

LONG-TERM PERFORMANCE PROSPECTS OF SOLAR PANELS (PHOTOVOLTAIC SYSTEMS) AND BATTERIES

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Annotation: Growing global interest in renewable energy sources has increased the scientific, technical, and economic significance of the long-term performance of solar panels (photovoltaic systems) and their associated energy storage technologies. This article analyzes the lifespan, efficiency, and technological prospects of batteries used in conjunction with solar panels. The main focus is placed on lithium-ion, lead-acid, and next-generation energy storage systems.

The article examines the following issues: battery operating cycles (charge–discharge cycles), degradation mechanisms, the influence of climatic conditions, methods to improve storage efficiency, and the role of energy management systems. The study also provides insights into the environmental and economic aspects of batteries, their recyclability, and anticipated technological advancements in the future. Based on analytical data, the article evaluates the prospects for developing modern battery technologies aimed at maximizing the efficiency of solar energy utilization, their compatibility, and practical implementation scenarios. The findings highlight the decisive importance of energy storage technologies in the transition to alternative energy sources.

Keywords: solar panels, batteries, lithium-ion batteries, energy storage, renewable energy, technological prospects.

Introduction.

In recent years, as global energy demand continues to rise, ensuring environmental sustainability and energy security has become an urgent priority. In particular, climate change and the limited availability of traditional fuel sources are prompting humanity to turn to renewable energy resources, including solar energy. Solar energy is clean, widely accessible, and environmentally safe, making it an essential component in achieving long-term energy independence.

For the efficient utilization of solar power, solar panels (photovoltaic systems) and energy storage devices—namely, batteries—must operate in an integrated manner. While solar panels serve as the primary source for generating electrical energy, batteries store the energy produced and make it available during periods without sunlight. However, the long-term performance of both components depends on numerous factors that require in-depth examination. Advancements in battery technology aim to ensure efficient energy storage, enhance system performance, and reduce operational costs. Moreover, ongoing scientific research on new materials,

intelligent control systems, and optimal working conditions is contributing to extending the lifespan of batteries.

This article examines the technical, physical, and operational factors influencing the long-term performance of solar panels and their associated batteries. It also analyzes existing technologies, identifies their advantages and limitations, and discusses promising future directions. The objective of the article is to propose scientifically grounded solutions and practical recommendations for ensuring the long-term operation of energy storage systems.

1. Efficiency and Degradation of Solar Panels

According to data from the **IEA (International Energy Agency, 2022)**, solar panels typically operate efficiently for **25–30 years**. However, their efficiency decreases by an average of **0.5–1% per year**. Research conducted by **Green et al. (2019)** indicates that the main causes of solar panel degradation are **ultraviolet radiation, thermal stress, and humidity**. These factors significantly affect the long-term performance of **PV (photovoltaic)** systems.

2. Service Life of Battery Types

According to studies conducted by **NREL (National Renewable Energy Laboratory, 2020)**, lithium-ion batteries are identified as one of the most efficient energy storage systems, with a service life of **10–15 years**, depending on charge–discharge cycles. Lead–acid batteries, although relatively inexpensive, last only **3–7 years** and exhibit lower efficiency (**Luo et al., 2015**).

3. Impact of Temperature and Climatic Conditions

A study conducted by **Park et al. (2017)** demonstrated that temperature fluctuations have a direct impact on the efficiency and life cycle of batteries. High temperatures, in particular, accelerate the chemical degradation of lithium-ion batteries, while low temperatures limit their ability to accept charge.

4. Modern Management Systems and Their Role

Recent studies on Battery Management System (BMS) technologies—also known as intelligent energy management—(**Zhang et al., 2021**) demonstrate that they significantly extend battery lifespan. BMS monitors depth of charge, temperature, and current in real time, ensuring that the battery operates under optimal conditions.

5. Technological Developments and Future Prospects

In recent years, research on **sodium-ion** and **graphene-based** batteries has intensified (**Yao et al., 2022**). These new materials are considered promising in terms of energy density and safety, contributing to the extension of battery service life. In addition, ongoing scientific developments related to the use of **perovskite materials** in solar panels are expected to further increase their efficiency. The analysis of the literature above shows that the long-term performance of batteries used in solar energy systems depends on technological choices, operating conditions, management systems, and climatic factors. Modern scientific advancements aim to improve the

durability and stability of these systems, and research in this field continues to remain highly relevant.

Main part

1. Operating Principle and Efficiency of Solar Panel Systems

Solar panels (photovoltaic or PV systems) are made of semiconductor materials that convert sunlight into electrical energy. The basic operating principle of PV cells is based on the **photoelectric effect**: photons of light release electrons from semiconductor atoms (typically silicon), generating an electric current. The direct current (DC) produced in the cells is converted into alternating current (AC) through inverters and then delivered to consumers or stored in batteries.

Efficiency of PV Panels and Their Types

The overall efficiency of solar panels depends on the material used and the level of technological processing, typically ranging between **15–22%**. Modern PV panels commonly fall into the following categories:

- **Monocrystalline silicon panels**

They have the highest efficiency (18–22%). The uniform crystal structure of silicon allows electrons to move freely, reducing energy losses.

- **Polycrystalline silicon panels**

They are more affordable but have slightly lower efficiency (15–17%). The divided crystal structure can hinder electron movement.

- **Amorphous (thin-film) PV panels**

They have the lowest efficiency but are inexpensive to produce and can be manufactured in flexible forms. They also perform relatively well under low-light conditions.

Degradation of PV Panels

Over long-term operation, solar panels naturally lose efficiency. Studies show that PV panels experience an average **0.5–1% degradation** per year. The main causes of degradation include:

- **Ultraviolet (UV) radiation** – affects the chemical stability of semiconductor layers.

- **Heat and thermal cycles** – expansion and contraction cause microcracks to form.

- **Dust, dirt, and atmospheric pollutants** – reduce light absorption.

- **Moisture and rain** – increase corrosion of metal connections inside the panel.

These factors represent the primary technical limitations determining the long-term performance of PV systems.

2. Types of Batteries and Their Characteristics

For energy storage in solar power systems, the following main types of batteries are used:

2.1. Lead-acid batteries

- Low-cost but heavy, with a short lifespan (3–5 years)
- Require frequent maintenance
- Deep discharge cycles significantly shorten their lifespan

2.2. Lithium-ion batteries

- High energy density
- Service life of 10–15 years
- Require minimal maintenance
- Sensitive to high temperatures, but can last long with effective management

2.3. Next-generation batteries (flow batteries, sodium-ion)

- Long lifespan (up to 20 years)
- Suitable for storing large amounts of energy
- Technology is not yet widely commercialized

3. Factors Affecting the Lifespan of Batteries

The main factors determining the lifespan of batteries include:

• Depth of Discharge (DoD):

100% charge–discharge cycles lead to faster degradation. The optimal DoD is around 50–80%.

• Temperature:

The ideal operating temperature is 20–25 °C. Temperature fluctuations negatively affect chemical reactions inside the battery.

• Battery Management System (BMS):

By controlling temperature, voltage, and current, the BMS significantly extends battery lifespan.

• Charging Technology:

MPPT (Maximum Power Point Tracking) technology ensures efficient energy production and optimal charging performance.

4. The Need for Proper System Design and Operation

To ensure long-term operation, a solar energy system must be designed as follows:

- Determine the capacity of the panels and batteries based on annual energy demand
- Protect the system from overcharging and over-discharging
- Choose the correct installation angle and a location free from shading
- Perform regular maintenance (cleaning dust, monitoring panel temperature)

5. Technological Prospects and Innovative Directions

In the near future, solar energy and battery systems are expected to develop in the following directions:

- **Sodium-ion batteries:** low-cost, safe, and increasingly widespread
- **Graphene-based supercapacitors:** extremely high charging speed

- **Smart management systems (AI-powered):** optimization of energy consumption
- **Recycling technologies:** environmentally friendly processing and recycling of batteries

Conclusion and Recommendations

This article analyzed the key technical, physicochemical, and environmental factors that ensure the long-term operation of solar panels and the associated energy storage systems—namely, batteries. Research shows that while photovoltaic panels can typically operate efficiently for 25–30 years, batteries are comparatively less durable, with a service life limited to around 5–15 years. The performance and lifespan of batteries are significantly influenced by factors such as depth of discharge, temperature conditions, chemical composition, and intelligent battery management systems.

Recent innovations in battery technology—particularly the widespread adoption of lithium-ion and sodium-ion technologies—are helping to address challenges related to long-term performance. However, for solar energy systems to work efficiently, all stages—from technical system design to operational conditions—must be properly and strategically implemented.

Recommendations:

1. **Careful selection of batteries.** Choosing batteries based on lithium-ion or sodium-ion technologies is essential for creating a long-lasting, efficient, and safe energy storage system.
2. **Installation of a Battery Management System (BMS).** Intelligent control systems that regulate temperature, voltage, and charge status can significantly extend battery lifespan.
3. **Optimizing charging and discharging cycles.** Continuously charging and discharging batteries at 100% reduces their lifespan. Operating within a 20–80% range is more efficient and less degrading.
4. **Maintaining proper temperature control.** Batteries should be protected from extreme heat or cold. The optimal operating temperature is 20–25 °C.
5. **Proper installation of solar panels and batteries.** Establishing panels at the correct angle, in a location free from shading, has a direct impact on system efficiency.
6. **Adopting innovative technologies.** It is advisable to monitor and gradually integrate new technologies such as sodium-ion batteries, flow batteries, and graphene supercapacitors as they mature.
7. **Recycling and eco-friendly practices.** Systems for environmentally safe disposal or recycling of worn-out batteries should be established.

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