Ensuring Reliability and Sustainable Development of the Central Asian Power System in the Context of Growing Energy Consumption

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***Abstract* — A set of necessary conditions for sustainable development of the Central Asian Power System (CAPS) is considered with an emphasis on economic, environmental, and social aspects against the backdrop of widespread integration of renewable energy sources (RES). Such conditions are provided for by the decisions of the governments of the countries in the region in the context of growing energy consumption. The efficiency of utilizing renewables in Central Asia is assessed. The findings highlight primary scientific and engineering issues related to the large-scale use of renewables in the power system and ways to address them. The use of energy storage facilities in power systems of the Central Asian countries, as well as the joint implementation of renewables and energy storage systems in the CAPS are discussed.**

***Index Terms* — power system, reliability, system accident, renewable energy, energy storage.**

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I. Introduction

In today's world, sustainable development of the Central Asian Power System (CAPS) requires a comprehensive approach. Such an approach should include several key conditions to balance energy demand and economic, environmental, and social aspects.

At the same time, there is more to power systems than the necessity to efficiently utilize available energy resources when energy consumption grows. Strengthening energy security, reducing reliance on limited natural resources or suppliers, and lowering greenhouse gas emissions from electricity generation require addressing a wide range of issues. These include diversification of energy sources, adoption of renewables, utilization and advancement of energy storage technologies as well as the use and development of methods for bolstering energy efficiency, increasing energy conservation, and managing load.

The energy profile of Central Asian countries for 2019 is given in Table 1 [1].

Table 1 shows that a significant percentage of electricity in some of CA countries is generated by thermal power plants running on fossil fuels.

To give an example, CO_2 emissions in Kazakhstan in 2021 amounted to 0.56% of the total emissions in the world and the country ranked 31st in the world with respect to this metric [2]. This is primarily due to the fact that coal-fired generation in the country is the dominant technology of electricity and heat generation. Its share is about 70%. In 2021, coal accounted for more than half of the country's domestic consumption of primary energy resources, according to the Kazakhstan Electricity and Capacity

TABLE 1. Concise Energy Profile of Central Asian Countries for 2019

Country	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Uzbekistan
Installed net capacity of power plants, MW	23 965	3 869	6 451	5 201	15 948
TPPs running on fossil fuels, %	83.8	19.0	11.1	100	88.0
Gross electricity generation, mln kWh	106 879	15 100	20 676	22 534	63 021
Electricity generation by TPPs, %	89.2	8.3	7.3	100	89.7

Market Operator. Moreover, most of the coal burned at TPPs comes from the Ekibastuz coal basin and is characterized by high ash yield (over 40%), which makes its beneficiation unprofitable. However, the low cost of such coal makes electricity cheap, thus ensuring the competitiveness of Kazakhstan's economy. This is facilitated by the energy infrastructure that has been developing in the country for decades.

At the same time, main and auxiliary equipment of TPPs in Kazakhstan is highly worn out. On average, wear and tear have reached 66% in the country, and in the case of TPPs located in some large cities, they even exceed the critical level of 80% [3]. By 2035, Kazakhstan plans to ensure new capacity additions of 17.5 GW in total [4].

In Uzbekistan, the share of CO_2 emissions in 2021 was 0.56% of total emissions in the world and the country ranked 42nd in the world with respect to this metric [1]. The energy sector is the leader in greenhouse gas emissions in the country, accounting for 80% of total emissions. A significant part of TPP units commissioned in Uzbekistan in the middle of the last century have reached the end of their useful fleet lives, are energy inefficient and do not meet energy efficiency requirements. By 2030, Uzbekistan plans to commission 15.6 GW of new and modernized generation capacity and decommission 6.4 GW of obsolete generation capacity at TPPs [5].

At the same time, Central Asia has recently experienced increasingly more acute power shortages. For example, Kazakhstan has faced major power shortages in the past two years, especially during peak load hours. In 2022, power shortages were recorded for a period of 8 months. According to the projection of the Ministry of Energy of the Republic of Kazakhstan for 2023–2029, the amount of electricity used in the country will increase by an average of 3% annually, but the projection assumes that the balance of production and consumption in the electricity sector for the next seven years will be negative. Last winter, Kyrgyzstan started to switch off electricity to reduce its consumption. The electricity shortage was caused by the lack of necessary generation capacity in the country. Furthermore, this year, the country may also face a significant electricity shortage of as much as 1.9 billion kWh. The current situation is similar in Uzbekistan. Power outages lasting for hours are quite frequent there due to the energy shortage in the country. During winter peak load, there is a recurring electricity shortage of approximately 18–20 million kWh.

According to the projections of the International Energy Agency (IEA) for 2023–2025, demand for electricity in Uzbekistan is expected to grow by 3% annually, while the annual growth rate in Kazakhstan will be 1.7% [6]. Projections until 2030 show that the annual growth of electricity consumption in Uzbekistan will be about 6–7% [5]. The increase in electricity consumption requires accelerated construction and commissioning of new generation capacity and expansion of power grids in the region. Given that different countries in the region are planning a large-scale use of renewables, it is imperative to make a preliminary assessment of the efficiency of the energy resources used.

The EROEI (Energy Return on Energy Invested) is a well-known criterion used to assess the efficiency of energy production. The EROEI is defined as the ratio of energy output from a particular resource to the energy used to produce that resource:

$$\text{EROEI} = E_{out} / E_{in},$$

where E_{out} – energy output, E_{in} – energy input.

This metric is methodologically inadequate in many respects. Its value may vary depending on the technology used and the location of the power plant. Nevertheless, it is instrumental in comparing energy alternatives over time. If the EROEI value is greater than one, the energy source is a net producer of energy; if it is less than one, it is a net energy sink. The higher the EROEI, the more useful the energy source is, as it provides more energy per unit than others. It is assumed that the energy return on investment must be at least 5:1 for stable operation of the energy sector.

Renewables (solar and wind power plants) have long been considered to have a lower EROEI than conventional plants. For example, the paper [7] explicitly states that nuclear, hydroelectric, coal-fired, and gas-fired power plants are orders of magnitude more efficient than photovoltaic and wind power plants. Furthermore, the study [8] claims that, in the case of Russia, alternative energy in the form of solar and wind power has completely compromised itself and this is no longer in doubt. Russia is known to be a major producer of oil and gas, has significant hydro resources and therefore conventional power plants are often powered by these natural and fossil resources. However, on the one hand, not all CA countries have such resources, and, on the other hand, RES potential in CA is also country-specific.

Our analysis indicates that for conventional power plants in CA, such as thermal power plants fired by fossil fuels (coal, oil, gas), the EROEI value is of about 10:1 to 30:1. This means that every unit of energy consumed to produce and process fossil fuels yields 10 to 30 units of energy in the form of electricity. It is known that the EROEI of the main fossil fuels (oil and gas) decreases over time, which will entail a decline in the EROEI of fossil fuel-fired thermal power plants [9].

The EROEI values of renewable energy sources such as solar power plants (SPP) and wind farms (WF) may vary depending on some factors, including technology, climatic conditions, placement, and production methods. However, they increase every year due to advancements in solar and wind technology [9]. Reduction in material consumption per unit of output (consumption of feedstock, whose production causes the largest energy costs associated with solar power) is the main driver behind the EROEI growth. Furthermore, the increase in the energy efficiency of photovoltaic cell production and longer lifetime of photovoltaic cells also contribute to this.

Common EROEI values for solar power plants, which are favored in many regions of CA, range from about 10:1 to 30:1. Although more precise values may vary depending on the type of solar technology (photovoltaic or solar power towers) and their location. For example, the EROEI of silicon solar installations with an estimated lifetime of 25 years, which are located in Switzerland with the number of sunny days much smaller than in Central Asia, is 9–10. Consequently, the energy payback period is 2.5–2.8 years [10]. The EROEI values of wind farms typically range from 15:1 to 40:1, although they can also vary depending on turbine size, wind speed, and other factors.

Our analysis shows that in the case of CA it is economically feasible to use SPPs and WFs along with conventional energy sources. Therefore, expansion planning in all CA countries, which are part of the CAPS, suggests both the construction of new conventional power plants (a nuclear power plant (NPP) and a pumped storage power plant in Uzbekistan, a planned NPP in Kazakhstan, and a major hydropower plant (HPP) in Kyrgyzstan) and a widespread integration of RES.

II. Expansion of the Integrated Power System of Central Asia with Renewable Energy Sources

The development of RES in Central Asia comes with many advantages and can be very feasible. The main reasons behind that include the following:

Resource potential. CA has a huge potential for RES development, making it ideal for intensive and efficient utilization of these energy sources.

Solar power. The region has vast areas with high solar activity and long sunshine duration. Therefore, SPPs can prove a viable option for clean power generation.

Wind power. CA is also characterized by strong winds, especially in its mountainous areas, where wind farms can be installed to generate electricity.

Hydropower. The region has significant potential for hydropower development. It is expedient to build large HPPs on the Amu Darya and Syr Darya rivers. Small and medium-sized hydropower plants can be in demand to serve local energy needs.

Energy independence. The development of natural resources will strengthen the energy independence of the countries in the region by reducing their reliance on energy imports. It will also contribute to diversification of energy production and the economy, and lead to a reduction in the use of oil, gas, and other conventional energy sources.

Ecological resilience. The development of renewables in CA will help to cut down greenhouse gas emissions, limit negative environmental impacts, and counteract climate change.

Economic benefits. Energy generation from renewables

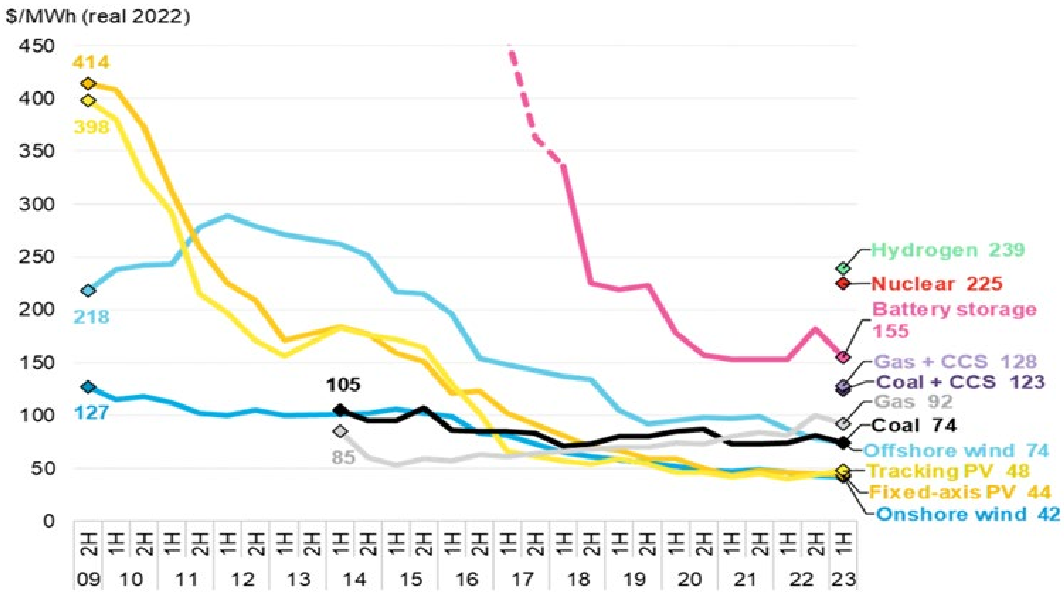

Fig. 1. Global benchmarks for levelized cost of electricity.

can outperform conventional energy sources in economic terms, which is especially important if the resource potential of the region is factored in.

It is crucial to emphasize here that BloombergNEF (BNEF), the global leader in strategic business and financial information, published a new report in 2023 [11] containing global benchmarks for the levelized cost of electricity (LCOE) for a variety of power generation technologies (Fig. 1).

The report notes that in the last six months, onshore wind farms and photovoltaic power plants have been the cheapest new electricity generation technologies in the countries that account for 82% of the world's total electricity production. Moreover, in 2022, the costs of both wind power and energy storage projects based on various types of storage, decreased compared to the levels of 2009 when BNEF began collecting data on these projects. The decrease was due to market developments.

For example, the global average LCOE for onshore wind power plant is $42 per MWh, for PV power plant – $44–48 per MWh (depending on the availability of trackers in the projects), for gas-fired power plants – $92 per MWh, and for coal-fired power plants – $74 per MWh. If, on the other hand, the cost of carbon capture and storage (CCS) is added to the cost of gas and coal-fired electricity generation technologies, their LCOE increases to $128 and $123, respectively.

An effective strategy for RES utilization in individual countries of the region has not yet been developed. However, the construction of RES-based power plants requires significant investment outlays. Therefore, the development of renewables in CA requires not only a legislative framework but also the development of mechanisms for their financing.

It is crucial to emphasize that the development of domestic grid infrastructure, as well as the strengthening of interconnectors both between countries within CA itself and with Russia will largely contribute to large-scale integration of renewables into the CAPS and increase the reliability of electricity supply.

Europe's energy transition to zero-carbon electricity by 2050, as stipulated in the Paris Agreement, involves more than the widespread construction of large numbers of solar panels and wind turbines. It also entails a comprehensive transformation of infrastructure. Cross-border interconnectors play a special part in this process and have a significant impact on its cost-effectiveness. Therefore, it is advisable for CA to follow the same path to create a more flexible system that can balance geographical differences in wind and solar generation and minimize fluctuations in power generated by RES. This path will enable the CA countries to capitalize on the optimal placement of renewable energy sources and their potential, improve their generation efficiency, and reduce the costs of implementing decarbonization policies.

In addition, increased interconnection between countries in the region can incentivize investors by bolstering their confidence in their ability to sell their output in both domestic and foreign markets, which will also encourage RES deployment in the region.

Solar power plants and wind farms are known to be intermittent and depend on weather conditions, which adversely affects the power system operating conditions. Furthermore, accidents in the power system, e.g. external short-circuits, can lead to a decrease in the voltage on the busbars in the locations of RES placement. If SPPs and WFs are not equipped with energy storage units that can maintain the voltage, the inverters that are part of RES are "flipped back" and the RES are disconnected from the grid by protective relays.

The accident will lead to a decrease in the available power of the system, equivalent to the disconnected capacity of SPPs and WFs

$$P^c_{avail\ emerg} = P^c_{initial} - (\sum P_{SPP} + \sum P_{WF}).$$

In this case, if there is insufficient operational ("hot, spinning") capacity reserve intended to compensate for the imbalance between power production P^c_{avail} and consumption P_{load} caused by failures or emergency shutdowns, the power system will have a power shortage equal to

$$\Delta P^c_{shortage} = P_{load} - P^c_{avail\ emerg}.$$

The resulting shortage of available power P^c_{avail} will lead to a decline in the frequency in the power system relative to the nominal value f_{nom} = 50 Hz

$$f^c_{emerg} = f_{nom}(1 - \Delta P^c_{shortage} / P_{load}).$$

If the automatic under-frequency load shedding scheme or operational actions fail to prevent the frequency decrease in the power system and it goes below some critical value $f^c_{critical} \approx$ 46.5–47 Hz,

$$f^c_{emerg} < f^c_{critical},$$

the low-inertia gas turbine units (GTU) and gas generator sets will be disconnected from the grid, which will create an additional power shortage in the power system and may lead to a cascading development of a system accident.

The effect of the share of power generated from SPPs and WFs in the presence of GTU and gas generator sets in the CAPS is discussed in [12]. The study demonstrates that in the absence of energy storage units in the power system, the probability of disruption of the normal operation of the power system and the damage caused by the shortage of generating capacity increase.

The above-discussed issues related to power regulation will become even more relevant when the first stage of a nuclear power plant with two 1 200 MW units designed for baseload operation in Uzbekistan is constructed. In addition, the increased demand for natural gas and fuel oil in the country predetermines the need to diversify the supply of primary energy resources and to perform a feasibility study on the construction of the second stage of the NPP with similar units.

It is worth noting that for solar and wind power, the installed capacity utilization factor (ICUF) can be relatively low due to the variability and intermittency of RES operation depending on natural conditions. Therefore, the ICUF for solar and wind power falls typically between 20% and 40% or is even less, depending on the specific operating conditions and the technology used. The value of ICUF varies across the world from 15 to 25%, on average.

In contrast, conventional power plants such as coal-fired, gas-fired, or nuclear power plants can have a higher ICUF because they typically operate continuously throughout the day serving both constant and variable load. The ICUF for these conventional power plants can be around 70–90% or more, depending on their operating conditions. Therefore, in order to eliminate the above disadvantages of RES and increase their efficiency, it is advisable to equip RES with energy accumulation and storage systems.

Renewables are becoming increasingly more important in Central Asia due to the significant solar and wind power potential there. Therefore, energy storage systems can not only enable the widespread integration of renewables in the CAPS but also improve the technical and economic performance of the power system. For this reason, it is crucial to install various energy storage units in the power system along with the construction of new power plants and the integration of renewables.

Storage units will make it possible to store excess energy and use it more efficiently during periods of absence or insufficiency of sunlight and wind during the day, compensate for the intermittent operation of RES, and ensure reliable energy supply. Furthermore, the use of energy storage systems in the CAPS can prove very feasible for the entire power system and make it technically and economically advantageous.

Storage units together with their power control system can improve the reliability of the power system, shave peak loads, and balance fluctuations in power generation and consumption. Energy storage units capable of long-term energy storage will increase the energy security of CA countries, given that some countries continue to encounter challenges with their electricity supply especially when demand is at its peak.

Energy accumulation and storage can reduce electricity costs by enabling the use of more efficient tariff schemes, e.g., energy can be stored during periods of low demand and used during periods of peak demand when electricity prices are higher.

At the same time, the use of energy storage systems (ESS) can reduce the cost of building additional power plants to serve peak demand and the cost incurred by overloaded transmission lines. Instead, surplus energy can be stored during periods of low loads and used during periods of peak demand, thus optimizing the use of available resources and delaying the construction of new transmission lines.

ESS can also influence the distribution of energy in the CAPS between different countries, which may have different energy demand at different times. This will also contribute to better economic efficiency of electricity supply. Energy storage allows efficient distribution of energy between countries according to their needs and reduction in power loss during long-distance transmission.

ESS will also be instrumental in improving environmental sustainability in CA. The use of ESS along with large-scale deployment of RES can help cut down the use of fossil fuels, limit negative impacts on the climate and the environment by lowering greenhouse gas emissions.

Common international practices favor lithium-ion batteries, which have a high rate of degradation – up to 5% per year, and a relatively short life span.

The recent years have seen a rapid advancement in liquid air energy and cryogenic energy storage technologies [13]. Such energy storage systems (especially high-capacity and high-power installations whose economic performance is way superior to that of lithium-ion batteries) are capable of recovering only 50% of stored energy. However, they will be in high demand not only for peak shaving but also for long-term energy storage and improvement of the power supply reliability.

When it comes to deciding on the adoption of ESSs in the CAPS, it is crucial to consider a multitude of factors. These are regional cooperation potential, level of infrastructure development, social and environmental aspects, costs of energy storage systems, technical feasibility of different systems and complexity of their implementation.

In this context, each of the countries should perform dedicated studies to determine the permissible penetration of RES in the mix of generation capacity deemed safe with respect to stable operation of the power system of this country as part of the CAPS. The counties should also select the necessary types of storage from a range of the most promising currently available types of storage units, decide on their placement, and calculate the necessary power and capacity of energy storage units.

III. Conclusion

The primary focus of published research is typically limited to the installation of storage units solely at RES-based plants. However, it is also important to install energy storage units at existing conventional power plants to improve their operation and energy efficiency. Moreover, it is crucial to place them in distribution networks and at the consumer’s end, which will also improve technical and economic performance and contribute to more reliable operation of the power system as a whole.

At the same time, an important factor in maintaining the reliability of the power system is the introduction of demand response practices, which implies actions on the part of load-controlled consumers to reduce their electricity consumption. The introduction of such consumers will help mitigate and overcome emergencies in the power system, such as a sharp increase in electricity consumption during weather changes or emergency shutdowns of individual units.

Integrating the load-controlled consumers within the acceptable power consumption limit during peak load hours and removing them from operation in the event of power shortages, as well as introducing automatic load and frequency control systems and stability margin monitoring systems are also priority solutions for the power system.

References

[1] EES EAEC. World Energy. [Online]. Available: https://www.eeseaec.org/energetika-galii.

[2] Wikipedia. List of countries by carbon dioxide emissions. [Online]. Available: https://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions.

[3] G. G. Trofimov, et al, “The development challenges of Kazakhstan’s Energy Sector,” in *Tomorrow Was Late: Environmental Risks of Kazakhstan*. Kazakhstan, Almaty: Kazakh-German University, 2021, 300 p. (In Russian)

[4] A. Elyubaeva, “New 17.5 GW power systems need to be committed – Ministry of Energy,” *Kapital*, Feb. 23, 2022. [Online]. Available: https://kapital.kz/gosudarstvo/103180/neobkhodimo-vvesti-novyye-energosistemy-moshchnost-yu-17-5-gvt-min-energo.html. (In Russian)

[5] “The vision statement of providing the Republic of Uzbekistan with electricity for 2020–2030,” Ministry of Energy of the Republic of Uzbekistan, 2020. Available: https://minenergy.uz/ru/lists/view/10. (In Russian)

[6] Zh. Mamyshev, “Electricity consumption in Kazakhstan is predicted to grow,” *Kursiv*, Feb. 8, 2023. [Online]. Available: https://kz.kursiv.media/2023-02-08/zhnb-electrokazakhstan/#:~:text=В%202023-2025%20годы%20ежегод ный,(МЭА)%20в%20очеред ном%20отчете. (In Russian)

[7] D. Weißbach, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, A. Hussein, “Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants,” *Energy*, vol. 52, pp. 210–221, 2013. DOI: 10.1016/j.energy.2013.01.029.

[8] S. A. Masyutin, “Alternative energy: myths and reality,” *Ruselprom*, Jun. 8, 2021. Available: https://www.ruselprom.ru/support/obuchayushchie-materialy/ obuchayushchie-prezentatsii/Альтернативная%20энергетика%20мифы%20и%20реальность.%20Масютин.pdf. (In Russian)

[9] M. Vaferi, K. Pazouki, A. V. Klink, “Declines in EROI of main fuels and the implications on developing LNG as a marine fuel,” *J. Mar. Sci. Eng.*, vol. 8, 719, 2020. DOI: 10.3390/jmse8090719.

[10] M. Raugei, S. Sgouridis, D. Murphy, V. Fthenakis, “Energy Return on Energy Invested (EROEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response,” *Energy Policy*, vol. 102, pp. 377–384, 2017. Available: https://www.sciencedirect.com/science/article/pii/S0301421516307066.

[11] “Cost of Clean Energy Technologies Drop as Expensive Debt Offset by Cooling Commodity Prices,” BloombergNEF, Jun. 7, 2023. [Online]. Available: https://about.bnef.com/blog/cost-of-clean-energy-technologies-drop-as-expensive-debt-offset-by-cooling-commodity-prices/.

[12] T. H. Nasirov, V. A. Nepomnyashchiy, H. A. Shamsiev, “Effect of wind and solar power plants on controllability and reliability of power systems,” *Journal of Scientific and Engineering Research “Problems of Energy and Sources Saving,”* no. 3. pp. 72–83, 2021. (In Russian)

[13] G. G. Trofimov, Yu. Petukhov, “Prospects for the use of cryogenic technologies in the power system of Kazakhstan,” *Power Engineering. Bulletin of the Union of Power Engineers of the Republic of Kazakhstan*, no. 4 (83). pp. 65–68, 2022. (In Russian)