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Original article

Cost metrics of electrical energy storage technologies in potential power system operations

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ABSTRACT

Modern power systems could not exist without the many forms of electricity storage that can be integrated at different levels of the power chain. In this work, the most important applications in which storage provides technical, economic and environmental benefits such as arbitrage, balancing and reserve power sources, voltage and frequency regulation, investment deferral, cost management and load shaping and leveling, are reviewed. Using a 5-function normalization technique the technical and operational characteristics relating to 18 electrical energy storage (EES) technologies are qualitatively assessed and the technology-application pairs identified across the power chain are presented. In particular, two functions were used to normalize the characteristics expressed in real units, two further functions were used for those in percentage values and one function was used to quantify the technical maturity. For large-scale/energy-management applications pumped hydro is the most reliable energy storage option over compressed-air alternatives whereas flywheel and electromagnetic EES devices are still focused on short-duration/power-based applications including frequency regulation, uninterruptible power supply, spinning reserve, etc. Encouraged by the appropriate market and regulatory structures, economics enable storing bulk electricity produced by intermittent sources connected to the grid, rather than using it at once. In medium-to-large scales advanced Pb-acid and molten-salt batteries are considered capable of storing distributed electricity, providing the advantage of load leveling of both the supply network and generation plant. In terms of safety and simplicity, Pb-acid and Li-ion systems are viable options for small-scale residential applications, giving consumers an incentive to reduce their time-of-use charges. Apart from their expected use in transportation sector in the forthcoming years, regenerative fuel cells and flow batteries may offer intriguing potential in stationary applications once mature to commercialization.

Introduction

Global efforts aiming to shift towards emission-free and renewable sources, and reduce the dependence on fossil fuels, have forced the whole energy system to dramatic changes. Some of the most important concern large-scale intermittent renewable sources connected to the grid, highly distributed generation, growing penetration of plug-in hybrid electric vehicles (PHEVs) and EVs, opening the field for active participation of EES [1–4]. EES topologies for micro grid (AC or DC) and smart grid system operations which are expected to thrive in the future are also of vital importance [5]. Since electricity is crucial to the development, progress, and overall lifestyle in the global economy, improvements in both renewable and storage technologies are continuously needed for the grid to accommodate the ever-increasing variable sources [6].

For several years now, EES is attracting increasing interest for power grid applications that provide regulation, contingency and management reserves [7]. Each technology possesses its own benefits and weaknesses in relation to the stakeholders and services across the different locations in power chain. Fig. 1 illustrates by technology the total installed capacity which almost 99% stems from pumped hydro. This is followed by compressed air and sodium sulphur with a contribution of 440 MW and 316 MW respectively, while the rest of 280 MW is held by flow battery (89 MW), lead-acid (75 MW), lithium-ion (49 MW), flywheel (40 MW), nickel cadmium (27 MW) and hydrogen-fuel cell (1MW) [8–11]. Factors limiting the global capacity of EES systems are the lack of regulatory and market structures which are developed for traditional power systems, as well as, the confusion caused by the term of storage as it occasionally acts as increased demand or generator [12,13].

The development status, comparisons and cost metrics regarding EES technologies have been extensively published in the literature.

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Nomenclature

AA-CAES	advanced adiabatic compressed air energy storage
AC	alternating current
Al	aluminium
BBES	buoyancy based energy storage
BES	battery energy storage
BHES	buoyant hydraulic energy storage
BS	black-start
CAES	compressed air energy storage
C_i	cost values
CR	contingency reserve
DC	direct current
DoD	depth of discharge
DS	demand shifting
EA	energy arbitrage
ECc	energy capital cost
EDLC	electrochemical double layer capacitor
EES	electrical energy storage
EFC	electrochemical flow capacitors
EB	emergency back-up
EVs	electric vehicles
FC	fuel cell
FES	flywheel energy storage
F_i	feature values
FHM	forecast hedging mitigation
FR	frequency regulation
FS	fluctuation suppression
HTS	high-temperature superconducting
LAES	liquid air energy storage
LF	load following
Li	lithium
$LiCoO_2$	lithium cobalt oxide
$LiMO_2$	lithium nickel manganese oxide
$LiNiO_2$	lithium nickel oxide
$LiPF_6$	lithium hexafluorophosphate
LL	load levelling
LVRT	low voltage ride-through
LTS	low-temperature superconducting
η	efficiency
NaNiCl	sodium nickel chloride
NaS	sodium sulphur
NiCd	nickel cadmium
NiMH	nickel metal hydride
O&M	operation and maintenance
OD	oscillation damping
ORES	ocean renewable energy storage
Pb-acid	lead acid
PCM	phase change material
PHEVs	plug-in hybrid electric vehicles
PHES	pumped-hydro energy storage
PS	peak shaving
PSB	polysulfide bromide
RS	reactive support
RES	renewable energy sources
SDR	self-discharge rate
SMES	superconducting magnetic energy storage
SS	seasonal storage
SS-CAES	small-scale compressed air energy storage
T&D CR	transmission & distribution congestion relief
UC	unit commitment
UPS	uninterruptible power supply
UW-CAES	underwater compressed air energy storage
VR	voltage regulation
VRB	vanadium redox flow battery
VRLA	valve-regulated lead acid
Zn	zinc
ZnBr	zinc bromine

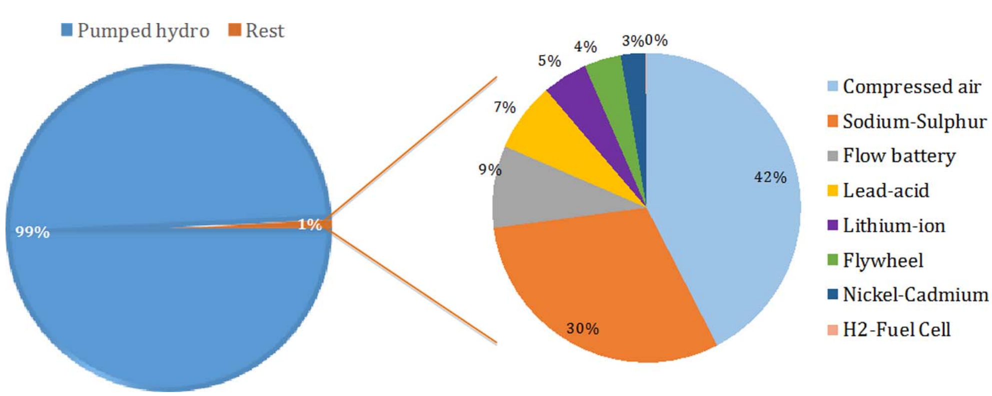

Fig. 1. Global EES capacity by technology.

Some recent research has been conducted on the performance of EES in power system operations. In [14], the status of battery energy storage technology and methods of assessing their impact on power system operations were discussed, while in [15] a look was taken at the field of application of different storage techniques. Francisco Diaz-Gonzalez et al. [16] reviewed the main characteristics of EES systems for stationary wind power applications.

In terms of technical characteristics, applications and deployment status, an executive comparison among various technologies was also made in Ref. [17]. Faizur Rahman et al. [18] identified the most suitable EES technologies for storing electricity generated from renewable energy sources (RES) via a comparative overview based on the climatic conditions and supply demand situation in Saudi Arabia. A techno-economic comparison of energy storage options for island autonomous electrical networks has been presented in [19], with a focus on RES integration increase and optimum operation of existing thermal power stations. The research in [20] focuses on the advantages and disadvantages of EES systems for the challenges imposed by variable renewable energy sources with reference to power quality, regulation, load following, unit commitment and seasonal storage.

A method of optimal sizing and operation of a battery energy storage system used for spinning reserve and frequency regulation was presented by Pascal Mercier et al. [21], while the authors in Ref. [22] developed a dynamic conditioning concept to smooth the fluctuating power output from wind parks through electrical storage. The research work in Ref. [23] demonstrated the feasibility of mechanical energy storage for short-term power back-up in high-reliability applications. The benefits of energy storage on distribution networks providing