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ANALYSIS OF ENERGY STORAGE METHODS FOR SOLAR POWER PLANTS

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Abstract. The paper looks at ways of storing excess energy generated by solar power plants. The aim of the study is to present the results of the analysis of the storage of the energy generated by solar power plants. Based on the results of the analysis, it can be concluded that, in the absence of infrastructure constraints, the most efficient way of storing the energy generated by solar power plants is by using a hybrid system. This energy storage system reduces the risk to the supply or storage of the energy generated by the PV plants in the event of a failure of the grid or the energy storage system. Where geographical conditions are limited, lithium-ion batteries are the most effective option due to their high efficiency and long lifetime, despite the higher initial investment cost.

Keywords: Solar power plants, energy storage systems, electricity grids, renewable energy

INTRODUCTION

Relevance: Renewable energy is key to stabilizing climate change. Most consumers are installing solar power plants in their own homes. One of the reasons for this is that the Environmental Management Project Agency in Lithuania supports the installation of solar power plants up to 10 kW. According to the Environmental Project Management Agency, the payback period varies between 3-5 years. The clean energy produced by a solar power plant is also an investment, and although the initial investment is high, in the long term it can pay for itself and even make a profit by selling the surplus energy it generates.

Research problem: Choosing the optimal way of storing the energy produced is very important, and to do this, it is necessary to analyze the possible ways of doing so. Since the performance of a solar power plant is directly dependent on the sun, this means that in cloudy weather, in the dark, in the shade, or in the winter, when there is less sun, the efficiency of the plant is reduced. At night, solar power plants do not generate any electricity at all. Energy storage technologies require large investments, and their availability is not always optimal. Also, energy storage systems are not perpetual and have a limited capacity, so other alternatives must be found to store the energy produced by the power plant and use it when needed.

Research methods: analysis of scientific literature.

The analysis was carried out on the following databases: EBSCO Publishing, IEEE and Science Direct.

The object of the study is solar power plants.

Objective of the study: Analysis of energy storage methods for solar power plants.

Objectives of the study:

1. To analyze the energy storage methods used to store the energy generated by solar power plants.
2. To compare the energy storage methods used to store the energy generated by solar power plants.
3. To present the most efficient way of storing the energy produced by solar power plants.

RESEARCH METHODOLOGY

This study employed a quantitative research method aimed at analyzing synthesized data from various primary studies. Publications by international authors were among the studied sources, enabling a thorough analysis of the topic. Research data and theoretical reviews published in *EBSCO Publishing*, *IEEE* and *Science Direct* were analyzed. Titles, abstracts, and full texts of scientific articles were reviewed to determine their appropriateness for analysis. The most pertinent databases, where the findings of studies on the topic were published, were chosen for the systematic and comprehensive literature search.

Table 1

Results of the literature search in scientific article databases

Key words	EBSCO Publishing	IEEE	Science Direct	Total
Solar power plants	3343	18016	179226	200585
Energy storage systems	5000	92308	1000000+	1097308+
Electricity grids	2888	65145	162846	230879
Renewable energy	5000	126326	527162	658488
Total	16231	301795	1869234+	2187260

A literature search was performed using every search word that may be utilised to describe the concept under investigation. Number of publications were found based on the keyword combinations used. The table that follows displays the outcomes.

Since the data needed for the investigation is available in scientific databases, the study complies with research ethical guidelines.

ANALYSIS OF THE METHODS OF SAVING ELECTRIC POWER GENERATION IN SOLAR PLANTS

As renewable energy has the disadvantage of being a volatile energy source, energy management systems require appropriate energy storage methods to make the most efficient use of energy (Gupta, 2021). In today's world, electricity has become very important in daily life, and batteries have become an integral part of the energy source. More advanced energy storage technologies are needed to enable the transition to renewable energy sources and smart grids (Gurung, 2018).

Solar power plants can be classified as grid-connected, off-grid, or hybrid. Grid-connected ones transfer excess energy to the grid, non-grid-connected ones to batteries, and hybrid ones can transfer to both the grid and batteries (Gupta, 2021). Solar batteries can be divided into four types: lead-acid, lithium-ion, nickel-cadmium, and flow.

The lead-acid storage system is the most mature and the cheapest energy storage system of all available energy storage systems (Kousksou, 2014). Lead-acid batteries are durable and cheap, making them a popular choice for stationary applications such as renewable energy storage (Faunce, 2018). Lead-acid batteries lead the rechargeable battery market, both in terms of sales value and MWh production (May, 2018). Lead-acid batteries are being used and increasingly developed by the Lead Acid Consortium for sustainable markets, such as next-generation hybrid cars and grid-scale energy storage applications (Prengaman, 2017). However, one of their drawbacks is that lead is heavy, and while the battery has sufficient power density, the energy density is not very high (Gutmann, 2009).

Lithium-ion batteries are mainly applied as a power source for portable electronic devices, especially mobile phones and laptops. The scope of application is currently expanding to large-scale energy sources and energy storage devices such as electric vehicles and renewable energy systems (Ariyoshi, 2023). Lithium-ion batteries have the highest energy density among practical secondary batteries (Hosaka, 2023). Lithium-ion batteries are most suitable for home energy storage systems, although this is not economically feasible compared to other batteries (Gupta, 2021).

Nickel-cadmium batteries, with electrodes made of cadmium metal and nickel oxide hydroxide. Nickel-cadmium batteries are also known as Ni-Cd batteries, where Ni refers to the nickel element and Cd refers to the cadmium element (Pandey, 2022). Ni-Cd batteries have high power and energy density, high charge/discharge efficiency, and a short lifetime. The main disadvantage is the relatively high cost due to the expensive manufacturing process. Cadmium is a toxic, heavy metal, which raises problems with the disposal of Ni-Cd batteries (Abdin, 2019).

A flow battery is a rechargeable battery in which energy is stored in one or more electroactive species dissolved into liquid electrolytes (Kularatna, 2021).

The development of renewable energy requires advanced energy storage technologies to ensure the stability of electricity supply under intermittent generation conditions. The analysis of the scientific literature shows that lithium-ion batteries, although they have the highest energy density, have a high initial investment. Lead-acid batteries are the most mature and the cheapest, but their energy density is quite low.

Nickel cadmium batteries have a high power and energy density but pollute due to the toxic metal cadmium. Further progress in this area is therefore necessary to achieve efficiency, sustainability, and wider use in different sectors.

COMPARISON OF THE STORAGE METHODS OF SOLAR PLANTS PRODUCED ENERGY

The advantages of grid-connected solar power plants are: long lifetime (25–30 years), low operation and maintenance costs, and no need for energy storage systems. However, mass connection of solar power plants to the grid can lead to grid congestion (Obi, 2016). The figure shows the operating principle of a grid-connected solar power system. First, the solar modules absorb the sun's rays and convert them into direct current electricity. This energy is then transferred to an inverter, which converts it into alternating current. The energy generated primarily meets the direct electricity demand of the home, while the excess energy is fed into the grid via the electricity meter. This meter records both the energy transferred to the grid and the energy consumed. Unlike stand-alone systems, which store excess energy in energy storage systems, here the excess energy is stored in the grid itself. In the event of a power shortage, consumers can use the energy stored in the grid. The advantage of a grid-connected solar PV system is that it does not need an expensive energy storage system to store excess energy, as it can store it on the grid.

Off-grid solar power plants are independent of grid disturbances. Off-grid solar power plants are mobile, which makes them particularly useful in settlements where it is not possible to connect the solar power plant to the electricity grid. (Ortega-Arriaga, 2021). The disadvantage of off-grid solar plants is that they require expensive batteries to store energy. The electricity supply is limited by the energy stored, but this ensures independence from the grid and operation even in the event of disturbances (Cho, 2020). According to the Lithuanian electricity and gas distribution and grid

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operators, an off-grid system is the more expensive solution, as its inverter is 30–40% more expensive than a grid-connected inverter. The grid of a microsolar power plant is shown below.

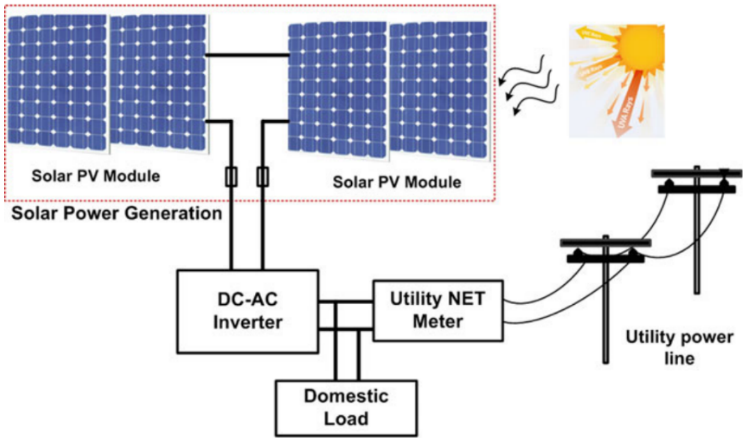

Figure 1. **Grid-connected solar power plant system**
Source: Karthikeyan, V., Rajasekar, S., Das, V., Karuppanan, P., & Singh, A. K. Grid-Connected and Off-Grid Solar Photovoltaic System. Green Energy and Technology, 2017

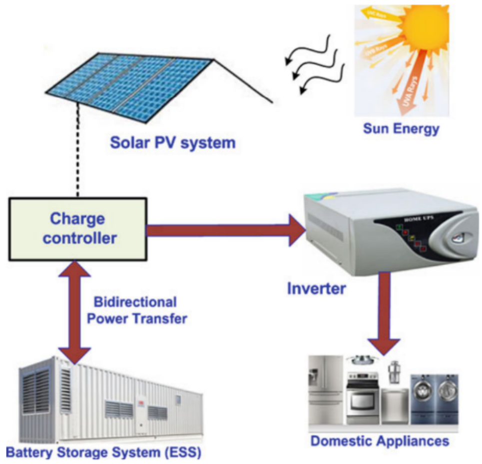

Figure 2. **Off-grid solar power plant network**
Source: Karthikeyan, V., Rajasekar, S., Das, V., Karuppanan, P., & Singh, A. K. Grid-Connected and Off-Grid Solar Photovoltaic System. Green Energy and Technology, 2017

In the figure, you can see the network and energy path of an off-grid solar power plant. First, the solar modules absorb sunlight and convert it into DC electricity. This energy is fed to a charging controller, which controls the flow of electricity and ensures that the energy storage system is charged safely and efficiently. The inverter converts the DC power supplied by the batteries into AC power. Excess energy that is not currently being used by household appliances is stored in the energy storage system. In the event of a power shortage, the stored energy from the energy storage system is used to supply electricity. The advantage of an off-grid solar PV system is that excess energy can be stored in the energy storage system, allowing the excess energy to be used in times of energy shortage.

The most commonly used battery types, lead acid and lithium-ion, have their pros and cons. According to research, lithium-ion batteries have a higher capacity and energy density, lower maintenance requirements, and a higher number of cycles compared to lead acid batteries (Kebede, 2021). Nickel-cadmium batteries are also direct competitors with lead-acid batteries since these batteries offer similar technical characteristics but with superior cycling abilities and energy density (Johnson, 2019). Ni-cd batteries have a higher power density and a slightly greater energy density (50-75 Wh/kg), and the number of cycles is higher (>3500 cycles) compared with lead-acid batteries (Revankar, 2019). However not like lead-acid batteries Ni-Cd batteries are made of highly toxic materials (Johnson, 2019). The recommended discharge rate for lead-acid batteries is 50%, while for lithium-ion batteries it is 80-90% (Gupta, 2021). Since large-scale energy storage systems require long-lasting power, flow batteries are one of the solutions, because they have longest lifetime (Kularatna, 2021). While lithium-ion batteries have higher efficiency of 90% compared to 80% in flow batteries, the following one has lower environmental impact with decreased CO^2 emissions (30 g/kWh) and a lower toxicity rating (Vafaeva, 2024). At higher temperatures, nickel cadmium, lead acid, and lithium ion batteries are the most resistant, with the lithium ion battery being the most resilient and the lead acid battery the least responsive. The materials and technologies used in lithium-ion batteries (e.g., ceramic separators) provide additional protection against high temperatures (May, 2023). Lithium-ion batteries are more economically sustainable and have a lower negative environmental impact compared to other batteries. Lithium-ion batteries are more expensive than lead-acid, nickel cadmium, or flux batteries (Phap, 2024). However, lead is the most efficiently recycled metal in the European Union and the United States, with more than 99% of lead-based batteries collected and recycled. In the West, 95-99% of batteries that reach end-of-life are recycled (May, 2018).

Table 2

Characteristics of lithium-ion and lead-acid batteries

Batteries	Capacity (MW)	Efficiency (%)	Capital costs ($/kWh)	Lifetime (in years)	Lifetime (in cycles)	Response time	Environmental impact
Lithium-ion	0.1	75-97	1000-2000	5-30	1000-10000	Fast	Very small
Lead acid	0-40	70-90	300-600	3-15	500-1000	Fast	Average

Source: Liu, J., Chen, X., Cao, S., & Yang, H. *Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings.*2019

According to the table, lithium-ion batteries with 75-97% efficiency outperform lead-acid batteries with 65-90% efficiency, which means that lithium-ion batteries can store and deliver energy more efficiently. In terms of capital costs, lead-acid batteries are more cost-effective, with a price between 300 and 600 $/kWh compared to lithium-ion batteries with a price between 1000 and 2000 $/kWh. In terms of number of life cycles and lifetime, lithium-ion batteries are superior, with a lifetime of 1 500 to 10,000 cycles and a lifespan of 5 to 30 years, compared to lead-acid batteries, which can only withstand 500 to 1 800 cycles and a lifespan of 3-15 years. In summary, lithium-ion batteries are more efficient, longer lasting, and less harmful to the environment, but more expensive, while lead-acid batteries are more affordable, although with lower efficiency, a shorter lifespan, and a higher environmental impact. Flow batteries have a low energy density but are distinguished by their longevity and environmental friendliness. Nickel-cadmium batteries, although quite durable and with a low energy density, are very harmful due to cadmium. When comparing grid-connected and off-grid solar power plants, according to ESOs, the cheaper option is the grid-connected solar power system, as the inverter of an off-grid solar power plant costs 30-40% more, but the off-grid solar power plants are protected against grid disturbances that could lead to power outages.

THE MOST EFFICIENT WAY OF STORING ENERGY PRODUCED BY SOLAR PLANTS

Finding the most efficient way to store surplus energy requires making the most of the advantages of a particular technology or finding a good compromise by combining different technologies (Ferreira, 2013). In the absence of difficulties due to geographical location or in the presence of certain infrastructures, the most efficient way to store surplus electricity is through a hybrid system. Hybrid system offers enhanced reliability, as they can switch to stored energy during grid outages and feed excess energy into the grid when connected (Nwaigwe, 2019). For isolated communities, hybrid systems offer a more sustainable and good quality electrical system to meet the community’s energy demand (Tabora, 2021). Many technical studies have been carried out on the hybrid solar PV energy storage system, and it has been observed that by stabilizing the voltage and providing power balance, the efficiency of the energy storage system can be increased (Liu, 2019). When faced with geographical or infrastructure problems, the most commonly used method for solar energy storage is batteries (Hou, 2011). Therefore, the most common way of storing the energy produced by solar power plants is in a solar farm, where a battery energy storage system is used so that the stored energy of the solar power plant is instantaneously stored and the grid is used to keep the power losses to a minimum (Mannepalli, 2022). All energy storage devices incur losses. To evaluate the performance of a storage system, the following must be considered: charging, maintaining, and discharging that charge; capacity; power and energy density; reliability; lifetime; and initial cost (Ferreira, 2013). The table below will give details of the four main batteries for energy storage.

Table 3

Detailed battery characteristics and prices

Technology	Lead acid	Ni-Cd	Lithium-ion	Flow batteries
Power (MW)	0.001-50	0.2-50	0.01-50	0.001-10
Discharge duration (h)	0.5-5	0.5-5	0.1-5	2-12
Gravitational energy (Wh/kg)	30-50	30-50	150-250	20-40
Volumetric energy (Wh/L)	50-90	50-150	200-400	15-35
Power (W/kg)	75-300	150-230	150-2000	10-40
Productivity (%)	70-90%	60-70%	85-95%	65-85%
Durability (years)	5-15	5-20	5-15	10-20
Durability (cycles)	500-2000	1500	2000-10000	13000+

Capital cost (€ per kW)	380-1140	570-1425	950-3325	570-2375
Capital cost (€ per kWh)	95-285	285-665	285-1140	237-760
Tchnological development	4	4	5	3
Availability	99.5%+	98-99%	97%+	96-99%

Source: Ferreira, H. L., Garde, R., Fulli, G., Kling, W., & Lopes, J. P. *Characterisation of electrical energy storage technologies*, 2013.

It can be seen that when all aspects are taken into account - efficiency, energy density, lifetime, and cost - lithium-ion batteries are considered the most efficient choice. They have a high energy density (200-400 Wh/L), a high efficiency (85-95%), and a longer lifetime (more than 2000 cycles), which makes them suitable for a wide variety of applications. These characteristics allow lithium-ion batteries to operate for long periods of time without loss of efficiency, which is particularly important for high-cycling applications such as power storage. In addition, although their initial cost (around 285–1140 €/kWh) is higher than some other batteries, the long-term efficiency and lower maintenance costs of lithium-ion batteries compensate for the initial investment. Lithium-ion batteries have become significantly cheaper over the last few decades due to advances in research, battery chemistry, and materials science. According to research, the cost of lithium-ion batteries has fallen by 97% between 1991 and 2018 (Ziegler, 2021). Based on the scientific literature on energy storage systems, it can be argued that the most efficient way to store the excess energy produced by solar power plants is by using a hybrid system, but in the face of infrastructural challenges, battery storage systems are the most used. Based on performance data, the most efficient battery is lithium-ion. Looking ahead, scientific literature (Li., 2020; Li., 2021) has consistently highlighted that one of the biggest challenges with energy storage systems is the limited energy capacity and lifetime. Research shows that other alternative materials are possible in the future. One such alternative is sodium-ion batteries, which are considerably cheaper because they do not use the expensive lithium metal, although their density is slightly lower, and with technological improvements in the future it could become a much more efficient way to store energy. Electricity grids will also be able to move to a new level with advanced smart grids that will optimize energy distribution and ensure more efficient integration of renewable energy into the grid.

CONCLUSIONS

1. The analysis of the energy storage methods used by solar power plants shows that even if the energy storage methods used by solar power plants are not the same as lithium-ion, nickel-cadmium, flow, or lead-acid batteries. All energy storage systems have a high initial investment, and energy storage systems are not forever and energy storage capacities are not infinite, so new technologies are needed to make energy storage systems more efficient and with a lower initial investment.

2. A comparison of the energy storage produced by a solar power plant shows that the main advantage of off-grid solar power plants is their independence from the grid, so that they are not affected by power outages, while the main disadvantage is the limited energy available, which is dependent on the capacity of the energy storage system.

The main advantage of grid-connected solar power plants is that the initial investment is lower than that of off-grid systems due to the energy storage system. A comparison of batteries for energy storage systems shows that the most efficient is the lithium-ion battery, which, although it is the most expensive, is the most efficient in the long term.

3. After analyzing and comparing the ways of storing the energy produced by a solar power plant, it can be said that without geographical or infrastructural problems, the most efficient way of storing energy is by using a hybrid system. Although the initial investment is high, the flexibility and efficiency of the hybrid system allow the most efficient use of solar energy. Reducing dependency on one or the other method of energy storage. The hybrid system allows for the storage of intermittent energy in energy storage systems for use in the event of grid failures and the need to sell surplus energy to the grid to earn credits or revenue, making it a long-term investment. When faced with geographical or infrastructural problems, the most efficient way to store the energy produced by a solar power plant is through a battery system. Considering all aspects - efficiency, energy density, lifetime, and cost - lithium-ion batteries are considered the most efficient choice.

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