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# Energy storage systems in modern grids—Matrix of technologies and applications

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ABSTRACT

Energy storage technologies are used in modern grids for a variety of applications and with different techniques. The range of applications and technologies is very broad, and finding the right storage solution for the job at hand can be difficult. In order to simplify the selection, this paper presents a matrix of the available technologies and applications. Along with proposing the matrix, the technologies and applications of Energy Storage Systems (ESSs) are described thoroughly and are compared on the basis of many different parameters, such as capacity, storage power, response time, discharge time, and life time. Moreover, the structure of energy storage, which is constituted of different steps and parts, is investigated. Since the implementing of an ESS is expensive, this paper also analyzes the possibility of integrating different types of ESSs and presents a comprehensive diagram to show the ESS technologies that can be integrated together in order to provide the needed performance in a cost-optimal way. Finally, the key results of this comprehensive study are summarized in a number of tables.


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## 1. Introduction

Power management and stability assurance are critical tasks in modern grids because of the variables involved in generation and on the demand side. There are many different methods of approaching these problems, such as de-loading the operation of Renewable Energy Sources (RESs) when the generation of power is greater than demand and load shedding during power shortages [1–5]. However, the absorption and injection of energy by energy storage systems may be the best solution for managing this issue well [6–9]. Investigations of the challenges and barriers to power systems indicate that ESSs should aim at the following three targets [10–12]:

- Enhancing the reliability of renewable energy sources;
- Improving the resilience of the grid and resolving its issues;
- Realizing the benefits of smart grids and optimizing generation to suit demand.

Indeed, by storing energy when it is easily available and dispatching it during shortages, the combination of energy storage technology and RESs can help to stabilize power output while also enhancing the reliability of RESs. Moreover, energy storage can increase the resilience of systems during weather variations, natural disasters, and so on [13–16].

In fact, determining the best arrangement of ESS can be the first critical issue in designing a system. From this point of view, storage systems may be either distributed or aggregated. In distributed arrangements, the energy storage systems are connected via individual power electronic interfaces to each RES. In this method, each storage system has responsibility for the control and optimization of the power output of the source to which it is connected [17–19]. The aggregated model operates so that the whole system—for example, a microgrid (MG)—is supported through a central energy storage system. Depending on the arrangement, such a system may be connected to the DC bus either directly or through a power-electronic interface [20–22].

The second critical issue for storage systems may be the control of each application and of the optimum storage type. Indeed, in implementing an optimum storage project, three different steps need to be considered:

- Investigating the type and size of the storage system and selecting the one that is best for the system.
- Defining the best control strategy for the application considering the selected storage system.
- Investigating the net present value of the storage system.

In the second step, control methodologies for ESSs can be classified as either central or decentralized and can cover both of the arrangements. Indeed, the control methodologies of storage units, and also the power-electronics interfaced DG system with them, are investigated in [23–25] for centralized methods and in [26–31] for decentralized methods. Moreover, the control strategy is comprehensively discussed by the authors in [32,33].

In recent years, there has been much interest in investigations into technologies and applications of ESS. Researchers have produced comprehensive reviews in this area, such as those by Tan et al. [17], Carnegie et al. [34], Bradbury et al. [35], and Cavanagh et al. [36] The first objective of the present paper is thus to cover the first step by creating a matrix of different storage technologies and their applications. Such a matrix may be beneficial in allowing industry and researchers to quickly determine the optimum storage technique for a given application. The second objective of this paper is to analyze the possibility of integrating different ESS technologies. Indeed, such an analysis can help to obviate the high cost of storing energy in certain applications.

The present paper is organized as follows: The structure of energy storage is discussed in Section 2. The energy storage technologies and applications are investigated in Sections 3 and 4, respectively. A comparison of these two issues and the matrix appear in Section 5. The possibility of integrating ESS is discussed in Section 6. Finally, the conclusion is presented in Section 7.

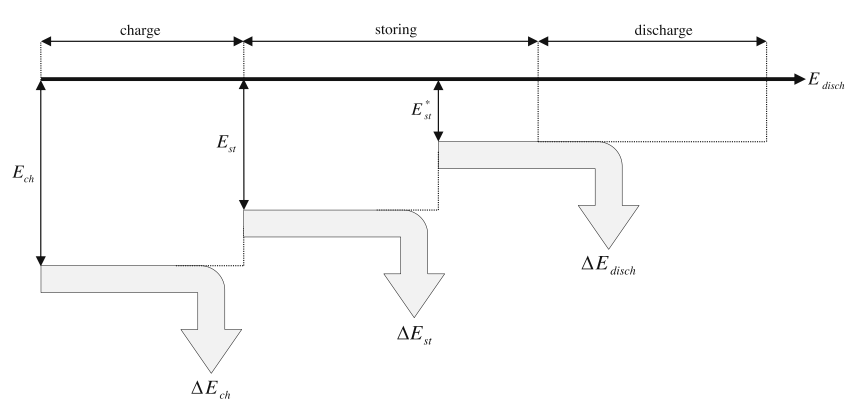


**Fig. 1.** Energy equilibrium in ESS.