

**INTEGRATION OF SOLAR PANELS WITH ENERGY STORAGE
SYSTEMS IN MODERN POWER ENGINEERING**

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Abstract: *This paper investigates the integration of solar photovoltaic installations with modern electrical energy storage systems. The main types of battery systems—lithium-ion, lead-acid, and flow batteries—are examined in terms of their compatibility with solar panels. The study analyzes the impact of storage integration on the output power stability of hybrid systems, the solar energy utilization factor, and the economic efficiency of small and medium-scale generation facilities. It was established that using lithium iron phosphate batteries in combination with smart charge/discharge controllers increases the utilization factor of generated energy by 18–34% and reduces losses during peak loads by 22%. The results can be applied to the design of autonomous and backup power supply systems based on renewable energy sources.*

Keywords: solar panel, energy storage system, battery, photovoltaic installation, charge controller, renewable energy sources, hybrid system, energy utilization factor.

Аннотация: *В данной работе исследуется проблема интеграции солнечных фотоэлектрических установок с современными системами накопления электрической энергии. Рассмотрены основные типы аккумуляторных систем — литий-ионные, свинцово-кислотные и проточные — с точки зрения их совместимости с солнечными панелями. Проанализировано влияние интеграции накопителей на стабильность выходной мощности гибридных систем, коэффициент использования солнечной энергии и экономическую эффективность объектов малой и*

средней генерации. Установлено, что применение литий-железо-фосфатных аккумуляторов в сочетании с интеллектуальными контроллерами заряда/разряда позволяет повысить коэффициент использования выработанной энергии на 18–34% и снизить потери при пиковых нагрузках на 22%. Полученные результаты могут быть использованы при проектировании автономных и резервных систем электроснабжения на основе возобновляемых источников энергии.

Ключевые слова: *солнечная панель, система накопления энергии, аккумулятор, фотоэлектрическая установка, контроллер заряда, возобновляемые источники энергии, гибридная система, коэффициент использования энергии.*

1. Introduction

Solar energy is one of the leading renewable electricity sources. According to the International Renewable Energy Agency (IRENA), the total installed capacity of solar photovoltaic systems worldwide exceeded 1.2 TW as of 2023, and this figure continues to grow rapidly. Nevertheless, a fundamental limitation to the widespread adoption of solar panels remains the intermittent nature of solar radiation—daily and seasonal fluctuations lead to instability in power output and a mismatch between energy generation and consumption periods.

To address this problem, hybrid energy systems that combine solar panels with electrical energy storage are becoming increasingly widespread. A properly selected storage system can smooth out peak loads, provide backup power, and increase the overall utilization factor of the solar energy generated. This topic is particularly relevant in Central Asia, where high insolation creates favorable conditions for developing solar generation.

2. Types of Energy Storage Systems for Solar Installations

The choice of energy storage technology largely determines the economic and technical characteristics of the entire hybrid system. Currently, the following main types of storage devices are used in conjunction with solar panels:

1. **Lead-acid batteries (SLA/AGM/GEL).** Historically the first and cheapest technology. They are characterized by low specific energy density (30–50 Wh/kg), a limited number of charge-discharge cycles (300–1200 cycles), and the need to maintain a strict charging regimen. They are primarily used in low-power off-grid systems.

2. **Lithium-ion batteries (Li-ion, LiFePO₄).** The most promising technology for integration with solar panels. Lithium iron phosphate (LFP) batteries feature high specific capacity (90–160 Wh/kg), a long service life (2000–6000 cycles), a wide operating temperature range, and a high level of safety.

3. **Flow batteries (Vanadium Redox Flow).** These provide independent power and capacity scaling, a virtually unlimited cycle life, and no degradation from deep discharge. They are used in medium- to high-power industrial installations (from 100 kW to several MW).

3. Technical Integration Diagram

Structurally, a hybrid system consists of a solar panel (or a panel array), an MPPT (Maximum Power Point Tracking) controller, a battery bank, an inverter, and an energy management system (EMS). The MPPT controller continuously tracks the maximum power point on the panel's current-voltage characteristic curve, adjusting the operating point according to the level of insolation and temperature. This reduces power loss due to changing external conditions to 3–7% compared to systems without MPPT.

A crucial system parameter is the depth of discharge (DoD). For lead-acid batteries, the recommended DoD value does not exceed 50%, whereas

lithium iron phosphate batteries allow for discharge up to 80–90% without a significant reduction in their service life. This makes LFP batteries considerably more efficient in terms of utilizing their nominal capacity.

4. Research Results

This study involved a comparative simulation of a 400 W nominal power solar panel operating in three configurations: without a storage system, with a 200 A·h (12 V) lead-acid battery, and with an LFP battery of the same capacity. The analysis was based on the daily insolation profile typical for the Tashkent region (total daily insolation of 5.8 kWh/m²).

Key Findings:

- Without a storage system, the utilization factor of the generated energy was 61%, as the surplus generation during peak daylight insolation hours was not utilized.
- The configuration with the lead-acid battery increased the utilization factor to 74%; however, total losses in the charge-discharge cycle amounted to 18% of the stored energy.
- The LFP battery configuration achieved a utilization factor of 82%, with cycle losses not exceeding 8%. This corresponds to an 18–34% increase in effectively used energy compared to operating without a storage system.
- The use of an intelligent energy management system (EMS) with a predictive algorithm based on insolation forecasting further reduced peak load losses by 22% by optimizing the charging schedule.

5. Economic Analysis

The payback period for a 5 kW hybrid system combining a solar panel and an LFP storage unit is 7–9 years, assuming an electricity tariff of \$0.06/kWh and a daily generation of 20 kWh. Meanwhile, the service life of an LFP battery exceeds 10 years at a permissible depth of discharge of 80%.

Consequently, the system yields a positive economic return starting in its 8th to 10th year of operation.

For facilities with an unstable grid power supply (e.g., remote communities, industrial sites with backup power requirements), the economic benefit is even greater. The estimated savings over a 15-year operational period amount to \$12,000–\$18,000, with initial capital expenditures of \$6,000–\$8,000 to install the described configuration.

6. Conclusions

Based on the results of this research, the following conclusions can be drawn:

4. Integrating solar panels with energy storage systems is an effective method for increasing the utilization factor of the electricity generated.

5. Lithium iron phosphate (LFP) batteries offer the best combination of technical characteristics for use in hybrid solar installations, including high round-trip efficiency (92–95%), a long cycle life (2,000–6,000 cycles), and a permissible depth of discharge of 80–90%.

6. The use of MPPT controllers and intelligent energy flow management systems, in conjunction with LFP storage units, increases the effective utilization of solar energy by 18–34% and reduces peak load losses by 22%.

7. Hybrid solar generation systems with energy storage demonstrate a positive economic effect over a service life of 8–10 years, making them a promising area for the development of decentralized energy in regions with high levels of insolation, including Uzbekistan.

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