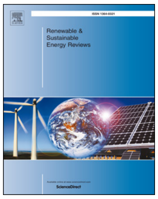
Renewable and Sustainable Energy Reviews 94 (2018) 804–821

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



# Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications

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## ARTICLE INFO

*Keywords:*
Energy storage
Renewable energy
Comparison
Grid
Applications
Hybrid storage

## ABSTRACT

Renewable Energy Sources have been growing rapidly over the last few years. The spreading of renewables has become stronger due to the increased air pollution, which is largely believed to be irreversible for the environment. On the other hand, the penetration of renewable energy technologies causes major problems to the stability of the grid. Along with the fluctuations of the renewable energy technologies production, storage is important for power and voltage smoothing. Energy storage is also important for energy management, frequency regulation, peak shaving, load leveling, seasonal storage and standby generation during a fault. Thus, storage technologies have gained an increased attention and have become more than a necessity nowadays. This paper presents an up to date comprehensive overview of energy storage technologies. It incorporates characteristics and functionalities of each storage technology, as well as their advantages and disadvantages compared with other storage technologies. Comparison tables with several characteristics of each storage method are included, while different applications of energy storage technologies are described as well. Finally, several hybrid energy storage applications are analyzed and different combinations of energy storage technologies are reviewed.

## 1. Introduction

Renewable Energy Sources (RES) have been growing rapidly over the last few years. The spreading of renewables has become stronger due to the increased air pollution, which is largely believed to be irreversible for the environment [1]. Moreover, the depletion of fossil fuel resources, the increased oil prices and the growth in electricity demand are important factors for the growing attention in RES. In addition to that, buildings in Europe are responsible for the 40% of the total EU energy consumption, and as a result they contribute to greenhouse gas emissions and, possibly, to climate change. Therefore, the reduction of the energy consumption and the use of RES in buildings are believed to have a positive impact on climate and gradual independency on conventional fuels [2,3].

On the other hand, the penetration of renewable energy technologies causes major problems to the stability of the electrical grid. This happens because renewable energy production cannot be predicted accurately, as it relies on weather conditions such as sunlight and wind. For instance, when the clouds suddenly appear or the wind stops blowing then the energy production from photovoltaics and wind turbines will be decreased dramatically. Thus, energy storage can allow energy to be stored during high renewable generation or low demand periods, and to be used during low renewable production or high demand periods [4]. Along with the fluctuations of the renewable energy technologies production, storage is important for power and voltage smoothing. Energy storage is also important for energy management, frequency regulation, peak shaving, load leveling, seasonal storage and standby generation during a fault. Thus, storage technologies have currently gained an increased attention and have become more than a necessity [5].

The various storage technologies are in different stages of maturity and are applicable in different scales of capacity. Pumped Hydro Storage is suitable for large-scale applications and accounts for 96% of the total installed capacity in the world, with 169 GW in operation (Fig. 1). Following, thermal energy storage has 3.2 GW installed power capacity, in which the 75% is deployed by molten salt thermal storage technology. Electrochemical batteries are the third most developed storage method with 1.63 GW global power capacity, followed by

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*Abbreviations:* CAES, Compressed Air Energy Storage; CES, Cryogenic Energy Storage; CSP, Concentrated Solar Power; DoD, Depth-of-Discharge; EES, Electrical Energy Storage; FES, Flywheel Energy Storage; PCM, Phase Change Materials; PHS, Pumped Hydroelectric Storage; PSB, Polysulfide bromide battery; RES, Renewable Energy Sources; SMES, Superconducting Magnetic Energy Storage; TES, Thermal Energy Storage; UPS, Uninterruptable Power Supply; VRB, Vanadium Redox flow Battery; ZBR, Zinc-bromine Battery

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https://doi.org/10.1016/j.rser.2018.06.044
Received 22 November 2017; Received in revised form 22 May 2018; Accepted 20 June 2018

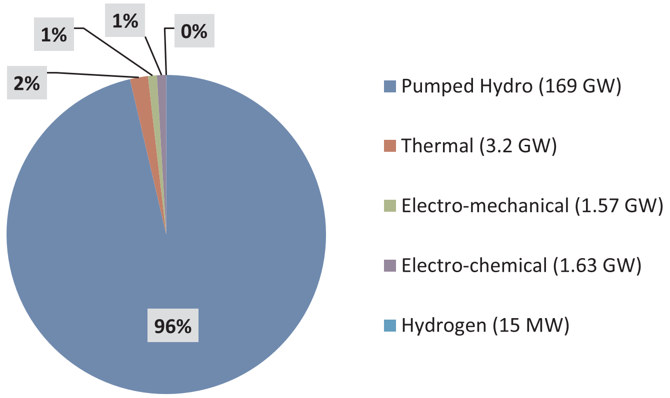

**Fig. 1.** Global energy storage power capacity by technology group until 2017.

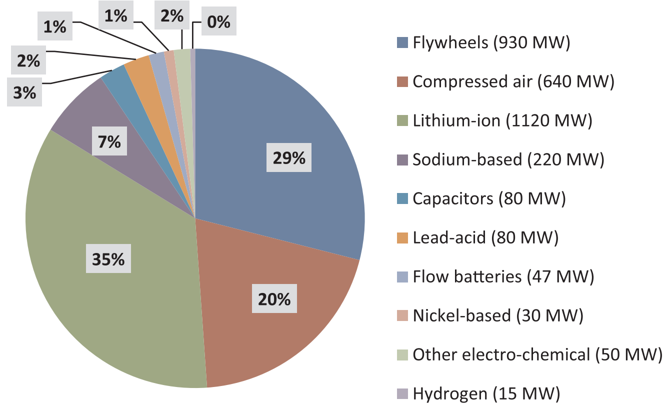

**Fig. 2.** Global energy storage power capacity shares in MW of several storage technologies until 2017.

electromechanical storage with 1.57 GW global installed power capacity. Finally, a promising energy storage technology is that of hydrogen, which accounts for a small share compared to the above storage groups, with almost 15 MW global installed storage capacity [6–9].

Fig. 2 presents the current global storage shares of electrochemical and electromechanical technologies. Regarding the electromechanical storage, flywheels and compressed air are the most developed storage technologies with storage capacities of 930 MW and 640 MW respectively. However, the storage capacity of flywheel and compressed air storage is concentrated in only three large projects respectively. Lithium-ion batteries account for the largest share of the installed power capacity, with 1.12 GW in operation. The remaining electrochemical technologies are the sodium-based batteries (220 MW), capacitors (80 MW), the lead-acid batteries (80 MW), the flow batteries (47 MW) and the nickel-based batteries (30 MW) [6–9].

This paper analyses all storage technologies, particularly those for electricity generation. Specifically, an updated overview of Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), several types of batteries (lead-acid, nickel-based, sodium-based, lithium-ion, metal-air, redox flow), Hydrogen Storage, Thermal Energy Storage (TES), Superconducting Magnetic Energy Storage (SMES), Flywheel Energy Storage (FES) and Supercapacitors is performed. The main aim of this paper is to present an updated comprehensive overview of the above storage technologies, focusing on their functionalities and characteristics with graphical representation of their operation.

For clarity, a brief explanation of several key terms regarding the characteristics of energy storage technologies is given in the sequel. Firstly, the self-discharge rate indicates the percentage of discharge during a period that a storage method is either not in use or in an open-circuit condition. The response time of a storage method is the duration of time for the transition from no discharge state to full discharge state. Furthermore, the cycle life of a storage method is the total number of charge-discharge cycles before it becomes unusable for an application (e.g. when its capacity is reduced dramatically). Additionally, the Depth-of-Discharge (DoD) is the amount (or percentage) of rated capacity that has been used from a battery. On the other hand, the State-of-charge is the complement of Depth-of-Discharge and represents the percentage of the remaining capacity in the battery [10,11]. Finally, a Control and Power Conditioning System (C-PCS) is presented in most of the figures of the energy storage technologies. A Power Conditioning System is a bi-directional system for conversion of power between the grid side and the storage side. The current produced by most of the storage technologies is direct (DC), thus a conversion to alternating current (AC) is necessary to follow the grid requirements (voltage value, phase, frequency) for connection to the grid [12,13].

In Section 2, all energy storage technologies are presented and examined with regard to their characteristics and functionalities, as well as their advantages and drawbacks. Furthermore, Section 3 compares all energy storage technologies by their energy and power density, lifetime in cycles and years, energy efficiency, response time, capital cost, self-discharge rate and maturity. A brief comparison is given by the form of tables. In Section 4, a discussion of the grid scale energy storage applications is presented. Moreover, in Section 5 several hybrid energy storage applications are analyzed. Finally, the conclusions are summed up in Section 6.

## 2. Energy storage technologies

Electrical Energy Storage (EES) is a process of converting electrical energy into other forms of energy that can be stored for converting back into electrical energy when needed. One can categorize the storage technologies by storage duration (long-term, short-term storage), by the kind of storage (electrical, mechanical, chemical, thermal, etc.) or by other criteria like capital cost, capacity, efficiency and environmental impact. Fig. 3 shows a classification of Energy Storage technologies by

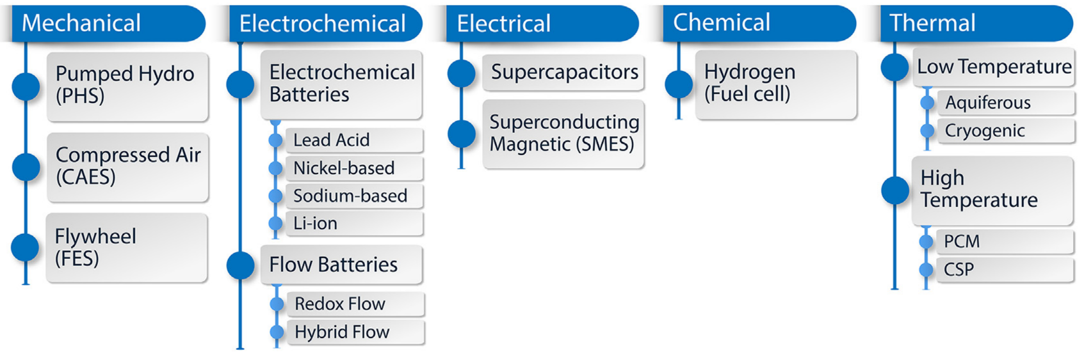

**Fig. 3.** Classification of energy storage technologies by the form of stored energy.