

Ensuring Reliability of the Central Asian Power System Under High Penetration of Renewable Energy Sources

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Abstract— The plans for massive integration of renewable energy sources in country-specific power systems within the Central Asian Power System (CAPS) pose the research challenge of balancing generation and consumption of electric power and capacity. Intermittent nature of renewable energy output could seriously affect CAPS stability. This study considers modern systems of energy storage as a solution to address unresolved capacity imbalances and ensure the stable power supply to consumers. We also highlight the types of energy storage that are best suited for the geographical area. Finally, this study outlines how to eliminate capacity shortages by integrating renewables into the system.

Index Terms — Power system, storage, reliability, security, economic feasibility, redundancy, integration.

I. INTRODUCTION

The Central Asian countries remain dependent on energy imports thus jeopardizing their energy security. The renewable energy development minimizes this dependency and strengthens the stability of power systems in the region. Around 85% of power generating facilities in Uzbekistan are natural gas-fired. Given the surge in energy consumption and the finite nature of fossil fuels, the large-

scale use of renewables has become a priority. The “Uzbekistan-2030” strategy envisages an increase in electricity generation up to 120 bln kWh per annum with a 40% share of renewables [1].

The envisioned measures to ensure stable operation of the power system include (i) grid modernization, (ii) construction of new substations and power transmission lines, (iii) adoption of automated power protection systems and digital control systems (SCADA/EMS), as well as (iv) increase in the reserve capacity and energy storage systems (ESS). The growing electricity demand and active penetration of renewables requires better control of electrical systems. The integration of distributed generation, most notably solar and wind power, poses risks to security, power quality, and control. The efficient integration of distributed energy sources is a key prerequisite for energy stability. An inadequate control causes voltage swings, frequency deviations, and power quality degradation. Addressing these issues requires introduction of intelligent systems and energy storage technologies [2, 5–8, 10].

In the post-1991 period, Central Asian countries prioritized energy self-sufficiency, often without technical and economic analysis, which ultimately eroded the advantages of the interconnected power system. Parallel operation became less efficient due to limited power exchanges, revised rules of interactions and functions of the coordinating bodies. The differences in national approaches and prioritization of self-interests undermined the long-term stability of the power systems [2–4].

II. THE CENTRAL ASIAN POWER SYSTEM AIMS

The Central Asian Power System (CAPS) aims to provide power system redundancy under normal and emergency operating conditions, cross-border power

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exchanges under inter-governmental agreements, and rational energy use. National power systems of the region should meet the baseload, peak load, and reserve power demand while advancing power sector development within the CAPS framework. This includes exploring alternative power generation options, constructing resource-efficient power plants, and introducing renewables and energy-saving technologies [11, 12].

At its current stage of development, Uzbekistan's power system faces the capacity and power shortage, primarily driven by the following factors:

1. *Population growth.* In recent years, the annual population growth in Uzbekistan has exceeded 2%. The country's population is projected to reach 41 million people by 2030, with a 1.5-fold expansion of the economy;

2. *Higher energy consumption and insufficient capacity additions.* The rapid growth of Uzbekistan's economy requires more generation capacity. In 2035, the demand is expected to reach 135 bln kWh, which is 1.7 times higher than the current levels [5]. There are plans to increase the penetration of the "green" energy to over 50%, aiming to lower the generation cost;

3. *Constraints on capacity and infrastructure.* The lack of new baseload capacity additions hinders the growth of power generation. The aging power transmission infrastructure leads to power losses and impedes power supply to consumers even when the resources are available in specific geographical territories;

4. *RES integration and stability issues.* Uzbekistan's RES capacity is growing at a high pace. Intermittent nature of output from solar power plants (SPPs) and wind farms (WFs) requires reliable baseload and flexible capacity, as well as energy storage units. Addressing these variability issues requires capital investment in modernization, construction of new plants, development of infrastructure and energy storage systems;

5. *Challenges of flexible and baseload capacity.* Daily demand fluctuations require prompt response from generation sources; however, the existing power plants lack the operational flexibility to respond, which results in power shortages. Flexible resources, such as hydropower plants (HPPs) and gas-turbine power plants (GTTPs), are essential for load balancing during peak load hours and mitigating intermittency of renewable generation.

However, the available flexible facilities are insufficient. As a result, there is a more pronounced imbalance between the rapid growth of renewables and lack of flexible capacity. There is also inadequate baseload

capacity - essential to ensure the minimum consumption levels - which stems from the lack of domestic natural gas production and a deficit of flexible and baseload capacities. In recent years, this has led to a number of system-wide outages across the CAPS, driven by overloads of high-capacity power plants and several interconnectors. The shortage could be eliminated by electricity and natural gas imports as well as large-scale RES integration. In both cases the integration of energy storages in power systems is critical. It is worth noting that since 2023, Uzbekistan has imported natural gas through the Bukhara-Ural pipeline in reverse mode, under the intergovernmental agreement with Russia [2].

III. BUILDING UP RESERVE CAPACITY IN CAPS

The reserve capacity needed to maintain the stable frequency in CAPS power systems is inadequate: the frequency is regulated by the Unified Energy System (UES) of Russia. The reserve capacity at the balancing plants of the CAPS could resolve imbalances of 200 to 250 MW. Peak loads, however, must be met independently by each power system within the CAPS. If its capabilities prove insufficient, the power system must import power from neighboring power systems, however, available reserves may fall short of the demand. Another challenge is to integrate the large capacity of emerging SPPs and WF, maintaining the required tertiary reserve to offset the imbalance due to disappearance of RES generation. A regional market mechanism is needed to incentivize energy storage systems (ESSs) and peaking power plants capable of providing reserve power to the grid to integrate large-scale intermittent RES. High rates of RES integration into CAPS cause power imbalances daily, thus increasing the risk of failures, as was evidenced by the 2020-2022 events. The transmission capability of transit lines between the UES of Russia, Kazakhstan, and CAPS is close to its physical limit, which may result in regular load shedding to preserve the system stability [2-4].

As a result, accelerated integration of RES into CAPS may lead to the following consequences:

1. *Increased frequency and scale of power imbalances:* intermittent and unpredictable SPP and WF output leads to higher loading of cross-border transit lines, which is exacerbated by the insufficient energy storage and generation flexibility;
2. *Higher risk of power system instability:* the blackout of January 25, 2022 shows that substantial

imbalances can quickly destabilize key transit routes (e.g., North-East-South of Kazakhstan), triggering cascaded outages [4];

3. *The need for an expansion in the transfer capability of cross-border interconnectors:* the existing 700–1 000 MW capacity is insufficient for resolving the imbalances, most notably during the peak load, i. e. mismatch between the renewable generation and demand;
4. *More stringent requirements for flexibility and response of control systems:* the extensive use of intelligent control systems, automated regulators, FACTS devices, and energy storage systems is becoming increasingly critical;
5. *Compromised reliability of parallel operation within CAPS framework:* uncoordinated planning and regulation of renewables may pose a risk of instability in the interconnected power system [4].

IV. ELECTRICITY STORAGE TECHNOLOGY AND ITS EFFECT ON POWER SYSTEM AND POWER FLOW SCHEDULING

Reliable continuous power supply to consumers requires sufficient reserve capacity to meet peak loads of the power system and the capability to ramp down generation during off-peak hours at technically feasible rates.

Electricity consumption is uneven throughout the day, therefore maintaining the current frequency requires the regulation of the power plant output to continuously balance the generated and consumed active power. Furthermore, there is increased equipment degradation, elevated fuel consumption, and technical constraints on generation facility startup. Grid failures driven by inadequate reserve capacities lead to unserved loads and economic losses to the power system.

High penetration of RES in CAPS, predominantly wind and solar, present numerous challenges for grid stability due to their intermittent power generation, complicating the seamless integration of these sources into the power system [6]. To find solutions, we forecasted their active power and studied their effect on power system efficiency [7–12].

According to the data of the International Renewable Energy Agency (IRENA), the total installed capacity of RES by the end of 2024 reached 4 448 GW, which is 15.1% higher than in 2023 [13, 14].

Key figures of the global RES growth in 2024 are as follows:

- Solar power demonstrates the record high 452 GW of new capacity additions, which accounts for 77.3% of the total RES growth;

- Wind power growth reaches 113 GW, or 19.3% of the total capacity increase.

The total increase in RES capacity additions in 2024 was 585 GW, which is the historical high.

Consequently, the integration of RES into the power mix is a global trend, exhibiting accelerating growth rates.

Power balance in the interconnected power system can be ensured by utilizing energy storage systems that accumulate energy during load-valley hours and release it to the grid when the demand is high. Rapid ESS expansion is expected in developing countries and remote territories. Combining SPPs/WFs, energy storage systems, and a diesel generator proves more cost-effective than new grid construction or conventional generation running on fossil fuels.

Wood Mackenzie, a global research and consultancy group, predicted a 13-fold expansion for the global market for energy storage systems by 2024, or from 12 GWh to the cumulative 158 GW in physical terms [7, 17].

The following briefly outlines the types of energy storage systems mentioned above:

1. According to statistical reports, up to 98% of ESS are *pumped-storage power plants (PSPP)*. Following the IEA data, the global energy storage capacity is 200 to 210 GW, of which up to 90% is PSPP as the most efficient storage solution [5];

Available hydropower resources and the terrain of the river runoff preclude the construction of PSPP of required capacity in Uzbekistan.

2. *Superconducting magnetic energy storage systems* utilizing both high-temperature superconductors and low-temperature superconducting materials are characterized by high power density, near-instantaneous response, unlimited number of charge-discharge cycles, and the round-trip efficiency of 95% [10];

3. The British company Highview Power launched the world's first 5 MW/15 MWh *liquid air energy storage* [16]. The company reported about development of a similar "cryogenic" system with a leveled cost of storage of \$140/MWh, while that of lithium-ion systems is \$200–300/MWh. This makes substituting gas-fired peaking plants for the SPP+WT+ESS system an economically viable option [8, 9, 16];

4. *Gravity-based storage* systems utilize excess electricity to lift solid masses, such as concrete blocks, to

store gravitational potential energy. During the discharge phase, these masses are lowered to drive generators, allowing the stored energy to be dispatched back to the grid. It takes 3 seconds for such storage to reach its maximum capacity, the efficiency is 90%, the useful life is up to 40 years, and the cost is 50% lower than that of other storage solutions [7];

5. Power systems commonly use *battery storage systems* that rely on various electrolytes. However, the service life of such storage systems is less than 10 years. The costs of lithium-ion battery storage systems continue to fall, making them an increasingly attractive option. Bloomberg NEF predicts a 52% drop in the cost of lithium-ion battery storage by 2030 [17];

6. *Supercapacitors* are characterized by a high capacity, long storage duration and service life, low internal resistance, and fast delivery of stored energy, which distinguishes them from electrolytic capacitors and rechargeable batteries of relatively low capacity [10];

7. *Hydrogen technologies* is a form of chemical storage of energy that converts electricity into hydrogen. This energy could then be released back by using hydrogen as the fuel [7].

The use of ESSs is crucial in virtual power plants (VPPs), the platforms coordinating distributed energy sources (RES, storage, manageable loads, etc.) in real time. VPPs offer flexibility and reliability, and enable optimization of generation and consumption. This dual capability cuts down costs and enhances the efficiency of power systems [12].

The ESSs play an important role in smart grids, where

they interact with the grid to inject power and perform peak shaving. They also serve as an uninterruptible power supply source used during unforeseen external power outages.

A *successful case* of South Australia became a milestone in ESS and RES integration: in 2017, Elon Musk promised to complete a 100MW/129MWh energy storage project within 100 days for USD 50 million and successfully delivered it. Later, the power system suffered an unprecedented outage. However, the installed storage units responded immediately to the grid instability, stabilizing the frequency, saving almost USD 40 million in the first year of its operation. This proved that ESS can promptly and effectively offset fluctuations in power systems by responding 5 times faster than conventional power regulation systems of power plants [15].

A *failure case* of the SPP and WF impact on power system not backed up by ESS: on April 28, 2025, a major power blackout occurred across the Iberian Peninsula affecting Spain, Portugal, Andorra, part of France, and Morocco. At the moment of the outage, the Spanish power system had excessive generation capacity, up to 70% of the output was contributed by SPPs and WFs, which led to a power imbalance and subsequent collapse of the grid.

Over the recent years, CAPS countries have approved several projects of SPP, WF, and HPP construction. In Uzbekistan alone, in 2022-2024, the generation capacity surged by 41%, rising from 17 048 MW to 24 182 MW. Simultaneously the number of power plants grew by 37%, increasing from 73 to 100. By the end of 2025, the capacity was expected to reach 29 479 MW, which is 73% higher

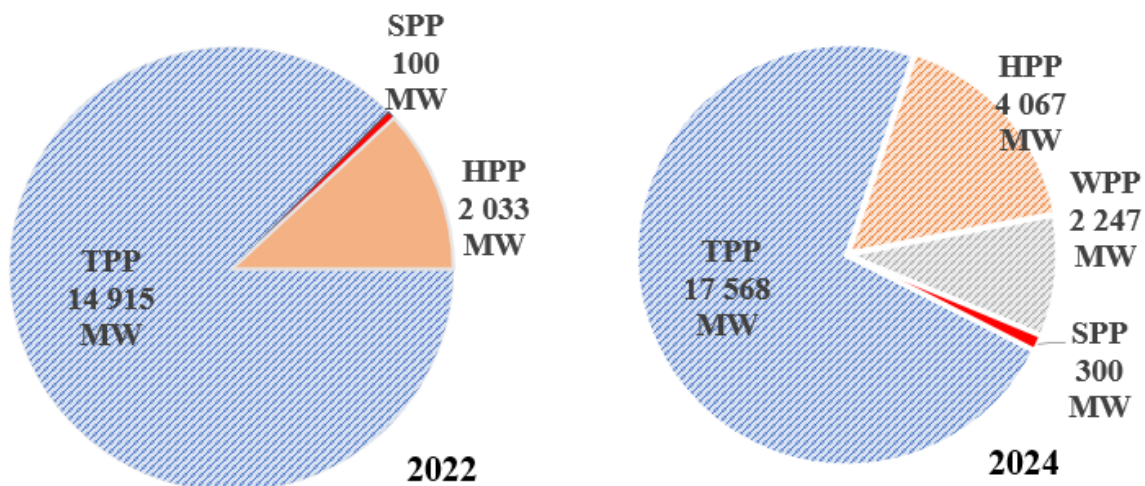


Fig. 1. Generation capacity mix in Uzbekistan.

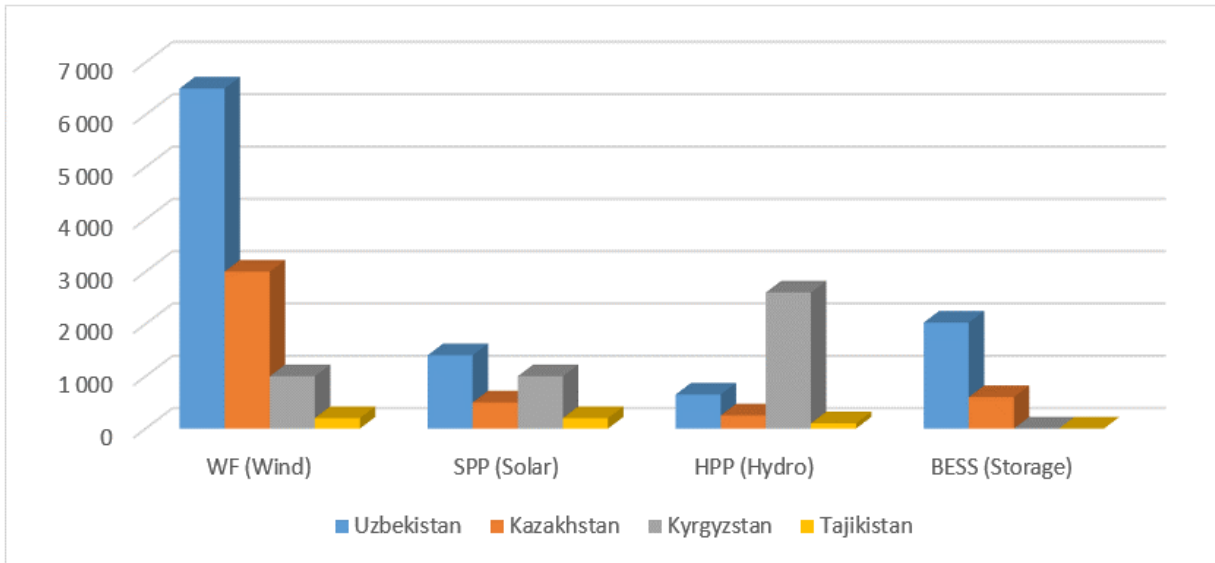


Fig. 2. RES projects in CAPS countries to 2030.

than in 2022 (Fig. 1).

The total SPP and WF capacity in Uzbekistan is expected to reach 8 000 MW, which will increase the RES share in the national energy balance by 25%. The first two SPPs with a capacity of 100 MW each were built without energy storage. However, higher RES penetration requires extra measures to maintain stability, such as ESS, high-performance regulators, FACTS devices, and adaptive

automatic emergency control systems. It is worth noting that RES penetration in EU countries (e.g., Germany and Denmark) surpassed 40–50%, which is a result of major investment in storage and digitalization, advanced infrastructure, and cross-border balancing [5, 12, 13].

The growth in power generation, most notably from RES, requires more stringent supervisory control. To this end, potential imbalances between generation and

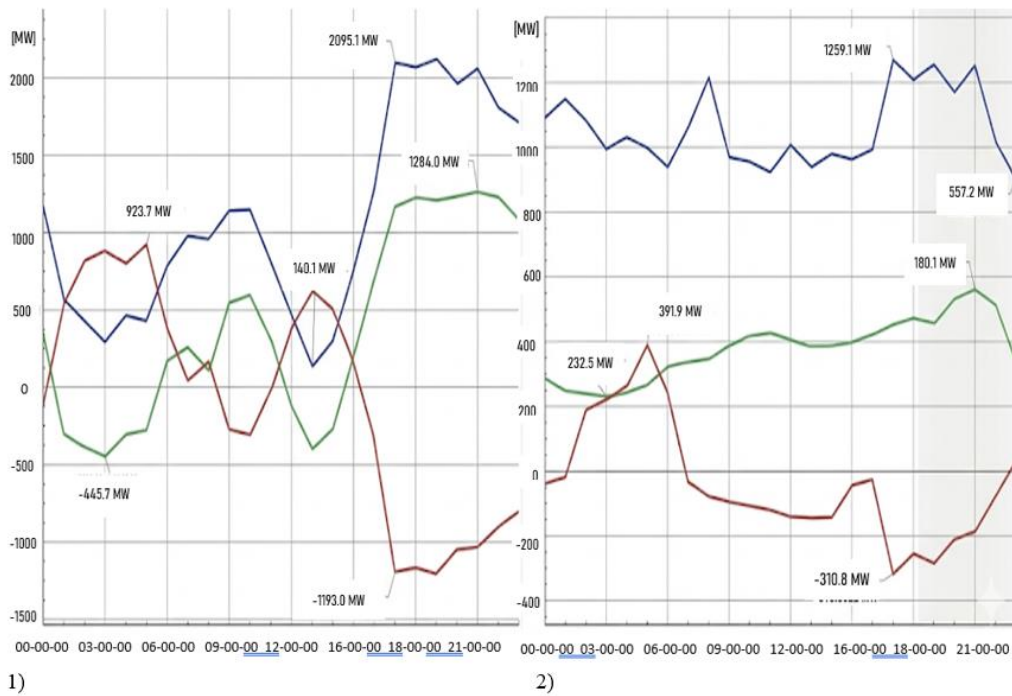
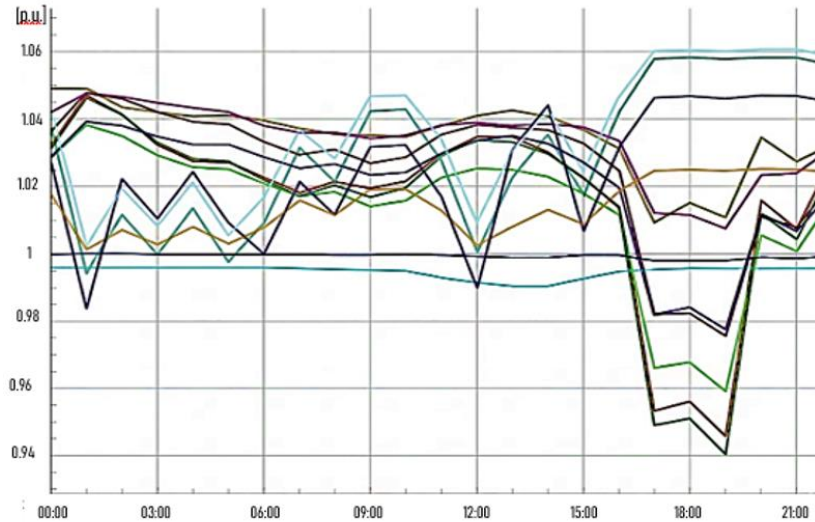
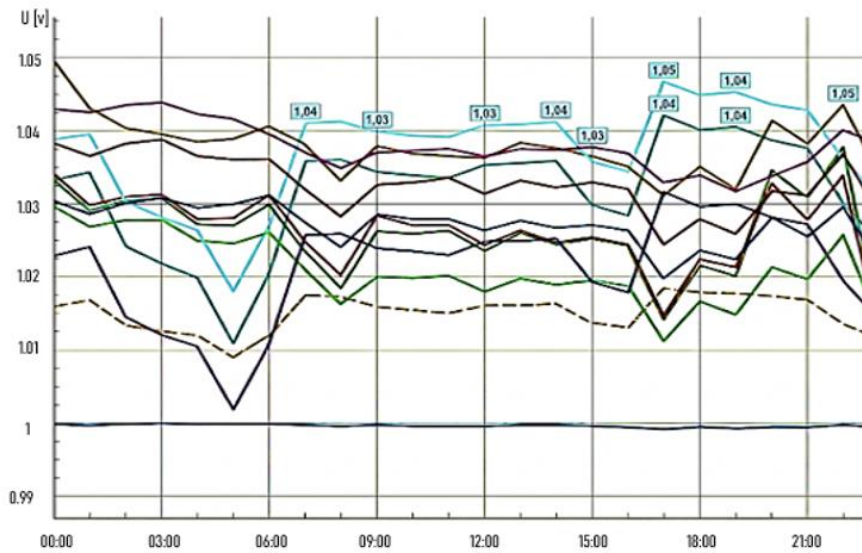


Fig. 3. Power flows across 500 kV tie-lines: without ESS (1) and with ESS (2).



1)



2)

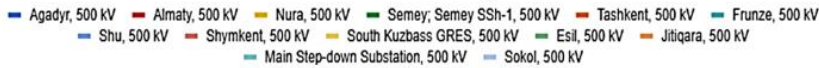


Fig. 4. Voltage magnitudes at the CAPS buses: without ESS (1) and with ESS (2).

consumption in CAPS were estimated by considering inertia and flexibility of operating TPPs, HPPs, along with imported power, as well as the requirements for capacity redundancy and frequency regulation. Daily power balances to 2030 were compiled for each power system based on plans for (de)commissioning of generation facilities and consumption growth. Quasi-dynamic modeling was performed using DlgSILENT PowerFactory software. The modeling involves [11, 12]:

- Building load and RES generation profiles;
- Calculating power balances and grid parameters;
- Factoring-in transients within hourly intervals;
- Maintaining ESS models with capacity and power constraints.

The comparative analysis of load flow calculation demonstrates the advantages of using ESS in CAPS (Figs. 3 and 4):

- Power transmission line flows are leveled, thus

preventing overloading;

- The number of generation constraints decreases;
- Thermal power plants loading is leveled and lowered;
- Grid reliability and stability performance improves;
- Power system operation efficiency increases;
- Voltage stability at the points of RES PCC coupling is enhanced.

Given the growing RES penetration in the power balance, the above-mentioned power flow analysis was utilized for ESS siting within the CAPS grid. Currently, Uzbekistan alone has approved 17 projects for construction of energy storage systems. According to the data on the projects currently under implementation, the total design capacity of battery energy storage systems (BESS) exceeds 4 GWh, which makes Uzbekistan the Central Asian leader in the adoption of energy storage technology [11, 12].

V. CONCLUSION

The integration of renewables into CAPS creates both new opportunities and major challenges to the power system. While renewables are a sustainable alternative to fossil fuels generation, their intermittency and weather dependence could, however, compromise the stability and reliability of the power supply. These limitations could be mitigated through state-of-the-art power system modeling combined with statistical and forecasting tools. These approaches facilitate more efficient RES integration and enhanced grid stability.

A key prerequisite for reliable and efficient operation of the power system is now the adoption of appropriate energy storage technologies. There is a rapid growth of RES in Uzbekistan, and battery storage systems are the most promising solution. In the future, efficient operation of the power system can be reinforced by hybrid solutions combining BESS and PSPP at existing water reservoirs, intelligent load control and automatic emergency control systems. This approach leverages the advantages of different technologies, ensuring sustainable long-term development of Uzbekistan's energy sector.

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