Comparative Analysis of Energy Storage Technology for Solar Water Pump

Ede Tiekuro, Koroye Solomon Ziakede, Ozekizibe Captain

Department of Physics, University of Africa, Toru-Orua.

DOI: https://doi.org/10.51244/IJRSI.2025.12060015

Received: 20 May 2025; Accepted: 24 May 2025; Published: 27 June 2025

ABSTRACT

This study provides an evaluation of the efficiency of energy storage technologies of Lead-Acid batteries and the Maxwell supercapacitor of capacity 2.5V 3000F by comparing their energy storage capacity, charging and discharging efficiency, life cycle, cost effectiveness and performance in solar water pump applications. It contributes to the increasing knowledge on energy storage technologies by highlighting their respective advantages and limitations. Solar water pump systems rely strongly on energy storage solutions for effective operation during periods of low or no sunlight radiation. The study was carried out by the installation of solar water pump system using 500 watts Photovoltaic panel which was connected to a 12V, 200Ah deep cycle Lead-Acid battery and Maxwell supercapacitors 2.5V 3000F. The process involves setting up the system, testing the system, data collection on energy stored, energy efficiency, charging and discharging times and life cycle under similar conditions. The results from the study shows that while Lead Acid batteries are commonly used due to their affordability, they face challenges such as short cycle life and declining efficiency. Conversely, the Maxwell supercapacitor 2.5V, 3000F offer longer life cycle and faster charging and discharging but have limited energy storage capacity. The findings will help engineers, researchers,and end users make informed decisions when choosing the energy storage technology for solar energy systems, especially in off-grid regions or location of unreliable conventional power supply. Furthermore, this study promotes sustainable energy practices by identifying the most cost effective and efficient storage technology for long-term use, potentially influencing future designs of solar water-powered systems.

Keywords: energy density, power density, capacitor, battery, solar water pump

INTRODUCTION

Solar energy is a renewable that occurs naturally in abundance. Solar water pumps are a renewable and sustainable solution that utilizes solar energy to pump water for various purposes, such as irrigation, livestock watering, and domestic water supply. It offers a clean and cost-effective source of power which can be used to power water pumps. In recent years, solar water pumps have become useful technology for sustainable water resource management, particularly in areas with unreliable or limited access to conventional power supply. According to Mekhilef, et al. (2012), solar power systems can significantly reduce energy costs and negative impacts on our environment as compared to fossil fuel powered pumps. Also, Solar water pumps technology contribute greatly to reducing greenhouse gas emissions as emphasized by the Inter-governmental Panel on Climate Change (IPCC, 2018).

In the light of the above, energy storage technologies are vital for ensuring continuous operation of solar water pumps, particularly during periods of limited radiation from sunlight. Traditional energy storage methods, such as batteries, have been widely used because they have the capacity to store large amount of energy over long period of time (Sharma, et al. 2015). Recent advances in technology have introduce devices such as capacitors, particularly supercapacitors, as an alternative to battery technology due to their ability to charge and discharge rapidly and withstand more charge cycles (Burke, 2010). The comparative analysis of the performance of these technologies in the application of solar water pump is vital to know which system is more efficient, cost-effective, and sustainable over the long term.

In solar systems, batteries have been preferred for energy storage, because they have relatively high energy density and capacity to supply power even during cloudy weather conditions (Mani and Pillai, 2010). However, there are concerns raised regarding battery life, maintenance costs, long term viability and environmental hazards associated with battery disposal (Wang et al., 2018). Lead-acid batteries, which are commonly used in solar water pump systems, have a less durability and require regular maintenance to function optimally, while lithium-ion batteries, though more efficient, are expensive and have complex recycling processes (Arun et al., 2017). According to Luo et al. (2015), supercapacitors can undergo thousands of charge and discharge cycles with no significant degradation, which makes them more durable than batteries. Furthermore, capacitors can charge and discharge more quickly than batteries, enabling solar water pumps to operate efficiently even under limited solar radiation (Zhou et al., 2017). However, the lower energy density of capacitors compared to batteries presents a challenge for their widespread adoption in solar water pumps, particularly in applications that requires longer periods of operation without radiation from the sun (Belhadj and Kermadi, 2011).

In light of the increasing global focus on sustainability and clean energy, this study aims to evaluate and compare the performance of batteries and capacitors as energy storage systems for solar water pumps, with a focus on efficiency, cost, and environmental impact. This comparative analysis will help determine which technology is better suited for specific use cases and under varying operational conditions. Several studies, including the one conducted by Zhou et al. (2017) and Wang et al. (2018), have called for more empirical research into the performance of these technologies in real-world applications so as to make tangible choices about energy storage in solar water pumps system. The findings will provide valuable insights for farmers, engineers, and policymakers looking to implement or improve solar-powered water systems.

LITERATURE REVIEW

Solar water pumps utilizes solar energy to pump water for various purposes, such as agricultural projects and domestic water supply. These pumps offer an environmentally friendly alternative to fossil fuel or other electric-powered pumps, particularly in off-grid or remote areas where access to electricity is limited. Solar water pumps are widely regarded for their potential to reduce operating costs, minimize environmental impacts, and improve access to water in developing regions (Alawaji, 2001).

Components of Solar Water Pumps

A typical solar water pump system consists of several essential components, which include solar photovoltaic (PV) panels, a controller or inverter, the water pump, and energy storage systems, such as batteries or capacitors.

The solar (PV) panels are the basis of the solar water pump system, that convert energy from sunlight into electrical energy through the photovoltaic effect. The efficiency and power output of the panels depend on several factors, including the intensity of sunlight, the angle of installation, and the type of photovoltaic cells used (Sharma & Goel, 2017).

The controller or inverter regulates the flow of electricity generated by the solar panels to ensure consistent and safe operation. In direct current (DC) systems, the controller manages the power supply to the pump, while in alternating current (AC) systems, an inverter is needed to convert the DC power from the panels into AC electricity for the pump (Hossain et al., 2015). The controller also plays a crucial role in optimizing energy use and preventing overcharging or over-discharging of batteries (Odeh & Yohanis, 2006).

Energy storage systems are critical to ensuring the continuous operation of solar water pumps, particularly during periods of low sunlight or nighttime. Traditionally, batteries have been the primary storage technology, but capacitors and supercapacitors are gaining interest due to their longer lifespan and rapid charge-discharge capabilities (Ghofrani et al., 2019). The choice of energy storage technology can significantly influence the cost, reliability, and environmental impact of the system (Luo et al., 2015). While the initial capital costs of solar water pumps may be higher than traditional systems, the long-term savings on fuel and maintenance make them cost-effective. Solar pumps require minimal maintenance and have low operational costs, as sunlight is a free and abundant energy source in many regions (Hossain et al., 2015).

Traditional batteries used in solar water pumps, such as lead-acid or lithium-ion batteries, have limitations in terms of lifespan, maintenance, and environmental impact (Luo et al., 2015). While supercapacitors offer promising alternatives with faster charging times and longer lifespans, they generally have lower energy density and are more expensive than batteries (Burke, 2010). The choice of energy storage technology directly affects the long-term efficiency and cost of the system.

Batteries in Solar Water Pump Systems

The primary function of batteries in solar water pumps is for electrical energy storage generated by photovoltaic (PV) panels, which can later be used to power the water pump when solar radiation is insufficient or unavailable during cloudy weather or sunset. The effective integration of batteries in solar water pump systems can enhance their reliability, efficiency, and overall performance (Rajput et al., 2013; Mehta et al., 2021).

This ensures a consistent supply of water, which is essential for agricultural irrigation, drinking water, or other industrial uses. Additionally, batteries help smooth out the variability in solar power generation caused by fluctuating weather conditions (Odeh & Yohanis, 2006).

Types of Batteries Used in Solar Water Pumps

Several types of batteries can be used in solar water pumping systems, each with unique characteristics in terms of efficiency, cost, lifespan, and environmental impact. These include: Lead-acid batteries, Lithium-ion (Li-ion) batteries and Nickel-based batteries, particularly nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) batteries.

Lead-acid batteries operate on the basis of chemical reactions between lead dioxide (PbO_2) on the positive plate and sponge lead (Pb) on the negative plate. During discharge, both react with sulfuric acid (H_2SO_4) to produce lead sulfate ($PbSO_4$) and release energy. The primary equation governing this reaction is:

$$PbO_2 + Pb + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O + \text{energy}$$

This reaction is reversible, allowing the battery to be recharged by reversing the reaction.

Capacitors in Solar Water Pumps

Capacitors are now an alternative energy storage technology in solar water pump systems. Capacitors, especially supercapacitors (also known as ultracapacitors), offer several unique advantages over batteries, including rapid charging and discharging rate, long life cycle, and high power density. These characteristics make capacitors suitable for specific applications within solar water pumps, particularly where quick energy storage and release are required, and long-term storage is not as critical as in batteries (Burke & Miller, 2011; Linden & Reddy, 2002). Supercapacitors and Electrolytic capacitors are used in some solar power applications for energy storage and filtering. While they have lower energy storage capacity than supercapacitors, they are often used to smooth out voltage spikes and provide short bursts of energy during pump startup or sudden power demands.

MATERIALS AND METHODS

The study design follows an experimental approach to compare the efficiency of lead-acid batteries and Maxwell supercapacitors 2.5V 3000F in a solar water pump system. The process is structured into four main stages: setup, testing, data collection, and analysis. Each energy storage system is tested under similar conditions to ensure a fair comparison. Figure 1 shows the flow chart of the experimental setup.

The setup starts with the installation of solar water pump having both the Lead-acid battery and the Maxwell supercapacitor 2.5V 3000F connected to solar panels. This is followed carrying out Lead-Acid Battery test and Ultracapacitor test by observing the Charge and discharge rate over a specific period under similar conditions, energy storage capacity, efficiency and life cycle of the storage system.

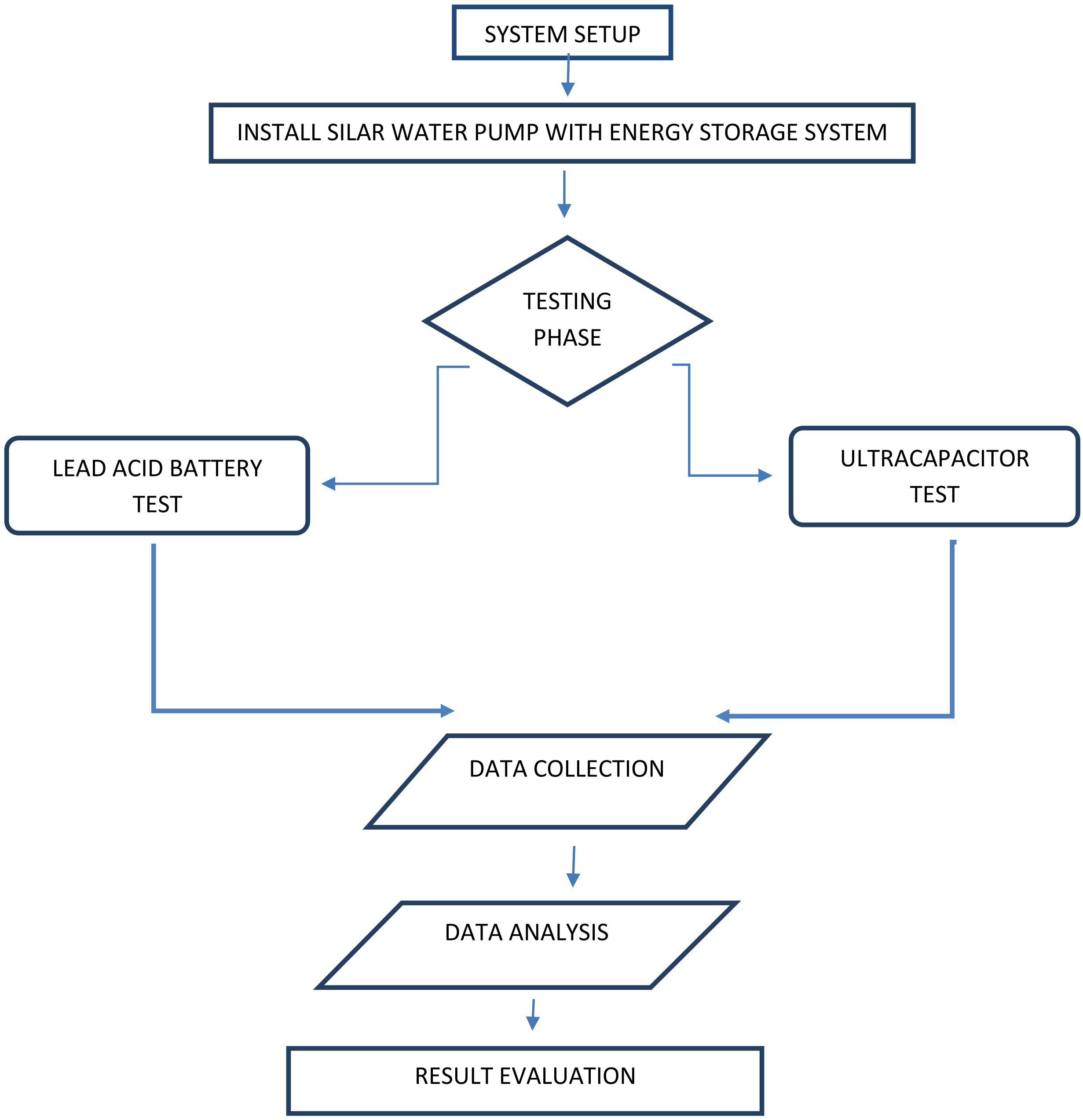

Fig. 1: Flow Chart of the research methodology:

Materials

This study involves the use of specific devices and software to conduct the experimental analysis in order to compare the efficiency of lead-acid battery and Maxwell supercapacitor in a solar water pump system. The materials used are list as follows:

1. A standard submersible solar-powered water pump which was connected to both a deep-cycle Lead-Acid Battery of capacity 12V, 200Ah and a Maxwell Supercapacitor of 2.5V, 3000F capacity.

2. Photovoltaic (PV) solar panels with 500W capacity was used to charge both the lead-acid battery and the Supercapacitor.

3. A solar charge controller was incorporated into the system to regulate the flow of energy from the solar panels to the energy storage devices. This prevented overcharging and ensured optimal charging efficiency for both the lead-acid battery and the supercapacitor.

4. A DC to AC power inverter was used to convert the DC output from both energy storage systems into AC power.

5. A data logging device was employed to continuously monitor and record key parameters such as voltage, current, and power output from both the lead-acid battery and the supercapacitor. This data was essential for analyzing and comparing the performance of the two energy storage systems.

Software used for analysis include; MATLAB used in processing and analyzing the experimental data collected by calculating energy efficiency, storage capacity, and cycle life, as well as simulating the performance of both energy storage technologies under different operational conditions, Microsoft Excel was used to organize the data that represent the performance differences between the lead-acid battery and the Maxwell supercapacitor, PV*SOL used to validate the experimental results by comparing actual performance with simulated data.

The Operations of the Solar water pump system

The first step for the operation of solar water pump system was installation and setting up the system. This was achieved by integrating both the lead-acid battery and the Maxwell supercapacitor as separate energy storage units. Each energy storage system was tested under the same environmental conditions, with identical solar input from the photovoltaic panels. During this phase, the correct configuration and functionality of all hardware components were verified to ensure consistent performance.

This was then followed by real-time data collection using a data logger connected to the system to continuously monitor and record the Voltage (V), Current (A), Power Output (W), Charging Time (hours), Discharging Time (hours). Data from both the lead-acid battery and the Maxwell supercapacitor were logged simultaneously under identical operating conditions. The data logger recorded the charging and discharging cycles, providing essential information on the efficiency, energy storage capacity, power density, life cycle and performance of each system in powering the solar water pump.

In addition to the performance data, environmental data such as temperature, sunlight intensity, and humidity were recorded using weather sensors to assess their impact on the energy storage systems. These data were used to normalize the performance results, ensuring that any environmental fluctuations were accounted for during analysis.

Comparative Efficiency Analysis

To compare the energy efficiency of the lead-acid battery and the Maxwell supercapacitor, the energy efficiency (E) of each storage system was calculated using the following formula:

$$\text{Efficiency} = \frac{Energy\ Output}{Energy\ Input} \text{ X } 100\ \% \qquad (1)$$

Where:

Energy Output is the total energy delivered by the storage system to the water pump and Energy Input is the total energy absorbed by the storage system during the charging process.

The energy density, a measure of energy stored per unit volume, for both devices is calculated as:

$$\text{Energy Density} = \frac{E}{V} \qquad (2)$$

where **E** is the total stored energy, and **V** is the volume of the device. Batteries typically have higher energy densities, while supercapacitors excel in power density (power delivered per unit volume).

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VI June 2025

Cycle Life Analysis

To evaluate the cycle life of both storage technologies, the number of charging and discharging cycles were recorded for each system. The depth of discharge (DoD) and the state of charge (SoC) were key parameters used to determine the durability of the lead-acid battery and the Maxwell supercapacitor over time.

Power Output Analysis

The power output of each energy storage system was analyzed to understand how effectively the lead-acid battery and the supercapacitor delivered energy to the solar water pump. The power output (P) was calculated using:

$$P = I\,V \tag{3}$$

Where:

V is the voltage across the storage device and **I** is the current supplied to the water pump).

The Maxwell 2.5V, 3000F supercapacitor, stores energy in an electric double layer, where ions in an electrolyte align at the surface of two carbon electrodes. The basic equation for the energy stored in a supercapacitor is given by:

$$E = \frac{1}{2} CV^2 \tag{4}$$

where:

E is the energy stored (in joules), **C** is the capacitance (in farads), **V** is the voltage (in volts).

This theory explains why supercapacitors can deliver quick bursts of energy and recharge faster than batteries.

Charge and Discharge Characteristics

Charge and discharge characteristics differ between batteries and supercapacitors due to their distinct energy storage mechanisms.

Battery Charge-Discharge Equation: The state of charge (SoC) of a battery at any given time (t) can be expressed as:

$$SoC\,(t) = SoC\,(t-1) + \frac{\eta \; X \; I \; X \; \Delta t}{C} \tag{5}$$

where:

η is the Coulombic efficiency, **I** is the current (A), Δt is the time interval (in hours),

C is the nominal capacity of the battery (in ampere-hours).

Supercapacitor Voltage Decay: The voltage decay of a supercapacitor during discharge follows an exponential pattern due to its RC (resistor-capacitor) characteristics, described by:

$$V(t) = V_0 e^{-\frac{t}{RC}} \tag{6}$$

where:

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VI June 2025

V(t) is the voltage at time (t), **V_0** is the initial voltage, **R** is the equivalent series resistance (ESR), **C** is the capacitance.

Equation (6) highlights the rapid voltage drop typical in supercapacitors compared to batteries, indicating why they are often used in applications that need quick, high-power bursts rather than sustained power.

RESULT PRESENTATION

The comparison of the performance metrics between Lead-Acid Battery Storage System and Ultracapacitor Storage System is shown in table 1

TABLE 1: Performance Metrics Comparison Between Lead-Acid Battery Storage System And Ultracapacitor Storage System

Metrix	**Lead-Acid Battery**	**Ultracapacitor**
Round-Trip Efficiency	75-80%	90-95%
Energy Density	0.03-0.04 Kwh/Kg	0.005-0.01 Kwh/kg
Self-Discharge Rate	0.10-0.16% per day	0.33-0.67% per day
Response Time	5-10 seconds	<1 second
Power Density	0.1- 0.3 Kw/kg	5-10 Kw/kg
Environmental Sensitivity to temperature change	Moderate impact at high temperature	Minimal impact at varying temperature

Table 2 shows the power output comparison between the two technologies

TABLE 2: Comparison of Power Out Put

Time (min)	Lead acid battery power output (W)	Ultracapacitor power output (W)
0	200	5000
10 (0.17)	195	4900
20 (0.33)	190	4500
30 (0.5)	180	4000
40 (0.67)	175	3500
50 (0.83)	160	3000

The charge and discharge rate of Lead-Acid Battery is analyzed in table 3

TABLE 3: Charging and Discharging Analysis of Lead-Acid Battery

Time (Hours)	**Voltage (V)**	**Current (A)**	**State of charge (SoC %)**	**Discharge capacity (Ah)**
0	12.6	5.0	100	0

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VI June 2025

1	12.4	4.8	90	5
2	12.1	4.5	80	10
3	11.8	4.3	70	15
4	11.5	4.0	60	20
5	11.2	3.8	50	25
6	10.9	3.5	40	30
7	10.6	3.2	30	35
8	10.2	3.0	20	40
9	9.8	2.8	10	45
10	9.5	2.5	0	50

Table 4 shows Charging and Discharging Analysis of Maxwell Supercapacitor 2.5V, 3000F

TABLE 4: Charging and Discharging Analysis of Maxwell Supercapacitor 2.5V, 3000F

Time (Hours)	Voltage (V)	Current (A)	Charge Stored (F)	Discharge Rate (A)
0	2.5	8.0	100	0
0.5	2.3	7.5	90	8
1.0	2.1	7.0	80	15
1.5	1.8	6.5	70	20
2.0	1.6	6.0	60	25
2.5	1.3	5.5	50	30
3.0	1.1	5.0	40	35
3.5	0.9	4.5	30	40
4.0	0.6	4.0	20	45
4.5	0.3	3.5	10	50
5.0	0	3.0	0	55

Table 5 is the comparison of the Efficiency and Energy Density between the two technologies

TABLE 5: Efficiency and Energy Density Comparison

Metrics	Lead-Acid Battery	Maxwell Supercacitor 2.5 V, 3000F
Initial voltage (V)	12.6	2.5

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VI June 2025

Full Charge capacitor (Ah/F)	50 Ah	3000 F
Energy Density (Wh/L)	40	5
Charge Time (Hours)	10	5
Discharge Time (Hours)	10	4
Round - Trip Efficiency (%)	85	90
Cost per unit (USD)	100	150
Lifespan (charge cycles)	500	1000

DISCUSSION OF RESULT

The results presented in the Tables 1-5 above offer insights into the charge-discharge characteristics, power output, and performance matrix of the lead-acid battery and the Maxwell 2.5V, 3000F supercapacitor in the solar water pump application. The findings focus on their power output, energy density, efficiency, and cost-effectiveness.

The charge-discharge cycle of the lead-acid battery in (Table 3) reveals a steady decrease in voltage as the state of charge (SoC) reduces over time. Initially, the battery begins at 12.6V with 100% SoC, which gradually declines as discharge progresses. The battery's steady voltage drop over the 10-hour discharge time aligns with typical characteristics of lead-acid batteries, which provide continuous energy output but degrade in current delivery over extended periods.

For the solar water pump system, this steady output supports long operational cycles, making the lead-acid battery suitable for applications demanding sustained power. However, the gradual voltage drop could impact the efficiency of the pump's performance, especially if power demand fluctuates or peaks at certain intervals.

The Maxwell supercapacitor from (Table 4) demonstrates a faster charge-discharge cycle with high current output, however, at a rapidly declining voltage. Starting at 2.5V with an initial output of 8.0A, the voltage decreases swiftly and reaches 0V within 5 hours. This rapid decline illustrates the supercapacitor's capacity for delivering high-power bursts over short periods rather than providing sustained energy over time, as seen with the lead-acid battery. This characteristic limits the supercapacitor's viability as a primary energy source for solar water pumps requiring prolonged operation. However, it may be beneficial for specific functions, such as starting the pump or meeting peak power demands. The supercapacitor's rapid charge-discharge capability also allows it to recharge quickly when power is available, which could complement the battery's slower discharge profile.

(Table 2) shows that the lead-acid battery maintains a relatively consistent power output throughout its discharge cycle, with a longer duration than the supercapacitor. This stable power output is essential for applications like solar water pumps, where a constant supply of energy is needed to maintain water flow. Conversely, the supercapacitor's power output peaks initially but declines more rapidly, which is less ideal for continuous applications but highly effective for short time interval and high-power bursts.

Table 5 shows that the lead-acid battery's energy density (40 Wh/L) is significantly higher than that of the Maxwell supercapacitor (5 Wh/L). This indicates that the battery can store more energy per unit volume, supporting its suitability for continuous, power-intensive applications like solar water pumps. The lower energy density of the supercapacitor underscores its limitations for applications requiring large energy storage but highlights its advantage in providing rapid energy release.

It is worthy to note that Maxwell supercapacitor has a higher round-trip efficiency (90%) compared to the lead-acid battery (85%) (Table 1). While this efficiency is advantageous in applications needing frequent, quick energy cycling, the benefit is less pronounced in solar water pumping, where extended, steady output is prioritized. Still, the high efficiency could make the supercapacitor an excellent supplement for short-term, high-power needs in a hybrid system.

Also, the Maxwell supercapacitor demonstrates a longer lifespan (1,000 cycles) compared to the lead-acid battery's 500 cycles (Table 5), which could translate into reduced frequency of replacement and lower long-term costs. However, its higher initial cost might be a consideration, especially in budget-limited circumstances. Over time, the supercapacitor's durability could justify the upfront cost by minimizing maintenance and replacement expenses.

In summary, the lead-acid battery is well suited for continuous energy demands, supporting the regular operations of solar water pump that has long duration. The Maxwell supercapacitor, with its rapid response time and high efficiency, is better suited for supplemental power needs or peak demand situations. The comparative analysis highlights that while each storage technology has distinct advantages, their combined use could maximize the overall system performance and efficiency for solar water pumping applications. This dual setup could optimize energy storage efficiency, improve the longevity of the system, and ensure a consistent power supply while maintaining cost-effectiveness.

CONCLUSION

The comparative analysis of energy storage technologies specifically, lead-acid batteries and Maxwell supercapacitors for solar water pumps highlights important considerations in the selection of appropriate storage systems for renewable energy applications. The study examined these technologies based on key performance metrics such as energy efficiency, life cycle, cost-effectiveness, and suitability for solar water pumping.

Lead-acid batteries have long been used in renewable energy systems due to their low initial cost, ease of availability, and reliable performance under moderate energy demands. However, their relatively short cycle life, reduced depth of discharge (DoD), and lower energy efficiency make them less suited for high-cycle applications or systems that require long-term durability. In the context of a solar water pump, lead-acid batteries provide sufficient energy storage capacity to meet daily operational needs, especially in systems where energy demand is consistent and moderate. However, to fully meet the demands of high daily energy consumption, multiple batteries would be required.

In contrast, supercapacitors offer an alternative with their rapid charge and discharge capabilities and longer life cycle. These attributes make supercapacitors highly suitable for high cycle applications and situations where frequent energy storage and release are critical. However, the supercapacitors have lower energy density which limits their ability to provide prolonged energy storage, as required by solar water pumps, which operate for extended hours each day. Additionally, while the long-term performance and durability of ultracapacitors reduce replacement costs, their high initial is a matter of concern, especially when large-scale energy storage is required.

This analysis underscores that while lead-acid batteries may be a practical and cost-effective solution for solar water pumps with moderate energy requirements, they are less ideal for applications requiring high durability and long-term sustainability. Conversely, ultracapacitors provide excellent longevity and reliability for high-frequency charge and discharge cycles but are less suitable for prolonged energy storage due to their low energy density.

RECOMMENDATIONS

Based on the findings from this comparative analysis of lead-acid batteries and supercapacitor for solar water pump energy storage, the following recommendations are made to optimize the performance, efficiency, and cost-effectiveness of such systems. For solar water pump systems that require both high energy storage capacity and fast energy delivery, it is recommended to adopt a hybrid energy storage system that combines lead-acid batteries with supercapacitors. This configuration would leverage the high energy density of lead-acid batteries for long duration storage and the fast charge/discharge characteristics and longevity of supercapacitors for handling power surges or frequent cycling.

In situations where the solar water pump operates with moderate and predictable energy demands, lead-acid batteries are recommended due to their cost-effectiveness and availability. However, care should be taken to avoid excessive deep discharges to extend battery life. In circumstances where high frequency cycling is required such as water pumps that start and stop frequently, supercapacitors should be considered. Although the energy density of supercapacitor is lower, they excel in delivering quick bursts of power and can significantly reduce wear on batteries by handling the initial load, thereby extending battery life in a hybrid system.

REFERENCES

1. Alawaji, S. H. (2001). "Evaluation of solar energy research and its applications in Saudi Arabia." Renewable and Sustainable Energy Reviews, 5(1), 59-77.
2. Arun, P., Banerjee, R., & Bandyopadhyay, S. (2017). "Sizing of solar photovoltaic systems for different energy storage technologies." Renewable Energy, 32(3), 195-204.
3. Belhadj, J., & Kermadi, M. (2011). "Study and design of a stand-alone photovoltaic energy system." Journal of Renewable and Sustainable Energy, 3(1), 1-12.
4. Burke, A. (2010). "Ultracapacitors: Why, how, and where is the technology." Journal of Power Sources, 195(4), 1001-1012.
5. Burke, A. F., & Miller, M. (2011). "Performance characteristics of ultracapacitors for electric vehicle applications." Journal of Power Sources, 196(1), 338-344.
6. Ghofrani, M., Mahmoodi, S., & Sheikhi, A. (2019). "Solar water pumping with energy storage: A comprehensive review." Renewable and Sustainable Energy Reviews, 115, 109-129.
7. Ghofrani, S., Arabali, A., Etezadi-Amoli, M., & Fadali, M. S. (2019). "Smart management of solar energy using a hybrid storage system based on batteries and supercapacitors." IEEE Transactions on Smart Grid, 10(4), 4155-4166.
8. Intergovernmental Panel on Climate Change (IPCC). (2018). "Global warming of 1.5°C: an IPCC special report."
9. Linden, D., & Reddy, T. B. (2002). Handbook of Batteries. McGraw-Hill.
10. Luo, X., Wang, J., Dooner, M., & Clarke, J. (2015). "Overview of current development in electrical energy storage technologies and the application potential in power system operation." Applied Energy, 137, 511-536.
11. Mani, A., & Pillai, R. (2010). "Impact of battery aging on solar energy storage." Journal of Solar Energy Engineering, 132(2), 021001.
12. Mehta, A., Mokhtari, H., & Espinoza, J. R. (2021). "An efficient energy management strategy for solar PV powered water pumping systems." Sustainable Energy Technologies and Assessments, 44, 101014.
13. Rajput, S. P. S., Verma, V. K., & Kumar, P. (2013). "Performance analysis of solar PV operated water pumping system." International Journal of Emerging Technology and Advanced Engineering, 3(3), 357-361.
14. Odeh, I., & Yohanis, Y. (2006). "Economic viability of solar water pumping systems in Zimbabwe." Renewable Energy, 31(5), 709-720.
15. Sharma, R. and Goel, S. (2017). Performance Analysis of a 11.2 KWP Roof Top Grid-Connected PV System in Eastern India. *Energy Reports*, 3, 76-84. https://doi.org/10.1016/j.egyr.2017.05.001
16. Sharma, A., Tyagi, V. V., Chen, C. R., & Buddhi, D. (2015). "Review on thermal energy storage with phase change materials and applications." Renewable and Sustainable Energy Reviews, 13(2), 318-345.
17. Zhou, Y., Cao, Y., & Sui, L. (2017). "Energy management of photovoltaic power generation and storage system." Energy Procedia, 143, 650-656.
18. Wang, Y., Dai, H., Meng, J., Liu, Y., & Wei, C. (2018). "Optimal sizing of a photovoltaic system with energy storage considering the uncertainty of weather forecast." Renewable Energy, 123, 295-307.