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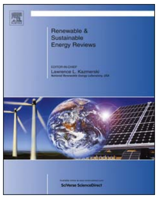

Energy storage in the energy transition context: A technology review

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ABSTRACT

Concerns about climate change as well as fossil fuel usage restrictions motivate the energy transition to a sustainable energy sector requiring very high penetration level of renewable energy sources in the World energy matrix, including those heavily hydrocarbon-based as fuel for transportation. Some of these renewable sources have an uncontrollable output and managing the variability is challenging. The current upward trend in renewables participation will demand even more flexibility from the energy systems. Among several options for increasing flexibility, energy storage (ES) is a promising one considering the variability of many renewable sources. The purpose of this study is to present a comprehensive updated review of ES technologies, briefly address their applications and discuss the barriers to ES deployment. Methodology involves the description and the analysis of ES many existing and developing technologies. ES applications are discussed briefly using logistic and parametric classification logics. As result of this study, it will be pointed out that no ES technology outstands simultaneously in all technical characteristics and consequently, selection should be driven on a case base analysis. Economic feasibility of ES business models and establishment of a well-suited regulatory environment are major issues to unlock ES deployment. Regarding energy transition, Power-to-Gas, Power-to-Liquids and Solar-to-Fuel technologies are very promising and further studies about these technologies are required to better understand their possibilities and how to overcome the barriers to their practical usage.

Contents

Abbreviations: AC, alternate current; A-CAES, adiabatic compressed air energy storage; AFC, alkaline fuel cell; BOP, balance-of-plant; CAES, compressed air energy storage; CHP, combined heat and power; Conv., conventional; DC, direct current; D-CAES, diabatic compressed air energy storage; DHW, domestic hot water; DOD, depth of discharge; DSM, demand side management; EES, electricity energy storage; ES, energy storage; FC, fuel cell; GHG, greenhouse gases; GtP, gas-to-power; HT, high temperature; HVAC, heat, ventilation and air conditioning; I-CAES, isothermal compressed air energy storage; LAES, liquid air energy storage; LH-TES, latent heat thermal energy storage; MCFC, molten carbonate fuel cell; NG, natural gas; PAFC, phosphoric acid fuel cell; PCM, phase-change material; PCS, power conversion system; PEMFC, polymer electrolyte membrane fuel cell; PHS, pumped hydro storage; PSB, polysulfide bromide battery; PTES, pumped thermal energy storage; PtG, power-to-gas; PtL, power-to-liquids; PtP, power-to-power; PV, photovoltaic; R&D, research and development; RES, renewable energy sources; RWGS, reverse water gas shift; SH-TES, sensible heat thermal energy storage; SMES, superconducting magnetic energy storage; SOFC, solid oxide fuel cell; T&D, transmission and distribution; TCES, thermochemical energy storage; TES, thermal energy storage; UPS, uninterrupted power supply; UW-CAES, underwater compressed air energy storage; VRB, vanadium redox battery; VRES, variable renewable energy sources; WGS, water gas shift; ZBB, zinc-bromine battery

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1. Introduction

During the last decades, there have been growing concerns about climate change and greenhouse gas (GHG) emissions by many researchers, especially those from anthropogenic activities. As some reports indicate, these emissions have grown about 10 billion tonnes of CO_2-equivalent during the last decade (2000–2010) [1] and, as a consequence, CO_2 atmospheric levels have increased by 2 ppm per year in the same period, potentially reaching 400 ppm by the end of 2015 [2]. According to some researchers, if the CO2 concentration keeps the current trend, global temperature can rise as much as 5 °C or 6 °C until the end of the century, but limiting CO2 concentration increase up to 450 ppm, global warming over 2 °C would be likely avoided [1]. In order to curb down GHG emissions growth rate, governments are negotiating more commitments on renewable energy, energy efficiency and emissions reduction [3]. In spite of all discussions, renewable energy sources have shown a significant deployment in the past years. Global wind power installed capacity has reached 370 GW, out of which 51 GW has been added only in 2014, and is estimated to reach 666 GW by 2019 [4]. Global solar photovoltaic installed capacity has increased by 39 GW only in 2014, reaching 177 GW [5], with some studies pointing out that it can reach approximately 400 GW by 2020 [6,7]. Nevertheless, primary energy demand will increase within the next years [8], reinforcing the need for low or zero-carbon sources like renewable energy sources (RES) in the energy transition to a sustainable energy system.

RES introduce numerous challenges to the conventional electrical generation system because some of them cannot be stockpiled, having a variable output with an uncontrollable availability [9–11]. RES like reservoir hydropower, biomass and geothermal can operate in a similar way as traditional power plants, but the most important RES exponents, wind and solar sources are variable and less predictable, being usually called as variable renewable energy sources (VRES) [12,13].

Studies have shown that the power grid can absorb variation and uncertainty from direct integration of VRES generation up to 10% of the system installed capacity without major technical problems without substantial additional costs [15,16]. However, large-scale VRES integration is expected in near future on the path to the energy transition, causing more and frequent mismatches between supply and demand, making urgent the need to aggregate more flexibility to the power grid [11,14,17–21].

There are many different possible solutions to increase flexibility: improving and strengthening the grid through upgrade, expansion and integration [22–26]; increasing traditional dispatchable back-up power [27]; improving VRES forecasting [28–31]; demand side management (DSM) measures [32–34]; integration of energy storage technologies [10,18,35–44]; systemic innovations (multiple energy markets integration and smart solutions) [45–48]. Meanwhile, these solutions have their own drawbacks: grid improvements are often delayed due to public resistance, among other aspects [49]; traditional dispatchable back-up power are hydrocarbon-based, emitting large quantities of GHG [50]; improved forecast diminishes uncertainty but not the variability of VRES output and consumer decision-making and behavioral aspects limit DSM feasible potential [51].

ES is promising because it can decouple supply-demand, time-shifting power delivery and then allowing temporary mismatches between supply and demand of electricity, which makes it a system tool with high valuable potential [18]. This ES feature enables untapped VRES surplus, that otherwise are valueless, to be harnessed, reducing curtailment and increasing renewables share in global generation [11,52,53]. ES can also boost distributed VRES generation by ensuring supply to isolated electricity systems and improving self-consumption of grid connected distributed generators [54–57]. In addition to VRES related applications, ES can also enhance other levels of electricity value chain. Reducing cycling of base load generation and increasing its average generation power, ES improves overall chain efficiency while reducing high-cost and high-emitting peaking power plants operation [58,59]. ES can relieve grid congestion and can smooth frequency and voltage fluctuations, ensuring grid reliability and security [60–63].

The purpose of this paper is to present a comprehensive updated review of ES technologies, a brief examination of their applications and an analysis of how these technologies and applications could work within an energy transition context. This work is structured as follows. ES technologies are classified, descripted and characterized in the Section 2. ES applications are classified and concisely characterized in the Section 3. In the same section, a discussion considering an energy transition context is also made. Conclusions are drawn in the Section 4, as well as recommendations for further studies.

2. Energy storage technologies

An extensive diversity of papers found in energy related journals and reports from several research centers discuss multiple subjects related to ES technologies. These studies allow a major comprehension of technological characteristics that undergird ES solutions, their potentials applications and limitations. However,