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STRATEGIC MODEL FOR INTEGRATION OF PV GENERATION AND HYDRO-STORAGE IN THE SOUTHERN NEVADA POWER SYSTEM: AN ECONOMIC RATIONAL CASE FOR US ENERGY SECURITY

Summary. *In today's energy system, where renewable energy is actively developing, Energy Storage Systems (ESS) are becoming particularly important. A promising direction for ensuring the reliable and uninterrupted operation of energy systems in the United States (US) is modern approaches to the integration of solar energy generation systems (PV generation) and pumped storage power plants. The study analyzed the technical characteristics of a strategic integration model, its advantages, and potential limitations using the example of Southern Nevada. The article presents key concepts of the economic rationale for integrating PV generation and pumped storage power plants for US energy security. It is argued that the combination of pumped storage and PV generation can effectively smooth out fluctuations in renewable energy generation and cover peak loads, increasing the flexibility and resilience of the power system.*

Key words: *power system, energy storage systems, PV generation, renewable energy sources, hydro storage, sustainability.*

Introduction. Under current conditions of US power grid operation, the use of energy storage systems increases the stability of power supply, levels out peak loads, provides energy reserves for possible outages, and reduces the load on power lines. Given that Southern Nevada is a representative location for the development of solar energy in the US due to its climatic characteristics, the potential for improving the functioning of the cluster around the Eldorado Valley (Nevada Solar One, Copper Mountain, and other projects) deserves special attention [1]. The energy transition based on hydro storage is seen as one of the key factors that will contribute to the flexibility of energy systems and the intensive introduction of RES, ensuring the smoothing of generation fluctuations and the efficient use of excess energy.

According to forecasts by the International Renewable Energy Agency (IRENA) [2] and the International Energy Agency (IEA) [3], a significant increase in electricity storage is expected by 2030–2040. General approaches to the integration of PV generation and hydro storage are presented in publications by R. Thaler, W. Hofmann [4], K. Xu et al. [5], F. Taghizadeh-Hesary, N. Yoshino [6].

Scientists F. Sabbagh [7], B. Subhadeep, P. Nayak [8], B. Bhayo [9] are investigating the relationships between economic growth, RES development, and energy diversification, while G. Lima [10], Sh. Zhang [11], and A. Blakers [12] are developing a concept for the development of energy systems that are adaptive and resilient to current challenges.

Contemporary researchers Y. Nassar [13], J. Waldman [14], and M. Stocks [15] focus on the problems of renewable energy development in the United States. At the same time, there is a need to find new approaches to renewable energy storage in order to increase the level of energy security in the United States.

The aim of the study is to develop a comprehensive strategic model for integrating PV generation and hydro storage into the Southern Nevada power system, taking into account economic considerations.

Research results. The scope of application of energy storage systems is constantly expanding, as these systems play an important role in improving the reliability and efficiency of power systems, improving the performance of technologies, and ensuring a more sustainable and environmentally friendly future. Energy storage systems solve a variety of problems, including:

- load optimization – energy storage systems can be used to store excess energy during periods of low load for use during periods of peak load;
- avoiding electricity losses during off-peak generation;
- backup power supply;
- managing the load on the power grid to avoid overloads and increase the cost of electricity;
- managing microgrids [16].

In general, energy storage systems have a wide range of applications and can be used to solve a variety of problems. They allow energy to be stored and used more efficiently, reduce the cost of electricity production and consumption, ensure the stability of power grids, and save resources [7]. Moreover, energy storage systems can serve as an important component in the development of renewable energy sources and contribute to reducing the negative impact of human activity on the environment.

The integration of PV generation and hydro storage systems plays a special role in the US energy security strategy. The main goal of increasing US energy independence is to reduce sensitivity to changes in supply and prices, as well as to gain the ability to achieve its geopolitical goals [13]. RES has gained recognition as an effective source of electricity generation in states with suitable climatic conditions. An example is the power system of Southern Nevada.

In the context under study, a pumped storage power plant (PSPP) accumulates energy by pumping water into an upper reservoir (reservoir) and then releasing the water through turbines into a lower reservoir. During nighttime and off-peak hours, electric pumps consume excess electricity and lift water uphill. During peak hours, water from the upper basin is fed back through hydro turbines, generating electricity. Thus, electrical energy is converted into the potential energy of water and returned when necessary, evening out the load schedule [4].

The capacity of pumped storage power plants varies from tens to several thousand MW. Plants with a capacity of ~3000 MW are in operation around the world (for example, Bath County, 3033 MW). The storage capacity reaches millions of kWh, which provides hours and days of generation. Modern pumped storage power plants have a cyclic efficiency of about 70–85%, i.e., most of the energy spent on pumping water is returned during generation. The advantage of this method is its long service life—hydraulic turbines and electrical equipment last 40–60 years, and engineering structures (dams, reservoirs) last up to 100 years with proper maintenance [2; 3].

Obviously, pumped storage requires appropriate geographical conditions – a difference in elevation and significant volumes of water. In Southern Nevada, the main powerful pumped storage power plant is Harry Allen Generating Station, which operates on the Harry Allen Reservoir, using the difference in elevation between Mead and Pyramid Lakes. Gira is the region's key pumped storage station, ensuring grid stability [1].

The active development of PV generation in the US (in 2024, solar energy production increased by 25.9% and capacity by 30 GW) [1] highlights the importance of pumped storage power plants for covering peak loads and reserving capacity. Despite certain limiting factors, such as environmental impact and dependence on the specifics of the locality, modern projects strive for closed circuits, are reinforced by preferential taxation, and form new standards for balancing supply and demand in the grid.

Potential opportunities for future improvement can be seen in the following areas:

- better adaptation to market demand dynamics: even with the reduction of subsidy programs, the economic competitiveness of PV generation shows a steady upward trend.

- active reshoring of production through government incentives (for example, First Solar is expanding the scale of its plant construction in the US with the aim of increasing capacity to 10 gigawatts);

- technological innovations to increase efficiency.

In general, the strategic model for integrating PV generation and hydro storage into the Southern Nevada power system as components of overall US energy security can be developed in the future according to several scenarios:

1) conservative – by 2030, active development and use of large storage facilities is expected, with the simultaneous development of hybrid power plants, involving the construction of storage facilities with renewable energy sources and the active participation of ESS in national power markets as full-fledged participants;

2) optimistic – additional development of the virtual power plant mechanism is expected, as well as improvement of electricity balancing mechanisms with the decommissioning of part of the reserve generation and networks due to the complete elimination of peak loads; in addition, a significant reduction in the specific cost of electricity storage systems of various configurations and an expansion of their application is expected due to lower requirements and costs;

3) Breakthrough – this option considers the possibility of accelerated technology development as a result of revolutionary solutions to issues related to storage and operation risks, in particular, increasing capacity, improving safety parameters, introducing new technologies and integrating them with existing developments, improving economic efficiency, and creating more environmentally friendly systems.

Positive factors for the further integration of hydro storage and PV generation include:

- increased development of renewable energy, which intensifies the potential for the application of hydro storage ESS;

- improvement of infrastructure for more optimal use of energy storage systems;
- prioritization of decarbonization and environmental sustainability;
- the existence of decentralized regions where renewable energy sources can be used most effectively, functioning efficiently in conjunction with pumped storage systems.

In an economic context, it is important to ensure timely and sufficient funding and investment in the development of PV generation and hydro storage integration systems, as well as the introduction of tax breaks and subsidies for investors and manufacturers.

Despite the significant advantages of the integration under consideration, a number of problems remain unresolved, in particular, limited-service life, high cost, and the problem of recycling individual components. At the same time, the active development of innovative technologies, government incentives and support, and demand for energy flexibility are creating favorable conditions for the promising strengthening of the role of PV generation and hydro storage integration in the US energy system.

The effectiveness of the integration model is determined by political, economic, social, and technological factors. Policy measures such as green tariffs and subsidies, as well as international climate commitments, create a favorable environment for the development of such a model. Economically important are the reduction of capital costs for storage facilities and increasing access to green investments, which increases the attractiveness of these technologies [10].

The social factor is reflected in increased public demand for environmentally friendly and independent energy solutions, as well as in the creation of new jobs. Technological innovations in materials science, hydrogen energy, and digitalization are creating powerful potential for breakthrough development and widespread integration of PV generation and hydro storage into the US power grid. At the same time, an important factor is the assessment of the effectiveness and reliability of technological solutions for their integration into energy systems based on renewable energy sources.

Among the basic recommendations for the promising improvement of the synergy model between hydro storage and PV generation in the context of strengthening US energy security, the following conceptual principles should be highlighted:

1) energy storage systems are currently positioned as an integral component of PV generation integration, given their potential to ensure a stable power supply with a high share of variable sources.

2) limitations in the economic context are gradually decreasing due to the scaling of innovations and rapid technological development, reduction of capital expenditures, and government incentive systems;

3) the expansion of the variety of technological integration solutions allows for the simultaneous solution of a wide range of tasks – from response speed for frequency regulation and short peak loads to medium- and long-term storage for balancing seasonal fluctuations and large volumes of production;

4) the need for comprehensive solutions for the optimal functioning of the integration model, combining market incentives through green certificates, preferential loans, support for national industry production, and regulatory measures to simplify the integration of hydro storage systems and PV generation.

It is reasonable to conclude that the strategic integration model considered in the study can be an effective solution for stabilizing the variable nature of renewable generation and ensuring a stable energy supply to end consumers.

Conclusions and prospects for further research. Flexibility and resilience in the US energy sector, which is characterized by a high share of renewable energy sources, can be achieved through the use of pumped storage. The proposed approach successfully mitigates the effects of the variability of renewable generation and reduces forced curtailment of excess energy, providing opportunities for long-term storage and seasonal balancing of energy production.

The key advantages of integrating pumped storage systems and PV generation are increased reliability and environmental friendliness of the energy system. At the same time, the successful implementation of a strategic model for such integration largely depends on external conditions: government incentives in the form of preferences and green tariffs, international climate commitments, economic trends towards cheaper PV generation batteries and the attraction of "green" investments, as well as social factors (demand for clean energy, energy autonomy) and the speed of technological innovation (new types of batteries, digitalisation of management, etc.).

What is needed today is the development and implementation of a comprehensive approach to the integration of PV generation and hydro storage, which involves the use of state support and incentive programs, reshoring of domestic production, preferential taxation and project subsidies, and the introduction of hybrid energy storage systems. It can be argued that the active practical implementation of the proposed model in the realities of the US energy system will allow for greater stability and autonomy, bringing us closer to achieving the strategic goals of sustainable development and an effective energy transition.

A promising vector for further scientific research in the field under study is the development and practical implementation of "smart" digital platforms that will allow for more effective management of the proposed model of integration of hydro-accumulative systems and PV generation.

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