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Umut Genç
Iskenderun Technical University, umutgenc.lee22@iste.edu.tr,
Hatay-Türkiye
Abdulla Sakallı
Iskenderun Technical University, abdulla.sakalli@iste.edu.tr,
Hatay-Türkiye
Mehmet Uğur Güçel
Iskenderun Technical University, mgucel.mfbe18@iste.edu.tr
Hatay-Türkiye

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ORCID ID	0009-0001-1108-9608	0000-0002-2488-7318	0000-0002-9754-333X
Corresponding Author	Abdulla Sakallı		

COMPARISON OF TRADITIONAL SEALED LEAD ACID BATTERY AND NEXT GENERATION SUPERCAPACITOR USAGE IN TERMS OF ENERGY EFFICIENCY IN SOLAR ENERGY STORAGE SYSTEMS

ABSTRACT

Solar energy is an important renewable energy source due to its accessibility and relatively low maintenance and operating costs. Due to the rapid increase in global energy demand, it has become crucial to enhance energy production capacity and store the produced energy more efficiently and sustainably. In recent years, hybrid systems have gained importance in energy storage systems. Additionally, the potential effects of environmental factors, such as temperature, on the efficiency and performance of these systems require attention. This study compared two energy storage technologies used in solar energy systems: sealed lead-acid batteries and supercapacitors. The study compared both technologies in terms of cost per unit, energy and power density, energy efficiency, and average lifespan. Additionally, the potential of hybrid systems combining both technologies was analyzed to develop more stable and efficient solar energy storage solutions. The analyses indicate that, technically, supercapacitors are significantly preferable to sealed lead-acid batteries. Despite this, their disadvantages in basic criteria such as energy density and cost make them challenging to use alone in every application. Hybrid systems, in which supercapacitors respond to sudden load needs and sealed lead-acid batteries meet long-term energy requirements, are considered the most ideal option for energy management.

Keywords: Solar Energy, Hybrid Storage Systems, Supercapacitor, Energy Efficiency, Lead-Acid Battery

1. INTRODUCTION

The increase in energy demand has become a serious agenda item worldwide in the last two decades [1]. With the acceleration of industrialization, the spread of digitalization, and the rise in living standards, per capita energy consumption is increasing in almost every geography [2]. However, the limited reserves of traditional energy sources like fossil fuels, their increasingly evident environmental impacts, and their contribution to the climate crisis have necessitated a radical transformation in energy production [3 and 4]. At this point, renewable energy sources are considered a strategic tool that enables not only environmental sustainability but also energy independence[3]. Among renewable energy sources, solar energy holds a special position due to its direct accessibility, cleanliness, and inexhaustibility [5].

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Thanks to cost reductions and efficiency increases in photovoltaic (PV) technologies, electricity generation from solar energy has become competitive with fossil fuels in many countries [6 and 7]. However, the production of solar energy is inherently intermittent. Solar radiation is only available during daylight hours and under clear sky conditions. Cloudiness, nighttime hours, and seasonal variations make solar-based production unstable. This situation brings to the fore the need for an effective and reliable storage system for energy continuity [8]. Energy storage systems not only ensure the balance between production and consumption but also support grid stability, respond to sudden load increases, and minimize energy losses [9]. In this regard, the selection of appropriate storage technology is extremely critical to increase the performance and ensure the sustainability of solar energy systems. Among storage technologies, sealed lead-acid batteries have been one of the most widely used from the past to the present. Thanks to their low initial investment cost, technological maturity, and easy availability, these batteries are particularly preferred in small and medium-scale systems [10]. On the other hand, some disadvantages, such as limited cycle life, low energy density, and maintenance requirements, make lead-acid batteries controversial, especially in terms of long-term efficiency [11].

In recent years, supercapacitors have attracted attention as a new technology in the field of energy storage. Supercapacitors are devices that store electrical energy electrostatically and can be charged in a much shorter time, and can perform millions of cycles compared to batteries [12]. Thanks to their high power density and rapid energy transfer features, they are extremely effective, especially in meeting sudden energy needs [13]. In contrast, the limited energy density and high unit costs of supercapacitors are the main obstacles to the widespread use of this technology in large-scale systems [14]. Today, many researchers are focusing on the development of hybrid systems where these two technologies are used together [15]. Hybrid energy storage systems aim to create more balanced and efficient systems by combining the rapid response capability of supercapacitors and the energy density of sealed lead-acid batteries [16 and 17]. However, the design, control algorithms, and cost-benefit balance of hybrid systems have not yet been fully optimized. Therefore, the question of which storage unit will provide an advantage, under which conditions, and to what extent in system design still maintains its importance [18]. Sealed lead-acid batteries are still a widely used energy storage solution today [19]. They stand out due to their cost advantage, especially in applications with low investment budgets where long-term energy storage is required [20]. Their higher energy density compared to supercapacitors allows for more compact system designs. On the contrary, disadvantages such as limited cycle life, long charging time, and performance loss over time reduce their effectiveness, especially in systems requiring intensive use [21]. Supercapacitors, on the other hand, are a technically very attractive alternative with their high power density, extremely short charging times, and long lifespans of up to hundreds of thousands of cycles [22]. However, two main weaknesses of this technology, low energy density and high cost, limit its application areas [23]. Especially in large-scale systems requiring long-term energy storage, the standalone use of supercapacitors is still not economically feasible [24]. However, if technological developments and reductions in production costs continue, these obstacles are expected to be overcome in the short term.

2. RESEARCH SIGNIFICANCE

This study aims to compare sealed lead-acid batteries and supercapacitors, which are energy storage technologies in solar energy systems, in terms of energy efficiency. Within the scope of the study, the technical parameters of both technologies will be discussed comparatively in light of literatüre data, and their performance in different application areas will be evaluated with analyses supported by graphs and tables. In line with the findings, it is aimed to provide guiding information for existing systems and to make technical recommendations for hybrid energy systems to be developed in the future. Furthermore, the study compared two different energy storage technologies that can be used in solar energy systems – sealed lead-acid batteries and supercapacitors in terms of basic criteria such as energy efficiency, cycle life, power density, and cost. For this purpose, a comparative analysis method was followed in light of technical data obtained from the literature, and the results were supported by tables and graphics.

Highlights:

- The study is quantitatively based and was conducted using a descriptive comparison method.
- The performance parameters of both technologies were compiled by considering previously conducted experimental studies, manufacturer data, and sectoral reports [25, 26, and 27].
- Parameters such as energy density (Wh/kg), power density (W/kg), cycle life, charge/discharge times, cost, maintenance requirement, and environmental durability were taken as a basis during the analyses [28 and 29].

3. ANALYTICAL STUDY

Data were primarily obtained from international academic publications, especially from studies published in reliable databases such as IEEE, ScienceDirect, and Springer [17, 30, and 31]. In addition, technical documents of supercapacitor and lead-acid battery manufacturers (e.g., Maxwell Technologies, Panasonic, Exide, and Trojan Battery) were examined. To ensure data consistency, data for the same parameter were taken from at least three different sources, and analyses were made using arithmetic averages.

3.1. Comparative Parameters

The basic comparison criteria used in the study [2, 4, 32, and 33] and the average values obtained for these criteria are presented in Table 1 below. According to the table below, it is observed that supercapacitors have a clear superiority in terms of power density and cycle life, while sealed lead-acid batteries are more advantageous in terms of energy density and cost [34 and 35].

Table 1. Technical specification comparison of Sealed-acid battery and Supercapacitor [2, 4, 32, and 33]

Feature	Sealead lead-acid battery	Supercapacitor
Energy density(wh/kg)	30	6
Power density (w/kg)	200	5000
Cycle life (cycles)	1000	100000
Charge time	2-8 hour	1-60 seconds
Discharge time	1-4 hour	1-60 seconds
Maintenance need	Medium	Low
Cost($/kWh)	150	500

According to the Table 1., it is observed that supercapacitors have a clear superiority in terms of power density and cycle life, while sealed lead-acid batteries are more advantageous in terms of energy density and cost [34 and 35].

3.2. Limitations of the Method

The comparison method used in this study does not include laboratory tests or real field applications. Data were taken from secondary sources and evaluated within a theoretical framework. Therefore, some effects related to environmental conditions, temperature changes, or long-term usage performance of both technologies may have been ignored [36]. However, the academic nature and technical accuracy of the sources used support the reliability of the study.

3.3. Evaluation Criteria

When evaluating energy efficiency, not only theoretical capacity but also factors such as energy losses within the cycle, thermal inefficiency, and converter efficiency were taken into account [26 and 37]. In addition, in the cost calculation, not only the initial investment but also maintenance costs and energy cost per lifetime (kWh/lifetime) were included. Thanks to this method, a fairer and more realistic comparison could be made [25].

3.4. Assessment of Environmental Factors and Temperature Effects

Environmental conditions, particularly temperature, play a critical role in the performance of energy storage systems. With dry-type lead-acid (SLA) batteries, an increase in temperature initially raises capacity but ultimately causes long-term degradation, including increased internal resistance and corrosion [32]. At low temperatures, energy efficiency decreases because electrochemical reactions slow down [11]. Supercapacitors, on the other hand, primarily operate on the principle of physical accumulation, making them less prone to chemical reactions. However, they are still negatively affected by temperature. For instance, electrolyte degradation and diaphragm deterioration can accelerate at high temperatures [33]. At low temperatures, internal resistance may increase, resulting in decreased energy storage efficiency [16]. Studies on both technologies have reported performance changes of up to 10–30% when operating outside of the ±25°C range [40]. Below -10°C, SLA batteries experience significant capacity loss, whereas supercapacitors are less affected [15]. Considering these factors, separate temperature management strategies must be applied in hybrid systems operating under environmental conditions. For instance, using active cooling systems to manage battery groups and thermal insulation to protect supercapacitors will increase the system's lifespan and efficiency [32 and 33]. Based on this, it is recommended that thermal control systems and cyclic efficiency simulations (e.g., heat balancing, thermal insulation, and temperature sensors) be developed for each technology to minimize the effects of temperature changes on performance. To minimize the effects of temperature changes on performance, it is recommended to develop thermal control systems and cyclic efficiency simulations (heat balancing, thermal insulation, temperature sensors) specific to each technology.

3.5. Focus on Hybrid Systems in Energy Storage

Renewable energy sources have an unstable production structure, which makes energy storage technologies even more important. In this regard, hybrid systems that combine the benefits of various energy storage technologies are receiving more attention. Specifically, the complementary characteristics of supercapacitors (high power density) and dry-type batteries (high energy density) play a decisive role in designing these systems [11]. Hybrid energy storage systems integrate multiple technologies within the same structure, typically offering advantages such as optimized charge-discharge times, balanced power fluctuations, and increased system efficiency [16]. Jossen indicated the need for careful management of battery dynamics in such systems, demonstrating how parameters such as thermal balance and internal resistance influence the design of hybrid structures. Zhang state that supercapacitors can play a supportive role in battery systems due to their high cycle life and ability to effectively meet short-term energy requirements. Hybrid systems were reported to have been successfully deployed in solar microgrids, increasing energy efficiency in a field application [41]. Hybrid systems are not only used in grid-scale applications but also offer effective solutions in areas such as electric vehicles and mobile power systems. [40] noted that hybrid systems ability to respond quickly to sudden power demands provides more reliable energy management than can be achieved with conventional systems. In this framework, hybrid energy storage systems are expected to be more widely adopted in the future due to their potential to enhance energy supply security, system stability, and sustainability.

4. FINDINGS AND DISCUSSIONS

In this study, two basic technologies used for energy storage in solar-powered systems, sealed lead-acid batteries and supercapacitors, were comparatively analyzed based on specific technical and economic criteria. In the analyses, criteria that directly affect system design in practice, such as energy density, power density, cycle life, charge time, and unit cost, were taken into consideration. The findings showed that sealed lead-acid batteries are much more advantageous than supercapacitors in terms of energy density. With average values around 30 Wh/kg, they can store more energy, which leads to the preference for sealed lead-acid batteries in systems that are more compact and have long-term energy needs. In contrast, the energy density of supercapacitors is quite low (approximately 5 Wh/kg). This difference shows that supercapacitors are essentially power-oriented storage units, not energy-oriented. However, when it comes to power density, the situation is reversed. Supercapacitors can provide very high amounts of power within seconds. Evaluations show that the power density of supercapacitors is almost 30 times higher than that of sealed lead-acid batteries. This feature proves how critical a role supercapacitors can play in situations where sudden load increases occur in the system. For example, when the high power demand of a DC motor at the initial start-up moment is met by supercapacitors, the stress on the batteries decreases. Cycle life is another significant difference between the two technologies. While sealed lead-acid batteries generally experience performance loss between 300–600 charge/discharge cycles, supercapacitors can last up to 100,000 cycles. This situation shows that supercapacitors significantly reduce maintenance needs and system downtime, especially in applications requiring frequent cycling. A similar advantage exists in terms of charge time. While sealed lead-acid batteries need several hours to reach full charge, supercapacitors can be charged in just a few seconds. Thus, supercapacitors are almost unrivaled in scenarios requiring short-term energy storage and release. However, the biggest weakness of supercapacitors is their high cost per unit of energy. Under current market conditions, supercapacitors are approximately 8–10 times more expensive than sealed lead-acid batteries. This difference limits the preference for supercapacitors as standalone long-term energy solutions. In conclusion, the comparison revealed that both technologies have their own unique strengths and weaknesses. While sealed lead-acid batteries offer long-term and economical energy storage solutions, supercapacitors stand out in areas such as rapid energy transfer and system balancing. Therefore, instead of relying on a single technology, hybrid system designs that combine the advantages of both technologies offer a much more sustainable approach both technically and economically.

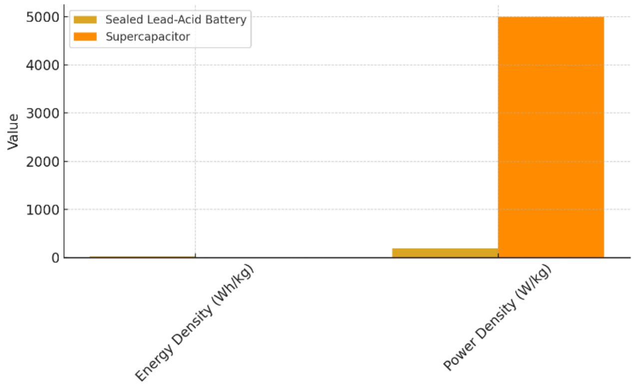

Figure 1. Energy and power density comparison [25, 30, 31, and 33]

As can be seen from figüre 1, the power density of supercapacitors is approximately 25 times higher than that of sealed lead-acid batteries. However, in terms of energy density, lead-acid batteries can offer up to five times higher capacity. This situation shows that supercapacitors are more effective not in long-term energy storage, but in high instantaneous power demands [31 and 38].

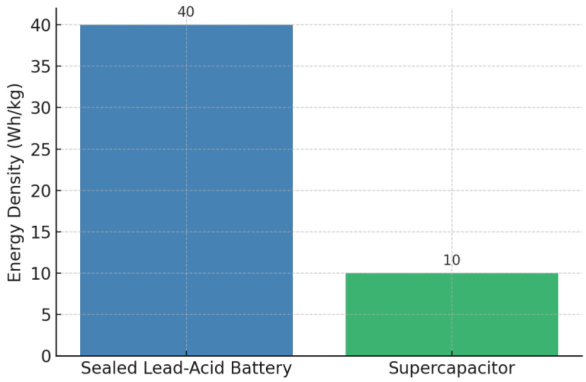

Figure 2. Energy density comparison [25, 33, and 34]

While sealed lead-acid batteries have an average energy density of 40 Wh/kg, this value is around 10 Wh/kg for supercapacitors. This situation causes supercapacitors to take up more space volumetrically and to be insufficient in meeting long-term energy needs [25 and 34].

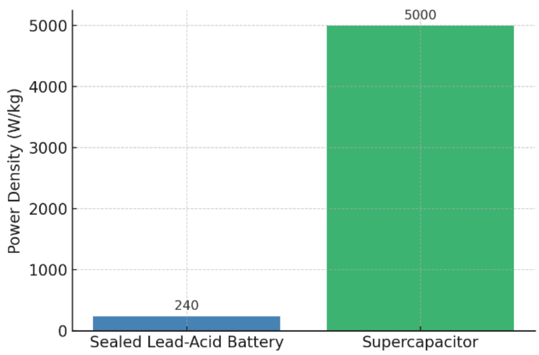

Figure 3. Power density comparison [25, 30, and 31]

Supercapacitors have a clear superiority in this area. Reaching an average value of 5000 W/kg, supercapacitors can provide high power in a much shorter time compared to the average 240 W/kg value of sealed lead-acid batteries. This difference offers a decisive advantage for electric vehicles and systems with sudden load demands [30 and 31].

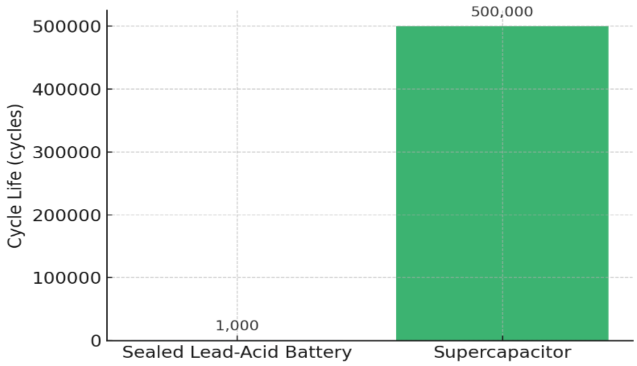

Figure 4. Cycle life comparison [26 and 27]

According to literatüre data, while sealed lead-acid batteries have a life of around 1000 cycles, supercapacitors can last up to 500,000 cycles. This difference makes supercapacitors much more attractive in terms of maintenance frequency, spare part needs, and operational continuity [26 and 27].

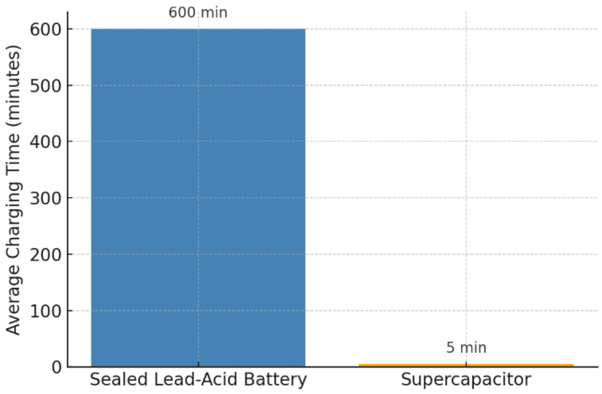

Figure 5. Sealed lead-acid battery and supercapacitor charge time comparison [4, 26, 27, and 36]

In solar energy systems, the charging times of energy storage units are a parameter that directly affects the overall efficiency of the system. The fact that solar radiation is available for limited periods necessitates the capacity of storage components to store maximum energy during this time. In this context, the ability to fully charge in a short time is very important for the system to adapt to dynamic load demands [26]. Lead-acid batteries, due to their chemical reaction-based charge-discharge characteristics, usually take between 8 to 12 hours to reach full capacity [4]. This situation can cause some delays or capacity losses depending on the system's usage scenario. Supercapacitors, on the other hand, can be charged in times ranging from seconds to minutes thanks to their electrostatic storage mechanism [36]. Especially their ability to store a large amount of energy in short periods, such as 1 to 5 minutes, provides a great advantage in applications where sudden energy is needed [27].

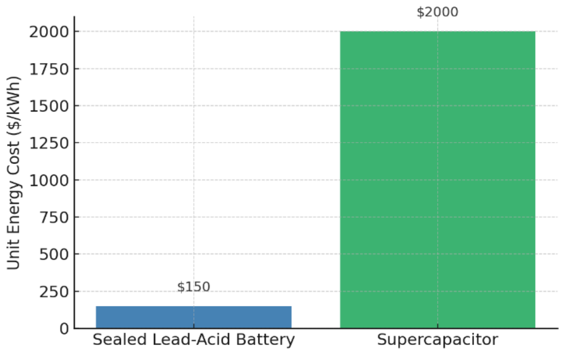

Figure 6. Cost comparison [25 and 39]

5. CONCLUSION AND RECOMMENDATIONS

In line with the findings, the development of hybrid systems that combine the advantages of both technologies offers an important opportunity to increase energy efficiency and ensure system stability in the future. For example, while supercapacitors are used to balance sudden load changes, sealed lead-acid batteries can remain active as continuous energy providers. Such multi-layered energy management solutions will support long-term sustainability not only technically but also economically. The analyses clearly show that supercapacitors are technically superior to sealed lead-acid batteries in many areas. However, their disadvantages in basic criteria, such as energy density and cost make it difficult to use them alone in every application. Therefore, hybrid solutions are prominent in many new systems. Hybrid systems, where supercapacitors respond to sudden load demands and sealed lead-acid batteries meet long-term energy needs, are considered the most ideal option in terms of energy management [17]. The analyses conducted within the scope of this study have shown that supercapacitors and sealed lead-acid batteries have complementary advantages. In such a system, supercapacitors can provide short-term energy balancing by intervening when solar radiation suddenly increases or load demands abruptly rise, while sealed lead-acid batteries will remain active to meet longer-term energy needs. The energy flow between these two components will be controlled by a microcontroller-based energy management unit placed at the center of the system. This unit will continuously monitor the panel output power, the state of charge of the supercapacitor and battery, and the load demand to decide which source will be activated.

NOTICE

This article is based on MSc thesis, entitled "Comparison of The Use of Traditional Dry Type Batteries and New Generation Super Capacitors in Solar Energy Storage Systems in terms of Energy Efficiency", a thesis which was carried out under the supervision of Prof. Dr. Abdulla Sakallı at Iskenderun Technical University, Iskenderun, Turkey.

CONFLICT OF INTEREST

The author(s) declare that they have no potential conflict of interest.

FINANCIAL DISCLOSURE

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DECLARATION OF ETHICAL STANDARDS

The authors of the article declare that the materials and methods used did not require ethics committee approval and/or regulatory approval.

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