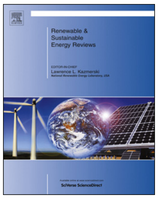
Renewable and Sustainable Energy Reviews 42 (2015) 569–596

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



# Electrical energy storage systems: A comparative life cycle cost analysis

Behnam Zakeri*, Sanna Syri

*Department of Energy Technology, Aalto University, PL 14100, FIN-00076 Aalto, Finland*

## ARTICLE INFO

*Article history:*
Received 8 May 2014
Received in revised form
1 August 2014
Accepted 5 October 2014

*Keywords:*
Battery energy storage
Cost of energy storage
Electricity market
Electricity storage
Renewable energy integration
Smart grid
Techno-economic analysis

## ABSTRACT

Large-scale deployment of intermittent renewable energy (namely wind energy and solar PV) may entail new challenges in power systems and more volatility in power prices in liberalized electricity markets. Energy storage can diminish this imbalance, relieving the grid congestion, and promoting distributed generation. The economic implications of grid-scale electrical energy storage technologies are however obscure for the experts, power grid operators, regulators, and power producers. A meticulous techno-economic or cost-benefit analysis of electricity storage systems requires consistent, updated cost data and a holistic cost analysis framework. To this end, this study critically examines the existing literature in the analysis of life cycle costs of utility-scale electricity storage systems, providing an updated database for the cost elements (capital costs, operational and maintenance costs, and replacement costs). Moreover, life cycle costs and levelized cost of electricity delivered by electrical energy storage is analyzed, employing Monte Carlo method to consider uncertainties. The examined energy storage technologies include pumped hydropower storage, compressed air energy storage (CAES), flywheel, electrochemical batteries (e.g. lead–acid, NaS, Li-ion, and Ni–Cd), flow batteries (e.g. vanadium-redox), superconducting magnetic energy storage, supercapacitors, and hydrogen energy storage (power to gas technologies). The results illustrate the economy of different storage systems for three main applications: bulk energy storage, T&D support services, and frequency regulation.

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*Abbreviations:* AA-CAES, advanced adiabatic compressed air energy storage; ALCC, annualized life cycle costs; BES, battery energy storage; BOP, balance of plant; CAES, compressed air energy storage; CRF, capital recovery factor; D-CAES, diabatic compressed air energy storage; DG, distributed generation; DOE, The US Department of Energy; DoD, depth of discharge; EES, electrical energy storage; FC, fuel cell; GT, gas turbine; IQR, interquartile range; LCC, life cycle costs; LCOE, levelized cost of electricity; LCOS, levelized cost of storage; NaS, sodium–sulfur (battery); Ni–Cd, nickel–cadmium (battery); O&M, operation and maintenance; PCS, power conversion system; PEM, polymer electrolyte membrane; PHS, pumped hydroelectricity storage; PSB, polysulfide–bromide (battery); RES, renewable energy source; RES-E, electricity from renewable energy source; SCES, supercapacitor energy storage; SMES, superconducting magnetic energy storage; T&D, transmission and distribution; TCC, total capital costs; TSO, transmission system operator; UPS, uninterruptible power supply; VRFB, vanadium-redox flow battery; VRLA, valve-regulated lead–acid (battery); ZEBRA, zero emission battery ($NaNiCl_2$ battery)

* Corresponding author. Tel.: +358 405007085.
*E-mail addresses:* behnam.zakeri@aalto.fi (B. Zakeri), sanna.syri@aalto.fi (S. Syri).

http://dx.doi.org/10.1016/j.rser.2014.10.011
1364-0321/

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## 1. Introduction

Power systems are on the threshold of a new transformation by the confluence of deploying variable renewable energy sources (RES) and free electricity markets. High share of variable RES intensifies the variability and intermittency of the power supply, disrupting the optimal operation of conventional power systems and grid reliability. Deregulated electricity markets introduce a competitive environment for power producers resulting in high capital cost requirement for meeting peak demands and volatile electricity prices. This new setting has imposed technical, economic, and environmental challenges for secure supply of electricity.

Energy storage is deemed as one of the solutions for stabilizing the supply of electricity to avert uneconomical power production and high prices in peak times. The recent World Energy Outlook (2013) published by International Energy Agency (IEA) predicts a significant growth in the share of variable RES in total electricity generation, from 6.9% in 2011 to 23.1% by 2035 within the EU [1]. Accordingly, the European Commission has recognized electricity storage[1] as one of the strategic energy technologies in SET-Plan in achieving the EU's energy targets by 2020 and 2050 [2]. The US Department of Energy (DOE) has also identified energy storage as a solution for grid stability, through the Energy Storage Systems Program (DOE OE/ESSP) for developing the energy storage technologies and systems [3].

A wide spectrum of studies address the technical features of electrical energy storage (EES) technologies. For instance, technical characteristics of different EES systems have been subject to study and review in a number of contributions [4–12]. There are other studies that have more thoroughly investigated operational features of certain EES technologies, including pumped hydroelectricity storage (PHS) [13], compressed air energy storage (CAES) [14], different types of batteries [15–17], flywheel energy storage [18,19], superconducting magnetic energy storage (SMES) [20], and supercapacitor energy storage (SCES) [21]. There is also a broad range of researches in modeling and optimization of EES in exemplary or real power systems [22–30]. The aforementioned and similar efforts have contributed to the better understanding of technical characteristics, functional limitations, and possible operational strategies of EES systems. Yet, further research is required to address the barriers in large-scale deployment of EES systems in existing energy systems.

In the absence of commercial, grid-scale adoption of the majority of EES technologies, their economic characteristics have remained obscure for energy system analyzers, power suppliers, grid operators, and policy makers. Moreover, cost analysis of the mature or commercial storage technologies, namely PHS and CAES, cannot be easily generalized as they are site-specific technologies [9,13,31]. According to different studies [27,32–34], this lack of adequate information regarding the economy of utility-scale EES systems is one of the major obstacles in the establishment of feasible business models, ownership structures, and required regulation strategies. In 2013, DOE announced four challenges in the widespread use of EES, of which cost-competiveness is to be addressed with focus on the life cycle costs (LCC) of EES systems [35]. To contribute in this regard, but not limited to that, this study provides an up-to-date, comprehensive, and comparative review of the available literature on cost analyses, capital cost data, and life cycle costs of different EES technologies. The focus is dedicated to recent publications considering their methodology, applied tools, and possible limitations.

The LCC of EES systems is directly associated with the use case and its techno-economic specifications, e.g. charge/discharge cycles per day. Hence, the LCC is illustratively analyzed for three well-known applications; including bulk energy storage, transmission and distribution (T&D) support services, and frequency regulation. Since the cost data of EES systems are rather dispersed and varying in the literature, this study applies a robust uncertainty analysis in the determination of LCC of EES systems.

This study is structured as follows. The main imperatives for the adoption of EES systems are briefly studied in Section 2. The cost analysis framework is established in Section 3, with describing the methodology for the representation of cost data. The cost elements of different EES technologies are discussed with respect to the recent publications in this field. Section 4 presents and discusses the results in three main parts: cost elements, total capital costs, and the LCC of EES systems. Conclusions are drawn in Section 5 supported with recommendations for the future work.

This study focuses on stationary, utility-scale EES systems that are capable for supporting the grid at a reasonable response time. Indirect energy storage processes, smart electric vehicles, thermal

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[1] The terms “electricity storage” and “electrical energy storage” are used interchangeably in the literature and are equal in this study, representing all the technologies that can store and then discharge back the electricity, with a reasonable response time.