter), antonis.marinopoulos@gmail.com, antonis.marinopoulos@se.abb.com (A. Marinopoulos).

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applications, which cover the entire energy supply chain from generation through the transmission and distribution network to the end-consumers.

In some markets, services are recognized as products that can be traded between market participants, whereas in others most of the services that ESSs can offer are internalized in the existing electricity system and are very difficult to valuate [5].

2.1. Services

Depending on the application, an ESS can provide multiple services, although it is important to consider whether or not these services can be called upon at the same time.

The definitions for services vary throughout the literature and can be somewhat arbitrary since each service is derived from the simple storage operations of energy charging (power absorption) or energy discharging (power injection) over a certain period of time. In this paper the services presented in Table 1 are considered and roughly grouped according to their most common applications.

2.2. Applications

An application is a use case of one or multiple services. Here only grid connected applications are considered, which are subdivided into applications located at the generation site, in the transmission grid, in the distribution grid, and behind the meter at the customer site.

ESSs can be applied to provide services in support of or instead of generation resources. Supporting power plants with different services can increase their efficiency and lifetime, resulting in less fuel consumption and less emissions per kWh. ESSs located near RES can provide capacity firming, ramp rate control, frequency regulation, etc., thus facilitating better RES integration and ensuring system stability. Finally, ESS located at a generation site can also be used for energy trading by shifting the produced energy, i.e. charging during low-price periods and discharging during peak-hours, see Table 1.

ESSs located in the transmission grid can reduce transmission congestion and support transmission infrastructure to extend equipment lifetime and defer investments. They can also provide similar ancillary services as the ones connected at the generation site, e.g. reserves, frequency regulation, load following, etc. This enhances system reliability and reduces the need for additional generation resources or existing generation to operate in partial load.

Energy storage in the distribution grid close to demand side can provide ancillary services like load leveling, voltage support, and power quality and is able to relieve distribution equipment and defer investments, supporting in that way increased RES penetration. Another way for ESS to support RES integration is by being placed closely to a RES in order to provide capacity firming, ramp rate control, and time-shift.

ESSs installed at the consumer behind the meter can help to reduce the electricity bill by peak limiting and thus reducing demand charges, or by time-of-use shifting. ESSs are also used to

Table 1
Energy storage services and their application groups.

Application Group	Service	Description
Generation Side	(Large scale) Energy time-shift	• transfer of electric energy from one time period to another • participation in the wholesale market: charging during off-peak, discharging during peak periods [3]
	Electric supply capacity	• reduction of the overall system peak: charging during off-peak, discharging during peak periods • replacement of peak power plants [13]
	Reserves	• inject power into the grid in order to cover unexpected deviations in generation and demand • short term reserves which require fast reaction times (spinning reserve, primary control reserve) [3]
	Frequency regulation	• balancing of expected short term deviations of generation and loads [13] • ESS follows regulation signals very closely → reduction of the need for frequency regulation [9]
	Black-start capability	• re-energizing the grid after a major power outage • providing power for restarting other generation resources [14]
	Load following	• maintaining the balance in the system by reacting to fluctuations in generation and demand [3] • following the load during increasing demand in the morning and decreasing demand in the evening
T&D System	Load leveling	• smoothing or leveling the load curve in the area served by the ESS • charging during low demand periods and discharging during high demand periods [15]
	T&D Congestion relief and upgrade deferral	• ESS installed electrically downstream of the congested or overloaded part of the T&D system [3] • reducing high loads on existing equipment and thus extending its lifetime • reducing the electrical strain on the T&D equipment by discharging during high demand periods [13]
	Voltage support	• managing reactance caused by inductive or capacitive grid equipment and consumers • injecting or absorbing reactive power (also active in case of distribution) into or from the grid [13]
	Power quality	• continuous monitoring of the power quality and improving it by discharging with smooth power output to balance variations in voltage magnitude, variations in the primary frequency, low power factors, harmonics, interruptions in service, etc. [16]
End-Consumer	Electric service reliability	• ensuring uninterrupted power supply to the load in case of a complete power outage • operating in islanding mode and resynchronizing to the grid once it is re-energized [13]
	Peak limiting	• limiting the maximum power draw from the grid • discharging during load peaks [2]
	Time-of-use (TOU) shifting	• storing energy during low demand for discharge during high demand • charging during cheap off-peak periods and discharging to load during expensive peak periods [3]
Renewables Integration	RE Capacity firming	• producing a nearly constant power output by absorbing peaks and suppressing valleys in generation • avoid the need for curtailing by buffering unexpected peaks [3]
	RE Ramp rate control	• limiting the rate of change in overall power output: charging during fast ramp up, discharging during fast ramp down [17]
	RE Time-shift	• storing abundantly (cheaply) available RE and discharging it when needed at high prices • avoid curtailment, increase self-consumption, increase profit [3]