Comparison of Mechanical Solar Energy Storage Methods: Current Situation and Future Perspectives in Türkiye and Azerbaijan

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Abstract*— Nowadays, energy storage technologies play a crucial role in optimizing solar energy utilization and addressing supply-demand imbalances. This study focuses on the energy storage potential and technologies in Türkiye and Azerbaijan, specifically examining mechanical methods for solar energy storage, such as Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), and Flywheel Energy Storage (FES). Both countries possess substantial renewable energy resources, including solar and wind. However, the integration of energy storage systems is necessary to maximize solar energy effectively. Türkiye has shown significant progress with a strong regulatory framework supporting energy storage investments, demonstrating its commitment to achieving net-zero emissions by 2053. In contrast, Azerbaijan prioritizes solar energy growth through international partnerships and national policies, such as the Law on Efficient Use of Energy Resources and Energy Efficiency. By comparing the efficiencies, costs, and environmental impacts of mechanical storage technologies, this study provides insights for optimizing solar energy deployment in these nations.

Keywords*— energy storage systems, pumped hydro storage, compressed air storage, flywheel energy storage, energy potential

I. INTRODUCTION

An increasing number of countries have been exploring various new policies and technological advancements to ensure that their energy futures are sustainable [1]. Given the environmental impacts and limited reserves of fossil fuels, solar energy emerges as a limitless, eco-friendly, and sustainable alternative.

The ratio of installed solar energy capacity between 2019 and 2023 is shown in Table 1 for Türkiye, Azerbaijan, and the world. The installed solar energy capacity in Türkiye has increased by 88.34% between 2019 and 2023, while this rate has risen to 138.28% worldwide [2]. For Azerbaijan rate of increasing installed solar energy capacity between 2019 and 2023 is 754.54%. The dramatic increase in Azerbaijan can be attributed to the commissioning of the Garadagh Solar Power Plant, which became operational in November 2023 with an installed capacity of 230 MW [3].

To protect the Earth, significant efforts have been made to increase renewable energy use while enhancing energy efficiency [4]. Energy storage is one of the methods of increasing energy efficiency. It enables the storage of energy during times of excess supply and the provision of energy to loads during times of excess demand. In addition, energy storage regulates frequency, voltage, and reactive-real power and helps power plants restart after a massive system failure [5].

TABLE I. INSTALLED SOLAR ENERGY CAPACITY (MW)

Year	Azerbaijan	Türkiye	World
2019	33	5,996	595,492
2020	35	6,668	728,405
2021	48	7,817	873,858
2022	51	9,426	1,073,136
2023	282	11,293	1,418,969

The amounts of electricity production from solar energy percentage of total energy between 2019 and 2023 for Türkiye, Azerbaijan, and the world are shown in Table 2. [6]. In Türkiye and globally, the share of electricity generated from solar energy relative to the total energy produced is similar. However, in Azerbaijan, this proportion is 18.5 to 21.5 times lower compared to Türkiye and 15.8 to 20.8 times lower compared to the global average.

TABLE II. ELECTRICITY PRODUCTION FROM SOLAR ENERGY PERCENTAGE OF TOTAL ENERGY

Year	Azerbaijan	Türkiye	World
2019	0.15%	3.19%	2.64%
2020	0.19%	3.71%	3.20%
2021	0.18%	4.05%	3.75%
2022	0.21%	4.73%	4.59%
2023	0.27%	5.75%	5.53%

The 12th Development Plan published by the Presidency of the Republic of Türkiye highlights that energy storage investments will play a critical role in achieving the net-zero emission target by 2053 [7]. The transition to green energy is a fundamental objective outlined in Azerbaijan 2030: National Priorities for Socio-Economic Development [8]. Similarly, the 2022-2026 Social and Economic Development Strategy for Azerbaijan emphasizes that being a "green growth" country and a clean environment are key performance indicators for strategic goals [9].

TABLE III. CUMULATIVE SUM OF ENERGY STORAGE RATED CAPACITY (KWH) BY YEAR [12]

Technology Broad Category	Storage Technology Types	2019	2020	2021	2022	2023
Electro-Chemical Battery And Chemical Storage	Electro-Chemical Capacitor	21.859	21.859	21.859	21.859	21.859
	Flow Battery	1.274.356	1.274.356	1.274.356	1.274.356	1.274.356
	Hydrogen Storage	101.059	101.059	101.059	101.059	101.059
	Lead- Acid Battery	192.357	193.383	193.383	193.383	193.383
	Lithium-Ion Battery	7.195.932	7.865.528	12.558.488	12.558.488	12.558.488
	Nickel-Based Battery	21.075	32.175	36.375	36.375	36.375
	Sodium-Based Battery	1.354.493	1.354.493	1.354.493	1.354.493	1.354.493
	Zinc-Based Battery	269.299	309.312	309.312	309.312	309.312
Electro-Mechanical Energy Storage	Compressed Air Energy Storage	37.087.770	40.087.770	40.087.770	40.087.770	40.087.770
	Flywheel	333.612	413.612	413.612	413.612	413.612
	Pumped Hydro Storage	777.053.386	777.062.386	777.062.386	777.062.386	777.062.386
Thermal Energy Storage	Heat Thermal Storage	337.925	337.925	337.925	337.925	337.925
	Latent Heat	660.343	660.343	660.343	660.343	660.343
	Sensible Heat	20.965.701	20.965.701	20.965.701	20.965.701	20.965.701
Unclassified		528.177	528.177	532.977	548.477	774.477
Total		847.397.344	851.208.079	855.910.039	855.925.539	856.151.539

Energy storage facilities significantly alter the prevalence and utilization of renewable facilities and contribute to sustainability [10]. Electrical energy storage systems can be categorized into several groups. Electrochemical storage (lead acid Li-ions. Nickel-Cadmium. Nickel metal hydride. Sodium Sulfur. and vanadium flow batteries). electromagnetic energy storage (supercapacitors and superconducting magnetic energy storage). hydrogen storage (on-board systems and utility-scale). mechanical storage (compressed air. flywheel. pumped hydro. spring). and thermal energy storage [11].

The U.S. Department of Energy data indicates that the most widely used energy storage method worldwide is electromechanical energy storage in Table 3. For this reason, this article focuses on the comparison of solar energy storage technologies with mechanical methods and energy potential analysis in both Türkiye and Azerbaijan.

II. THE MECHANICAL METHODS FOR STORAGE SOLAR ENERGY

Pumped Hydro Storage System

Among mechanical storage systems. pumped hydro storage (PHS) is the oldest electrical energy storage system [13]. The possibility of using water gravitational energy to obtain bidirectional storage for AC grids emerged at the dawn of the 20th century [14]. Given suitable geography, it is the cheapest and most advanced technology for large-scale (GW level) storage facilities [13]. Pumped hydro storage is a method of storing and generating electricity to meet high peak demands by transferring water from a lower reservoir to an upper reservoir [15].

PHS responds quickly, within minutes, to start up and adjust its output power. Therefore, it functions as a versatile on-demand energy resource [16]. The energy efficiency of the PHS varies between 70% and 85% [17].

Solar energy is only available during daylight hours [18]. In an on-grid solar energy system, the energy produced can be consumed during the day, fed into the grid, or used to supply energy for storage methods.

In Figure 1, there is an on-grid solar energy system combined with PHS. Energy generated by photovoltaic panels (PV) is first converted from DC to AC using an inverter. The energy control unit is responsible for determining the amount of energy to be supplied to the utility grid and the amount to be stored. Once energy is fed into the grid, the motor operates to pump water from the lower reservoir to the upper reservoir, thereby storing energy. When required, upon command from the control center, water from the upper reservoir can be transferred back to the lower reservoir, converting potential energy into kinetic energy to generate electricity, which can then be utilized by the end user.

At large scale, amongst many energy storage technologies only PHS can store enough energy for long periods with bulk capacity [19].

Compressed Air Energy Storage System

Due to their substantial capacity, exceptional efficiency, minimal environmental footprint, and economical operation, Compressed air energy storage (CAES) systems represent a highly promising technology [20]. In Figure 2, during periods of low electrical demand and low electricity prices, the energy generated by PV panels is used to operate the compressor. Compressors are used to compress air, which is stored in underground caverns that are impermeable and well-insulated. When energy demand rises, turbines are driven by compressed air to generate electricity. This method of energy storage requires impermeable and well-insulated environments for the compressed air to be stored effectively. Naturally occurring voids, abandoned mines, and salt caverns can serve this purpose [13].

Due to the loss of thermal energy and additional heat supply required, the efficiency of the conventional CAES is around 50% [21]. As an alternative to caverns especially in systems utilizing renewable energy sources, the use of

storage tanks located underwater in seas or oceans has been proposed. It has been calculated that such a system can achieve efficiencies up to 65.9% [22].

Flywheel Energy Storage System

The flywheel stores kinetic energy in a high-speed rotating disk linked to an electric machine's shaft and releases the stored energy back into the grid as needed [23]. In Figure 3, a solar PV-connected system integrated with flywheel energy storage (FES) is demonstrated. The energy generated by the solar PV panels is first converted to AC and then utilized to drive the motor of the storage system. This motor, in turn, rotates the flywheel rotor, storing energy in the form of mechanical motion. When energy is required, the flywheel rotor decelerates, enabling the generator to convert the stored mechanical energy back into electrical energy.

Frictional losses occurring in the bearings and surrounding air decrease the efficiency of flywheel storage systems. Typically employed for short-term storage, flywheel systems can mitigate losses from air resistance by operating within a vacuum environment [11].

The low-speed conventional FES is highly suitable for uninterruptible power supply and power reliability applications, and it is also cost-effective. In contrast, high-speed FESs are particularly well-suited aerospace applications and can be integrated partially or fully with electrical machines [24].

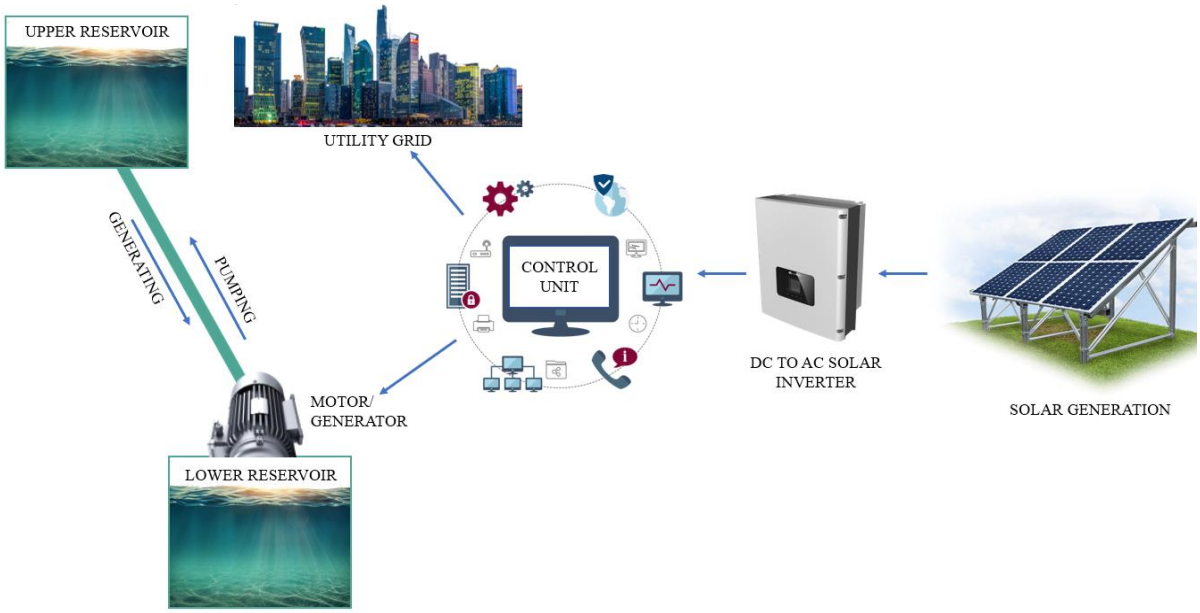


Fig. 1. Solar PV grid-connected system combined with PHS

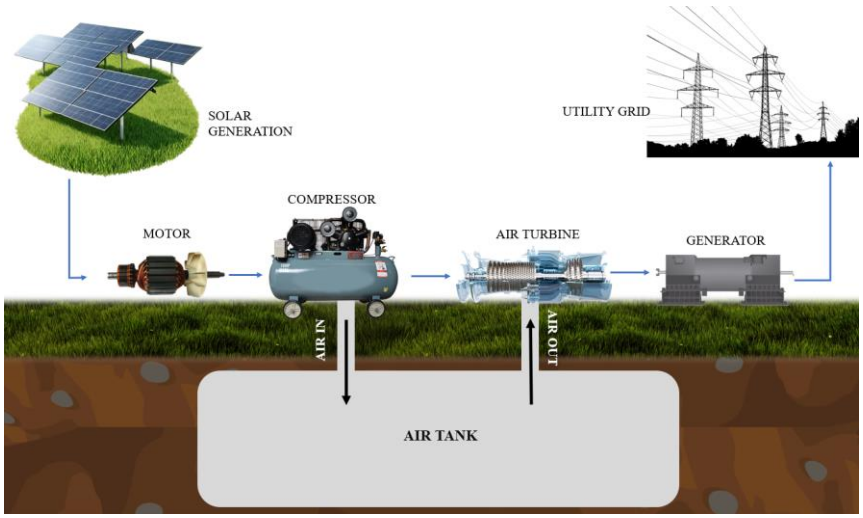


Fig. 2. Solar PV grid-connected system combined with CAES

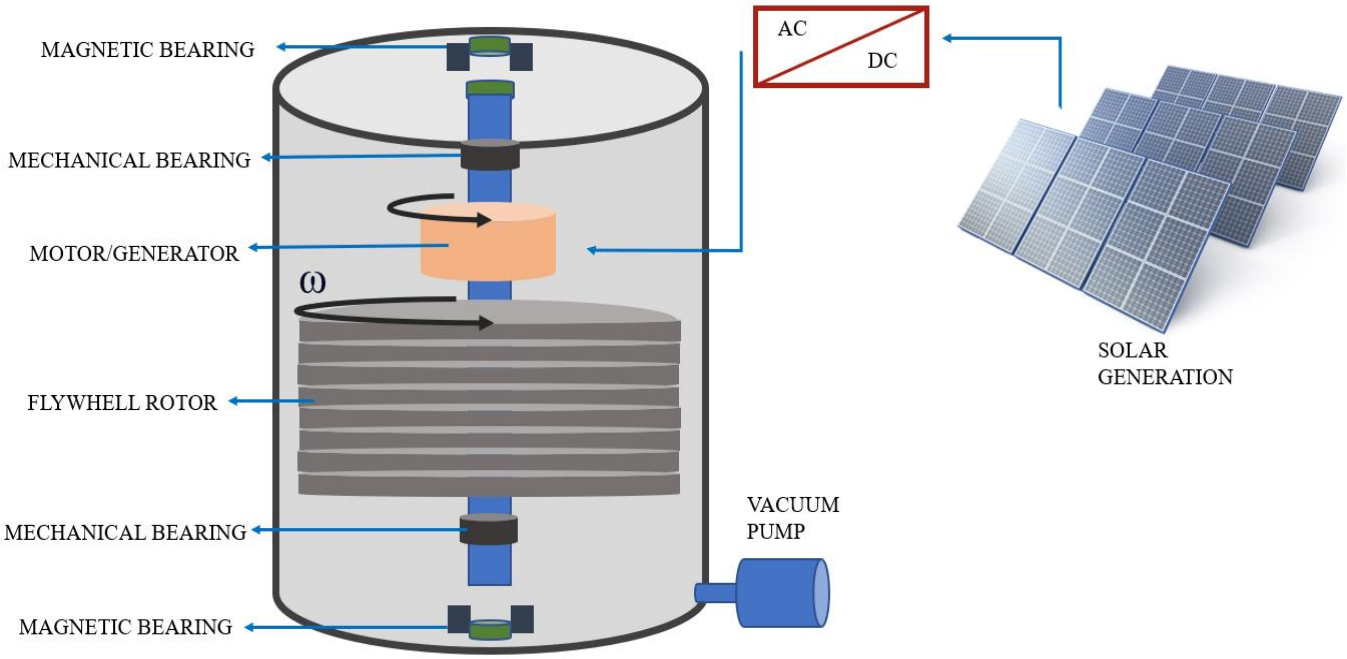


Fig. 3. Solar PV grid-connected system combined with FES

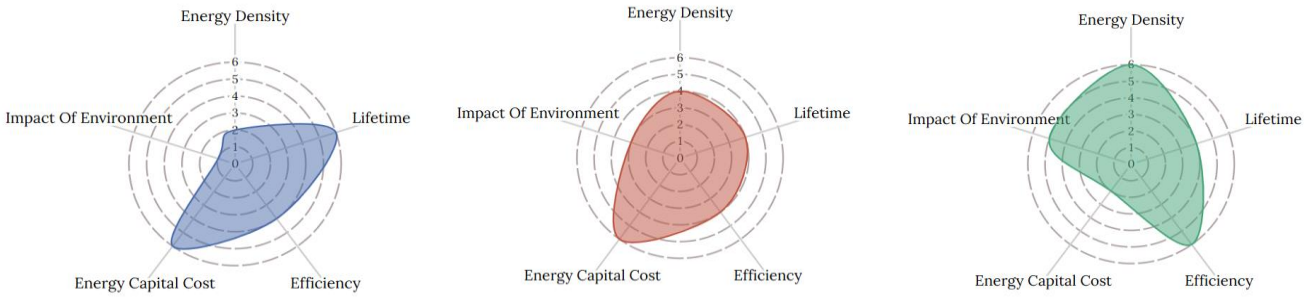


Fig. 4. Radar graph of (a) PHS, (b) CAES, and (c) FES

Flywheel energy storage is becoming an enabling technology for various applications such as energy storage for LEO satellites and providing pulse power for hybrid electric vehicles. potentially increasing their use over time [25].

Comparison of Different Types of Mechanical Methods

Solar energy storage methods are evaluated based on factors such as energy density, lifetime, efficiency, energy capital cost, and impact on the environment.

The amount of energy that can be stored in the material per unit volume is referred to as energy density [26]. Lifetime represents the operational lifespan of the energy storage method. Efficiency indicates how much of the input energy can be reused with minimal losses. Impact on the environment measures the environmental harm caused by the selected storage system. Energy capital cost is defined as the total capital cost per unit of rated energy output [27].

Using these parameters, radar graphs have been created for PHS, CAES, and FES systems, which are presented as Fig. 4(a), Fig. 4(b), and Fig. 4(c), respectively. During the construction of the radar graphs, efficiency, lifetime, and energy density were plotted proportionally, while impact on the environment and energy capital cost were plotted inversely. For example, a storage method with a high energy capital cost is represented with a smaller area for this parameter, whereas a system with high efficiency covers a larger area for the respective parameter [11, 28]. In a system where all parameters hold equal importance, the energy storage method with the largest area on the radar graph is deemed more applicable.

Current Situation and Future Perspectives in Türkiye and Azerbaijan

In Türkiye, factors such as technological advancements, population growth, and industrialization are driving an increase in energy demand. Addressing this situation is crucial for maintaining the balance between energy demand and supply. Energy demand in Türkiye is met with limited resources, highlighting the necessity of utilizing existing energy sources more efficiently and exploring alternative energy sources. Türkiye holds a strategic position for harnessing solar energy, owing to its high solar radiation levels and extended duration of sunlight exposure [29]. Since most alternative energy sources are renewable-based, the energy produced depends on natural conditions. This leads to

a mismatch between energy demand and supply. Therefore, energy storage technologies are becoming increasingly important to ensure that the total energy demand is consistently met.

In Türkiye, reservoir-based hydroelectric power plants are used to balance demand during peak hours [30]. Potential sites for pumped hydro storage (PHS) plants in Türkiye have been investigated based on criteria such as proximity to high-demand regions, as well as geological, topographical, and environmental constraints. Following a step-by-step elimination process, the conceptual designs of Gökçekaya PHS (1400 MW), with its lower reservoir located at the Gökçekaya Dam and hydroelectric power plant, and Altınkaya PHS (1800 MW) have been developed [31].

The investment for the Gökçekaya PHS project was approved in 2020, with the budget set at 6.3 billion TL, as published in the Official Gazette dated February 12, 2020 [32]. The investment is planned to continue until 2032. However, no information is available confirming the commencement of the Gökçekaya PHS project.

In Türkiye, activities in the field of electricity storage have been primarily focused on battery-based storage systems. The regulatory framework for electricity storage investments was announced in November 2022, and pre-licensing applications for storage-based power generation facilities commenced simultaneously. By the end of June 2023, it was observed that the number of pre-licensing applications for storage investments in wind and solar energy projects, which incorporate battery storage, exceeded 5,000, with a total capacity surpassing 270 GW [33].

Azerbaijan has significant potential for renewable energy development, with abundant solar and wind resources, as well as considerable opportunities in biomass, geothermal, and hydropower. Despite the wide availability of these resources and the nation’s ambitious long-term goals, progress in implementation has so far been relatively limited [34].

After its approval by Azerbaijan's parliament in 2021, the Law on the Efficient Use of Energy Resources and Energy Efficiency came into effect. The legislation sets forth regulations for conducting energy audits, implementing energy management systems, providing energy services, and enhancing efficiency across production, transmission, distribution, and storage processes. It also emphasizes promoting awareness and supporting various related initiatives [35]. This law provides for the development of the country’s first National energy efficiency action plan [36].

Azerbaijan’s geographical features and natural conditions make it highly suitable for investments in renewable energy sources. However, this also raises the issue of effectively storing the energy generated from these sources.

In November 2024, a Memorandum of Understanding was signed between the Ministry of Energy of the Republic of Azerbaijan and Power China Resources Limited for the development of renewable energy projects. The agreement outlines collaboration on industrial-scale solar photovoltaic (PV) projects, onshore and offshore wind power plants, pumped hydro storage (PHS) systems, and battery energy storage systems (BESS) [37].

III. CONCLUSIONS

The transition to renewable energy in Türkiye and Azerbaijan is marked by significant progress in solar energy capacity and policy frameworks. However, the effective storage of renewable energy remains a critical challenge. Mechanical storage systems such as PHS, CAES, and FES present promising solutions, each with unique benefits and limitations. Türkiye's increasing focus on energy storage investments and pre-licensing applications for battery storage facilities indicates strong momentum toward meeting long-term sustainability goals. Similarly, Azerbaijan's strategic initiatives, including international collaborations and legislative reforms, underline its commitment to becoming a "green growth" country. The implementation of advanced energy storage technologies is vital for both nations to fully harness their renewable energy potential, stabilize power systems, and achieve climate targets. Future efforts should focus on optimizing storage technology deployment, addressing geographical and infrastructural constraints, and fostering innovation to enhance energy efficiency and sustainability.

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