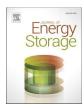


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#### Review article

# Flywheels in renewable energy Systems: An analysis of their role in managing intermittency

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#### ABSTRACT

This paper presents an analytical review of the use of flywheel energy storage systems (FESSs) for the integration of intermittent renewable energy sources into electrical grids and microgrids. An exhaustive search of scientific databases was first conducted which yielded 175 relevant articles encompassing 210 case studies. The studies were classified as theoretical or experimental and divided into two main categories: stabilization and dynamic energy storage applications. Of the studies considered, 48 % correspond to the former category and 52 % to the latter. Spain leads the way in terms of the development of experimental studies (18 of the 52 studies considered), followed by Australia (11). An examination was then conducted of the current uses, advantages, and limitations of FESSs. The results indicate a growing interest in research on FESSs and their implementation in renewable energy generation contexts. FESSs are characterized by their high-power density, rapid response times, an exceptional cycle life, and high efficiency, which make them particularly suitable for applications that require immediate power delivery and frequent cycling. However, challenges such as higher initial capital costs and integration into existing market designs hinder their widespread adoption. The discussion highlights the need for evolving market designs and regulatory frameworks that recognize the full value of FESSs, as well as continued technological advances to improve their economic viability. The study concludes that FESSs have significant potential to enhance grid stability and facilitate the integration of renewable energy sources, contributing to more sustainable and resilient electrical systems.

### 1. Introduction

Flywheels are among the oldest and most extensively utilized energy storage devices, having been employed for centuries to store usable energy for various purposes [1–3]. Their origins can be traced back to the potter's wheel, underscoring their longstanding role in human technological development [4]. Beyond pumped hydroelectric storage, flywheels represent one of the most established technologies for mechanical energy storage based on rotational kinetic energy [5].

Fundamentally, flywheels store kinetic energy in a rotating mass known as a rotor [6–9], characterized by high conversion power and rapid discharge rates [10]. They convert electrical energy into kinetic energy for storage and can swiftly revert it back to electrical energy when needed, effectively functioning as "mechanical batteries" [11–16]. This capability makes them an environmentally friendly alternative to electrochemical batteries, playing a critical role in sustainable energy transitions [17].

Advances in power electronics and materials science have facilitated the development of modern flywheel energy storage systems (FESSs) that can interface directly with electrical grids [18–20]. A typical FESS comprises a motor/generator unit, a bidirectional power converter [19,21], a rotor made of steel or composite materials [19,22], a bearing system—which may employ magnetic levitation—and a vacuum enclosure to minimize air friction losses [22,23]. The integration of electric machines, power electronics converters, and sophisticated control systems forms the foundation of energy transfer in FESSs [23].

FESSs can respond instantaneously to grid demands, providing rapid energy discharge to stabilize fluctuations [24]. Historically, flywheels have been used to smooth mechanical power transmission [9] and modern FESSs continue this legacy by mitigating variations between energy generation and load demand in electrical grids [24]. They offer several advantages in contemporary energy systems, particularly in applications requiring high power density and rapid response [5,8,23]. Their high power density makes them competitive for scenarios

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