Energy 115 (2016) 1109–1118

Contents lists available at ScienceDirect

Energy

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

Valuation of energy storage in energy and regulation markets

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ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form
11 September 2016
Accepted 15 September 2016

Keywords:
Storage value
Modeling
Energy market
Ancillary market
Regulation service

ABSTRACT

The recent trend in high penetration of renewable energy will lead to a significant mix of renewable technologies in the future power industry portfolio. One important inconvenience of these technologies is their intermittency of power generation. This variability of energy production leads to an increased need of services such as reliability, regulation and transmission congestion. In order to make the electric grid reliable and efficient, system operators have to deploy cost-effective ways to balance supply and demand in real time. Energy storage is considered a viable solution and can mitigate several problems. However, it is still unclear whether or not energy storage will generate enough profit by interacting with energy and ancillary markets. Current economic studies on the energy storage technologies are limited because they do not explore possibilities of using storage in arbitrage and ancillary services in both day-ahead and real time markets. This paper focuses on the economics of energy storage participating in arbitrage and regulation services within different markets. A case study on gravity storage system is used to verify the effectiveness of the proposed operation optimization model. Finally, this paper discusses the value of storage in various grid applications.

1. Introduction

Energy is a real time product which must be consumed when produced because it cannot be easily stored. To achieve this simultaneity of production and consumption, operators have to properly dispatch energy between loads and generators. This real time balancing can be realized with the help of energy storage systems. Storage technologies have the ability of storing electricity when there is an excess and realizing it during periods of needs.

Energy storage systems participate in energy markets in a number of ways depending on their characteristics. These technologies can serve multiple roles simultaneously such as arbitrage, ancillary services, and congestion relief [1]. Regardless the benefits that could be offered by some energy storage technologies, several markets still do not approve their participation in some services such as spinning, non-spinning reserves, and regulation services [2].

Due to the increasing penetration of renewable energy technologies, there is a high interest of economically evaluating energy storage [3]. Most energy storage has been considered historically unprofitable to install except for pumped hydro storage [4]. Methodologies to accurately identify storage systems' benefits are needed in order to determine the likely deployment of these technologies.

Much research has been devoted to economic studies about energy storage with the emergence of competitive energy markets. Multiple articles have valued storage while performing one or more grid functions; however, it is challenging to quantify the value of these services [5]. Drury et al. presented a co-optimized dispatch model to identify the value of compressed air energy storage (CAES) in energy and reserve markets; in multiple U.S. regions. The outcomes of this study indicate that revenues received from performing only energy arbitrage do not support CAES investment in most simulated markets locations. However, conventional CAES system is able to support its investment if revenues received from providing operating reserve are also taken into account. On the other hand, arbitrage and reserve revenues are unlikely to support adiabatic CAES investment in the investigated market regions [5].

Different programming methods have been used to model energy storage dispatch [6]. LP (linear programming) is usually used as a benchmark model while MILP (Mixed integer linear programming) is considered very powerful and has been applied successfully for large-size scheduling problems [6]. Pousinho et al.

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http://dx.doi.org/10.1016/j.energy.2016.09.093
0360-5442/

Nomenclature

C_d	Energy storage degradation cost ($/MWh)
C_S	Energy storage costs ($)
d	Energy storage self-discharge rate
DoD	Depth of discharge
$E_{AS}^{DA}(t)$	Energy offered to regulation service in day-ahead ancillary market (MWh)
$E_{AS}^{RT}(t)$	Energy offered to regulation service in real-time ancillary market (MWh)
$E_c^{DA}(t)$	Energy purchased at time t in day-ahead energy market (MWh)
$E_c^{RT}(t)$	Energy purchased at time t in real-time energy market (MWh)
$E_d^{DA}(t)$	Energy sold at time t in day-ahead energy market (MWh)
$E_d^{RT}(t)$	Energy sold at time t in real-time energy market (MWh)
E_S	Energy storage capacity (MWh)
L_C	Energy storage lifetime in cycles
LET	Lifetime energy throughput (MWh)
$P^{DA}(t)$	Hourly energy price in day-ahead energy market ($/MWh)
$P^{RT}(t)$	Hourly energy price in real-time energy market ($/MWh)
$P_{AS}^{DA}(t)$	Hourly energy price in day-ahead ancillary market ($/MWh)
$P_{AS}^{RT}(t)$	Hourly energy price in real-time ancillary market ($/MWh)
P_L	Energy storage power rating (MW)
R(t)	Hourly revenues ($)
S (t)	Storage level at time t (MWh)
$X_c(t)$	Charging period at time t
$X_d(t)$	Discharging period at time t
δ	Average dispatch to contract ratio (MWh/MW)
η	Energy storage round-trip efficiency

proposed a MILP approach to optimally schedule wind power with concentrated solar power plants having thermal energy storage [7]. The model outcomes show that the presented coordination results in an improvement of profitability for energy producers that trade in day-ahead energy and spinning reserve markets. Garcia et al. developed a two-stage stochastic optimization model of a wind farm combined with pumped hydro storage in an energy market [8]. The presented model is an effective approach to model decision of wind farm operators in a spot time market under uncertainty. In Ref. [9], Sioshansi et al. investigated the value of arbitrage in PJM (Pennsylvania New Jersey Maryland) interconnection for six years to determine the impact of fuel mix, efficiency, fuel prices, storage capacity, and transmission constraints. The quantification of energy storage varies significantly with contract, ownership, and market structure [9]. Denholm and Sioshansi conducted an economic analysis to determine the potential advantages of co-locating energy storage and wind. This co-location is less attractive if storage system is able to gain potential values from providing ancillary or capacity services. The authors claim that further studies are necessary to investigate the benefit of using CAES system to provide ancillary services [10]. In Ref. [11], DeCarolis and Keith evaluated the economics of using compressed air energy storage with wind plant while Bathurst and Strbac, in Ref. [12], analyzed the utilization of battery system combined with wind power plant to perform both energy arbitrage and reduce penalties from imbalance production. The results of this study show that this joint optimization of the battery storage and wind farm generates additional value.

Several articles investigated the economical profitability of energy storage used for arbitrage in different market locations. Perekhodtsev determined the potential revenues of pumped hydro energy storage in PJM market [13]. Arbitrage profit is investigated by Ref. [14] in North American, and European energy markets. The PJM interconnection was studied in Ref. [9], while the NYISO (New York Independent System Operator) interconnection was analyzed by Ref. [15]. The value of energy storage has been investigated in seven U.S. wholesale markets by Bradbury et al. [3]. Locatelli et al. assessed the economics of large energy storage plants with an optimization methodology in UK [16]. The results of this analysis demonstrate that energy storage working as price arbitrage and operating reserve requires subsidies.

Walawalkar et al. undertook an economic study to value storage providing both energy arbitrage and regulation in New York. Their analysis demonstrates that the installation of energy storage is attractive due to the potential opportunities that exist for regulation services in New York State. Deferral of system upgrades has been also quantified by these authors and is considered an important benefit that should be considered while making decision about the deployment of energy storage [15]. In Ref. [17], Kazempour et al. propose a self-scheduling approach for energy storage to determine the maximum potential of expected profit among multi-markets. The economics of emerging and traditional technologies have also been compared in this analysis. Economic viability of NaS battery plant and VRB energy storage in a competitive electricity market has been conducted in Refs. [18] and [19], respectively. He et al. presented a multi-stream value assessment of compressed air energy storage on the French energy market. Their analysis incorporate both regulated and deregulated sources of revenue [20]. Sioshansi et al. performed a value comparison between pure storage (pumped hydro) and compressed air energy storage. The output of this analysis indicates that the net annual arbitrage value of pure storage systems is significantly greater than that of CAES [21]. Hessami and Bowly developed a computer program which model the operation of three energy storage systems combined with a Portland Wind Farm (PWF). The objective of the model is to determine the maximum generated revenues. The simulated storage systems include pumped seawater hydro storage, thermal energy storage, and compressed air energy storage. It has been found that CAES is the most profitable storage system [22]. McKenna et al. evaluated the economic value of integrating lead-acid batteries in grid-connected PV under feed-in tariff in UK. The outcome of this analysis shows that the net value of the battery is negative and the financial loss for the systems is considered significant (£1000/year) [23]. An evaluation of the potential operating profit available through arbitrage operation for a price-maker storage facility in Alberta has been performed in Ref. [24]. It is shown that energy storage operation significantly affect market price, especially during high price hours. Fares and Webber proposed an optimal charge-discharge schedule to maximize daily revenue without violating the battery's operating constraints [25]. It has been demonstrated that energy storage used for only wholesale energy arbitrage in ERCOT (Electric Reliability Council of Texas) would be very negative. This analysis has also shown that it is important to consider the material degradation cost of performing a charge/discharge cycle in battery operational management.