Eurasian Development Bank

POWER SECTOR OF CENTRAL ASIA:

Modernization and Energy Transition

Report 26/4

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POWER SECTOR OF CENTRAL ASIA: MODERNIZATION AND ENERGY TRANSITION

KEY FINDINGS

ANALYTICAL REPORT 26

THE GLOBAL ENERGY SECTOR IS UNDERGOING ITS MOST SIGNIFICANT TRANSFORMATION SINCE THE INDUSTRIAL REVOLUTION

Share of renewable energy in global generation in 1H 2025

34.3%

(exceeding coal's share of 33.2% for the first time)

New challenges for the global energy sector

- Integration of hundreds of GW of variable renewable energy sources
- Electrification of industries (30% of the energy balance by 2040)

20% today — **30%** by 2040

A solution for economic policy

THE ENERGY TRILEMMA

Balance between sustainability, reliability, and affordability of energy

THE REGION FACES GROWING DEMAND, ASSET DEPRECIATION, AND THE NEED FOR DECARBONIZATION AND INTEGRATION OF RENEWABLE ENERGY SOURCES

+40%

Demand growth by 2030 (from 270 to 370 TWh)

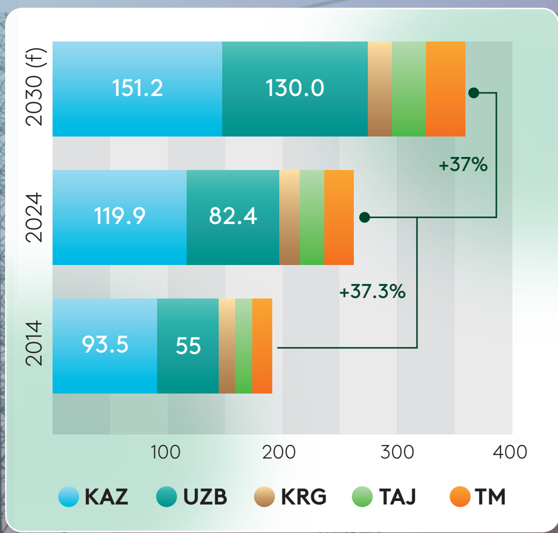
up to **70%**

Infrastructure degradation

1.4 trillion USD

Investment needed in the region for Net Zero by 2050

Electricity demand in Central Asia by 2030, TWh



THE "MIDDLE" PATH — A BALANCED AND PRAGMATIC APPROACH TO ENERGY TRANSITION

Generation

- Modernization of existing assets
- Flexible generation: CCGT, GTU, BESS, and PSP
- Low-carbon development: nuclear power plants, RE
- Decentralized generation

Grids

- Grid upgrades
- Digitalization: SCADA/EMS
- Smart sensors and meters

Market

- Elimination of cross-subsidies
- Development of ancillary services market
- Transparent rules for grid access and PPAs

Consumption

- Dynamic tariffs
- Energy efficiency in industrial and residential sectors
- ‘Smart’ load management

Integration

- Joint reserves and coordination of regulation
- Regional electricity market
- Joint network planning
- Seasonal complementarity of generation

Transition

- Staff retraining and job protection
- Diversification of company towns

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Full version of the analytical report

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The report analyzes the transformation of Central Asia's energy sector and proposes a "middle path" strategy. It is based on the World Energy Council's energy trilemma concept — the balance among security, affordability, and environmental sustainability. Against the backdrop of the global energy transition, with a record 585 GW of green capacity installed worldwide in 2024, Central Asia is facing rapid growth in electricity demand (*up to +40% by 2030*), high wear and tear on infrastructure (*up to 70% of networks and thermal power plants)* and dependence on coal and gas. At the same time, the region has enormous potential for the development of RE sources — solar, wind and hydro power — as well as opportunities for the introduction of nuclear and gas hybrid capacities. The proposed "middle path" strategy is based on a pragmatic combination of modernizing traditional generation, phased development of RE sources, introduction of energy storage systems and digitalization, as well as restoration of regional integration of energy systems to balance seasonal and resource differences. This approach will enable Central Asian countries to ensure reliable and affordable energy supplies, reduce their carbon footprint, strengthen energy security, and lay the foundation for sustainable economic growth in the 21st century.

Keywords: Central Asia, electric power industry, RE, energy transition, water-energy balance, sustainable development, "middle path".

JEL: C10, E17, L81, L91, R33, R42.

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CONTENTS

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INTRODUCTORY NOTE BY THE EURASIAN DEVELOPMENT BANK'S CHAIRMAN

Nikolai Podguzov,
Chairman of the EDB Management Board

The global energy sector is entering a new phase — the most significant transformation since the Industrial Revolution. In 2024, renewable energy sources accounted for 92% of all new power generation capacity worldwide, and their share in global electricity generation exceeded that of coal-fired power plants for the first time. However, global greenhouse gas emissions rose to record levels, showing that technological progress alone does not guarantee sustainability. The world is facing a new dilemma: how to ensure reliability, affordability, and environmental sustainability at the same time.

In these conditions, the energy trilemma — the balance between security, affordability, and environmental sustainability — becomes the central focus. For all countries, regardless of their level of development, the key question today is not only "how quickly to transition to clean energy," but also "how to make this transition sustainable and fair." The "middle way" concept presented in this report offers just such an approach: a pragmatic combination of modernizing traditional generation, gradually increasing renewable energy sources, digitalization, and developing energy storage systems.

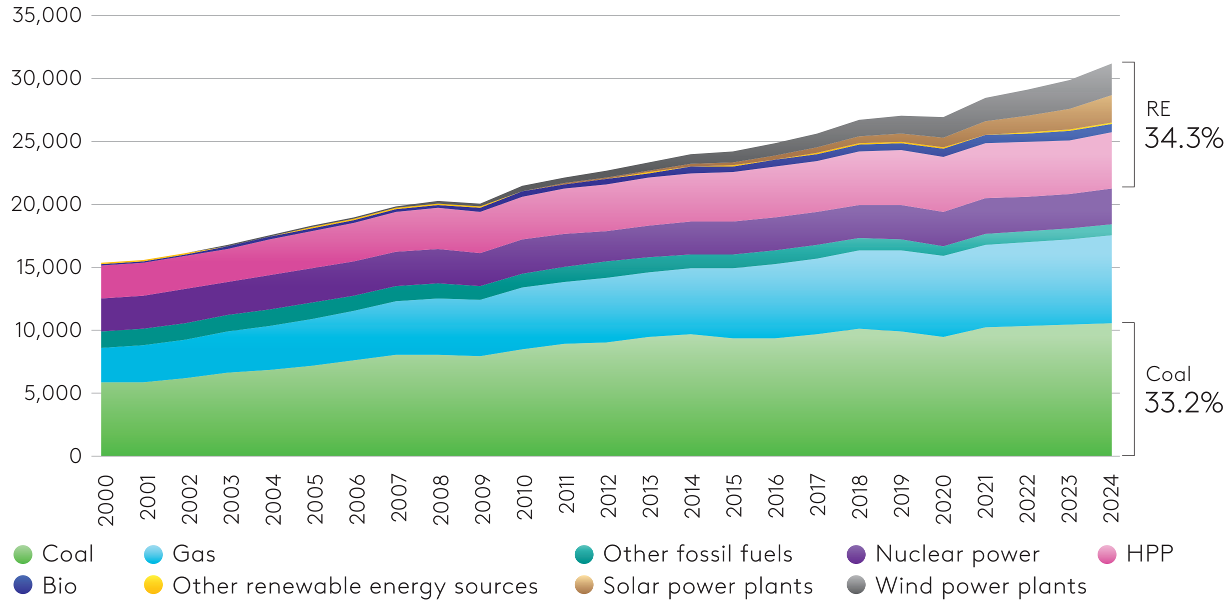
Central Asia is a region where the challenges and opportunities of the energy transition are particularly acute. Here, total demand for electricity could grow by 40% by 2030, while up to 70% of grids and thermal power plants are in need of modernization. At the same time, the region has unique resources: the largest hydropower potential, vast areas for solar and wind generation, significant gas reserves, and a strategic location between Russia, China, and South Asia. Strengthening regional integration plays a special role. Expanding cross-border ties and sharing water and energy resources can reduce systemic risks, balance seasonal differences, and attract large-scale private investment.

At the same time, a successful energy transition will require protecting vulnerable populations, maintaining affordable tariffs, and supporting employment in traditional industries. In this sense, Central Asia can offer a universal example for other regions of the world: a transition based on a balance of interests, capable of combining climate goals with the objectives of economic development, energy security, and justice.

SUMMARY

The global energy sector is undergoing **its most significant transformation since the Industrial Revolution**. Over the past decade, key clean technologies have reached scales that were previously considered unattainable: a record 585 GW of renewable energy capacity had been installed in 2024. For the first time in history, the share of renewable energy in global electricity generation — 34.3% — has exceeded that of coal (33.2%). This is largely due to the fact that renewable energy has become highly competitive with other generation technologies in terms of cost: since 2015, the levelized cost of electricity (LCOE) from utility-scale solar plants has fallen by 70%, and from wind power plant by 55%. Investments in the energy transition reached $2.2 trillion, twice the amount invested in fossil fuels.

↓ **Figure A. Global electricity generation mix, billion kWh**

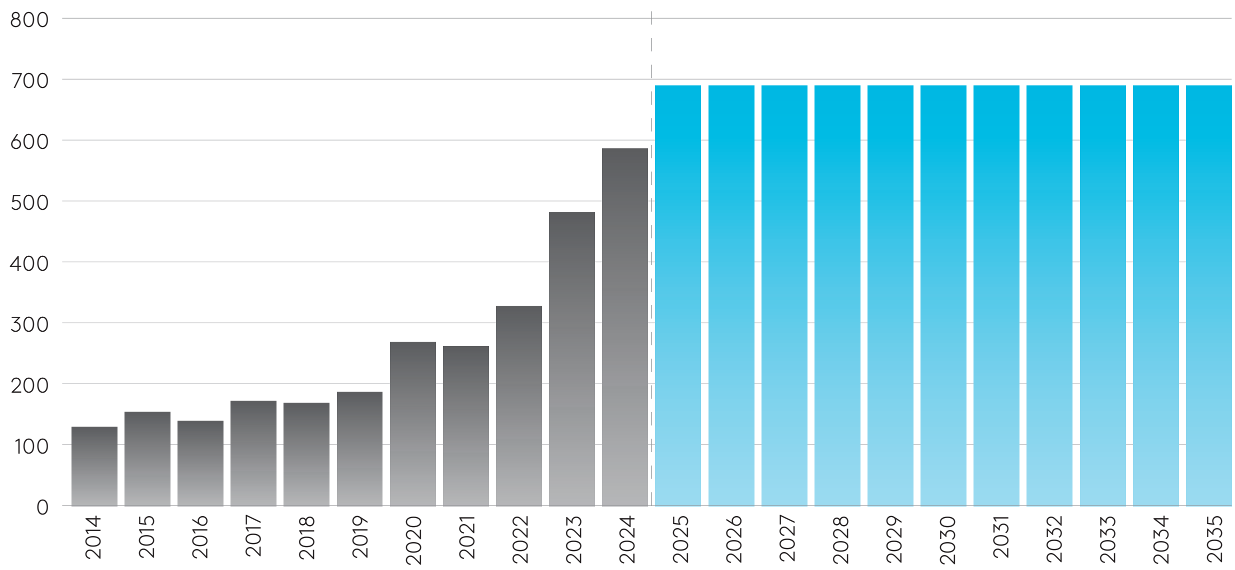


Source: Ember, 2025.

However, these achievements are accompanied by new challenges. **The electricity demand growth is outpacing the ability to integrate** new low-carbon technologies, so global CO_2 emissions rose again in 2024, reaching record levels. Hundreds of GW of RE objects are in queue for connection. The main constraints are technical in nature. If the drop in power output caused by weather changes is not immediately compensated for, the systems may be at risk of blackout. Power systems need to adapt to significant amounts of electricity from solar power plants in the middle of the day, which requires a ramp-down from other generators during the day and a steep ramp-up in the evening. Variable generation is being introduced faster than grids, storage systems, flexible reserve capacity, and operational management tools can develop. **Infrastructure in many countries is not designed for a high share of variable generation**, while weather forecasting accuracy remains insufficient to maintain an acceptable level of system reliability. Reforms of capacity, reserve, and tariff regulation markets in many countries are also lagging behind, which does not encourage the creation of the necessary support mechanisms. As a result, the real cost of renewable energy is higher than expected, and the risks to energy supply reliability are increasing.

At the same time, **electricity is becoming the central form of energy** in the global economy amid digitalization and the rapid expansion of artificial intelligence applications. The share of electricity in final energy consumption will increase from 20% today to 30% by 2040 as the electrification of industry, transport, and heating accelerates. Additional demand is growing: according to IEA estimates, investment in data centers will reach 580 billion USD in 2025. Electricity consumption by data centers could triple by 2035. In this scenario, the reliability of electricity supply comes to the forefront. New demand (*AI, data centers, digital services, electrified supply chains*) requires firm power and system stability, which can only be provided by dispatchable and stable sources along with upgraded grids and sufficient reserves.

↓ Figure B. Estimate of average renewable energy additions up to 2035, GW



Source: IEA, 2025a.

The global energy transition has now entered a new phase, where **system reliability and balance are becoming key issues**. Having achieved lower prices for green technologies, the global community is now faced with the challenge of integrating rapidly growing volumes of variable generation into engineering and infrastructure solutions — the development of networks, energy storage systems, flexible capacity, and digital management platforms — will determine whether low-carbon energy can be scaled up effectively. In this context, **the concept of the energy trilemma** — the balance between environmental sustainability, security of supply, and energy affordability — **comes to the fore as a key policy principle**. A unilateral pursuit of only clean energy goals without considering energy security and equity leads to vulnerability.

This is particularly evident in Central Asia, which fits into the global context with its own specific characteristics. **The region, with a population of over 80 million, is showing steady growth in electricity demand** of 3–6% per year, and by 2030, consumption could grow by another 40% or so — from the current 270 billion to 370 billion kWh per year. The energy infrastructure is worn out: in some countries, up to 70% of power grids and thermal power plants have reached the end of their service life, and on average across the region, more than 60% of distribution networks require replacement or major repairs. Transmission and distribution losses reach 15–20%, which is 2–3 times higher than in developed countries. Many of the existing power plants were built during the Soviet era and have long since recouped their capital costs, which is why they now provide the cheapest electricity — their wholesale price can be several times lower than that of new facilities. This temporarily keeps tariffs down, but at the same time masks the problem: a significant portion of generating assets have reached the end of their useful life, accidents are on the rise, and their imminent replacement will inevitably lead to higher energy prices.

The structural vulnerability of Central Asia's energy sector complicates the energy transition. The region's energy mix is not diversified: Kyrgyzstan and Tajikistan are almost entirely dependent on hydropower (*up to 90% of generation*), while Kazakhstan, Uzbekistan, and Turkmenistan rely on fossil fuels (*coal and gas provide the basis for generation*). Hydropower generation drops sharply in winter, leading to acute electricity shortages: hydro-dependent systems are prone to rolling blackouts and energy imports. In gas-dependent power systems, cold periods lead to consumption spikes and pressure drops in the gas network that affect power plan operations. The region also suffers from low energy efficiency, high specific fuel consumption at outdated thermal power plants, limited interconnectivity of energy systems, a lack of flexible capacity, and a low level of digitalization. The instability of water resources due to melting glaciers and the increasing frequency of extreme weather events (*frosts, droughts*) further exacerbate the situation. These factors underscore that the energy transition in Central Asia requires a systematic and pragmatic approach adapted to regional specifics.

Nevertheless, the region also has **unique opportunities for balanced development**. Central Asia has enormous renewable energy potential — rich resources of sun, wind, and hydropower — as well as significant natural gas reserves and uranium for nuclear power generation. The combination of serious challenges and rich resources dictates the need for a "middle path" strategy based on balancing the goals of the energy trilemma: reliability, affordability and sustainability. Extreme approaches — whether a forced abandonment of fossil fuel generation or, conversely, the zealous 'lock-in' to existing outdated infrastructure — carry unacceptable risks. The optimal scenario appears to be an evolutionary one, in which countries in the region modernize their existing energy sector, making the most of their current infrastructure, while simultaneously laying the foundations for a future low-carbon system. This pragmatic course will ensure energy security and affordability today without sacrificing sustainability tomorrow.

CONSERVATIVE SKEPTICISM

"Renewables are a scam"

- Focus on conventional generation (coal, gas)
- Priority — energy security (*including dependence on imported equipment and critical metals*)
- Fuel/electricity price stability
- Fossil fuels as the basis of the energy mix
- Climate goals are secondary
- Rejection of new technologies (electric vehicles, hydrogen, renewable energy sources)

"THE MIDDLE PATH"

Balance

- Combination of conventional (baseload) and variable (renewable energy sources) generation
- Modernization of existing thermal power plants and gradual phase-out
- Development of renewable energy sources with energy storage systems
- Recognition of the role of gas
- Development of nuclear energy
- A just transition for affected industries

GREEN MAXIMALISM

"Renewables are a panacea"

- Rapid decarbonization, even at the cost of short-term economic losses
- Complete phase-out of coal and ICE by 2040
- Large-scale expansion of renewable energy sources and full electrification
- Renewables should provideup to 90–100% of electricity
- Strict regulation of emissions, carbon tax, and elimination of subsidies for fossil fuels

First, **existing assets** need **to be modernized** where it makes economic sense. These assets currently provide the lowest cost of electricity for economic development and are often the only source of heat supply in severe climate of the region. It is critical to extend the life of existing coal, gas, and hydroelectric power plants by increasing both their efficiency and flexibility for future purposes, where possible. Upgrading equipment can reduce specific fuel consumption, cut emissions, and extend the service life of power plants by 10–15 years. At the same time, it is important to upgrade the grid infrastructure, reducing losses and introducing digital control and monitoring tools. Infrastructure can the growing volumes of renewable energy sources be safely integrated.

Secondly, **it is advisable to increase the flexibility of the region's energy systems**. The expansion of variable solar and wind generation must be accompanied by the creation of rapid response reserve capacity. It is necessary to build modern gas turbines that can be quickly activated when RES generation drops, as well as to introduce energy storage systems. Demand response mechanisms should be developed, both in industrial and residential sectors. Hybrid energy parks, which combine renewable energy sources, gas installations, and storage facilities on a single site for round-the-clock energy supply, are a promising solution. Without sufficient flexibility, a high share of renewable generation will lead to an increased risk of outages and accidents.

Thirdly, **tariff and market reforms** are important. The transition to economically feasible retail tariffs will eliminate chronic underfunding of the industry and create predictable conditions for private investment. Of course, tariff increases should be gradual and accompanied by targeted social support — subsidies for vulnerable groups instead of universal benefits. This will preserve energy accessibility for citizens without depriving energy companies of resources for modernization. It makes sense to update the electricity market design. Historically, the region has operated a model of trading only energy (*kilowatt-hours*) at fixed prices, which does not reflect the realities of the new era. As the share of renewable energy sources grows and demand patterns becomes more complex, it is becoming important to launch markets for capacity, reserves, and ancillary services. The capability of a power plant to provide power on demand, even if it is idle most of the time, is valuable for modern systems. Compensation for grid stability services (*supplying reserve capacity, frequency regulation, rapid recovery after accidents*) will create incentives for the construction of flexible gas units, large energy storage facilities, and fast-response generating units. The formation of fully-fledged wholesale and balancing markets, based on the experience of other regions, will increase transparency and reliability.

Fourth, **it is important to efficiently integrate renewable energy sources into the grid**. It is not enough to simply build hundreds of megawatts of solar and wind power plants — it is important to integrate them into the power grid in advance, taking into account the maximum capacity and future bottlenecks. New renewable energy plants should be located where the grid can accept additional capacity without loss of quality. It makes sense to build power lines to promising sites in advance. Another important element is the installation of energy storage systems at renewable energy parks to smooth out fluctuations in power output. At the same time, modern means of forecasting generation and load can be introduced — improving the accuracy of forecasts will allow reserves to be used more economically. A comprehensive approach also implies **a fair transition** for the people and industries affected by the transformations.

Finally, **regional integration is a key element of the strategy**. Expansion of interconnector capacity and regional coordination can significantly increase the resilience of Central Asia's energy systems.. The joint development of large projects — such as hydroelectric power plants or GW-scale wind farms designed to export electricity to neighbors — will give all participants access to cheap and clean sources. Coordination of water and energy regimes will allow for optimal use of hydropower potential without disrupting irrigation regimes. The creation of regional power and electricity markets will have economies of scale: countries will be able to share reserve generators. For investors, an integrated market with more than 80 million consumers is also much more attractive than fragmented ones. The experience of other integrated power systems shows that interconnection strengthens all aspects of the trilemma at once: reliability is increased through mutual backup, tariff pressure is reduced through optimal load distribution, and the introduction of renewable energy sources is facilitated by the geographical dispersion of generation.

A high-level comparative assessment of three scenarios for the development of the Central Asian electricity sector indicates that it is the integrated "middle path" strategy that provides the most sustainable profile across the entire energy trilemma. Based on the plans of Central Asian countries as stated in their strategic reports, the expected total new power generation capacity amounts to at least 62.8 GW by 2035, equivalent to 230 billion kWh of new annual generation. Comparative modeling shows that this scenario entails CAPEX of approximately 151–179 billion USD, which is 30–45% lower than the "green maximalism" scenario (*$239–254 billion*) and comparable to the conservative scenario (*150–170 billion USD*). In terms of normalized electricity generation costs, the "middle path" is also comparable to the conservative approach, ranging from 8.6 to 10.3 cents/kWh, which is 25–35% lower than "green maximalism" (*11–12.2 cents/kWh*), but is accompanied by a carbon footprint that is five times smaller. On a life-cycle basis, emissions amount to approximately 0.15 tonnes CO2e/MWh versus 0.8 tons of CO2e/MWh in the conservative scenario—that is, nearly five times lower—while maintaining high system stability.

A balanced "middle path" strategy provides Central Asia with a realistic roadmap to energy sector modernization. A set of measures — from extending the life of essential assets and increasing system flexibility to market reforms, proper integration of renewable energy sources, and a new phase of regional cooperation — will ensure reliable and affordable energy supply, significantly reduce its carbon footprint, and lay the foundation for sustainable economic growth in the 21st century.

INTRODUCTION

Energy is the foundation of the modern world and the key to sustainable economic growth. The functioning of industry, transport, social infrastructure and the digital economy directly depends on a stable energy supply. Electricity plays a particularly important role as the most versatile and flexible form of energy, accounting for around 20% of global final energy consumption and projected to reach 30% by 2040 in some scenarios (IEA, 2020). Some countries have already reached and exceeded this level (China, Japan). The electrification of economic sectors — from industry to heating and transport — is becoming not just a trend, but a strategic benchmark that allows countries to reduce their carbon footprint and increase productivity. Thus, the availability and reliability of electricity is not only a technical issue, but also a condition for national security, social stability, and economic competitiveness.

A power industry operates in a state of constant balance between generation and consumption: unlike most commodities, electricity cannot be stored on a system-wide scale, so at any given moment, the volume of generation must precisely match demand. Any deviation leads to a change in the frequency of the grid, which, in the event of significant imbalances, can lead to emergency shutdowns and cascading equipment failures. Traditionally, this task has been solved by large power plants with inertia and the ability to quickly regulate power. However, the growth in the share of variable generation, primarily wind and solar, complicates system management: such generation is increasingly dependent on the weather, requires additional reserves, while consumption side is also evolving — the peaks shift in time and space due to new sectors and consumption patterns.

Thus, RE sources are playing an increasingly important role while changing the very architecture of the energy sector. The share of RE sources in global generation has reached 34% and continues to grow. Digitalization, the development of storage facilities, flexible networks, distributed generation, and the integration of smart consumption are all shaping a new energy reality. At the same time, climate challenges are intensifying: the power sector remains the source of approximately 35% of global CO_2 emissions, making it a key area for achieving the goals of the Paris Agreement and the UN 2030 Agenda for Sustainable Development.

The share of renewables in global electricity generation mix has reached

34%

and continues to grow

Central Asia is part of this global picture, but with its own unique characteristics and challenges. The region, with a population of over 80 million, is showing steady growth in electricity demand, averaging 3–6% annually. However, much of the energy infrastructure is outdated: in some countries, up to 70% of the networks and power plants are in urgent need of modernization. The energy mix for independent countries is extremely unbalanced: while Kyrgyzstan and Tajikistan rely mainly on hydropower (*up to 90% of production)*, Kazakhstan and Uzbekistan are heavily dependent on coal and gas. This creates risks for both climate sustainability and energy security. The region also suffers from low energy efficiency and limited capacity for integrating new power plants without far-reaching reforms.

These challenges are exacerbated by institutional and historical factors. After the collapse of the USSR, coordination within the Central Asian Unified Energy System was lost. This has led to fragmentation: cross-border electricity flows reduced to only 5% of regional consumption. This leads to serious seasonal imbalances: some countries face electricity shortages in winter, while having surplus in summer. In addition, climate change increasingly affects water resources, on which hydroelectric power generation depends, and extreme weather conditions are increasingly disrupting the operation of energy systems. This underscores that regional energy transition cannot be achieved without a systematic, intergovernmental, and pragmatic approach.

In the context of technological instability and growing climate risks in Central Asia, it is necessary not only to increase capacity, but also to develop a balanced strategy for the transition to sustainable energy. This requires a comprehensive analysis that takes into account three interrelated goals: energy security, accessibility, and environmental sustainability. These principles underpin the energy trilemma concept proposed by the World Energy Council and are used in this report as an analytical framework. This approach allows us to assess the current state of affairs and identify realistic, rather than declarative, paths for energy development in conditions of high uncertainty.

The report is divided into four logically related areas of analysis. The first chapter reveals global energy transition trends and develops the concept of the energy trilemma. It discusses the rising share of RE sources, the growth of investment in clean energy, and the role of the electricity sector in achieving climate goals.

The second chapter moves on to regional diagnostics: through the prism of the trilemma, it analyzes the reliability of supply, tariff affordability, and social and environmental aspects of the electricity sector in Central Asian countries, including regional water–energy nexus.

The third chapter is devoted to technological solutions: from the modernization of traditional generation to the introduction of solar and wind energy, storage facilities, and digital management platforms.

The concluding fourth chapter proposes a “middle path” concept — a pragmatic balance among the development of RE sources, support for traditional sources, and institutional reforms. This approach is aimed at a sustainable energy transition tailored to the specific characteristics of the countries in the region.

CHAPTER 1.

CENTRAL ASIA, THE GLOBAL ENERGY TRANSITION AND THE ENERGY TRILEMMA

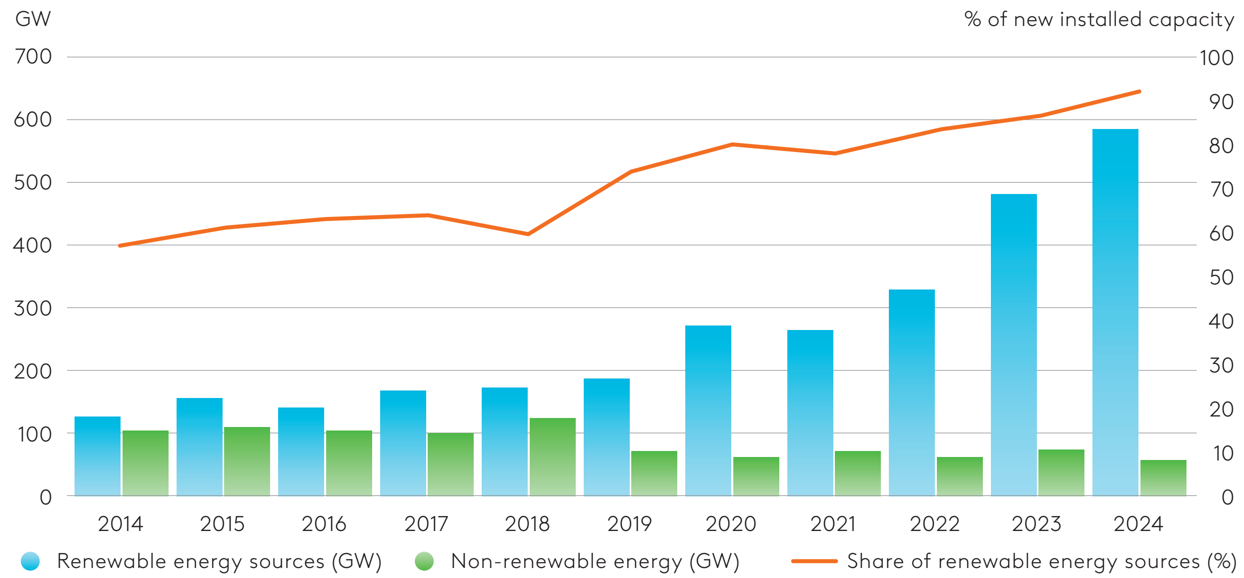
1.1. The current state of the global energy transition and SDG 7

92%

of all new power capacity additions in 2024 were renewables (585 GW)

By 2025, the global energy system had entered a state of profound transformation. Humanity is experiencing an era of unprecedented growth in clean energy sources: in 2024 alone, 585 GW of new RE capacity was installed worldwide, accounting for 92% of all new power capacity (IRENA, 2025). For the first time in history, the share of RE in global electricity generation — 34.3% — exceeded the share of coal (33.2%) (Ember, 2025). There has been record growth in investment in RE, energy efficiency, and transport electrification. In 2024, investment in clean energy and energy transition reached 2.2 trillion USD, surpassing investment in fossil fuels (IEA, 2025a). According to forecasts by the International Energy Agency, by 2030 renewable sources will be able to provide half of all global generation (IEA, 2024a).

↓ **Figure 1. Global RE capacity additions**



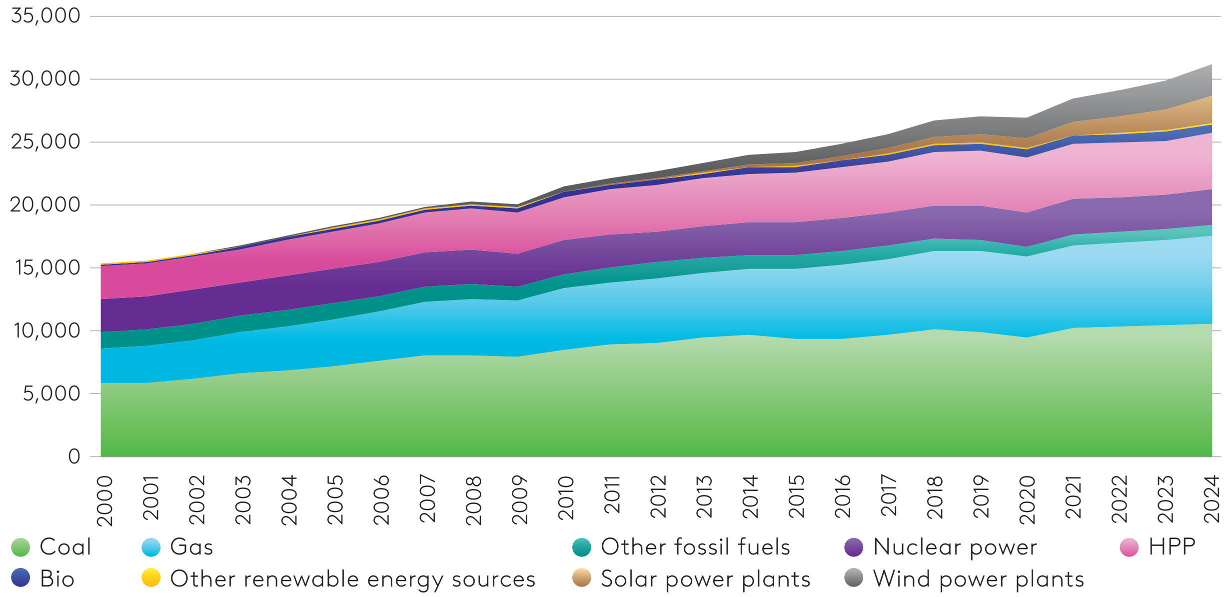
Source: IRENA, 2025a.

However, this progress has been accompanied by a global increase in CO_2 emissions, which, according to the IEA, rose by 1.1% *(410 million tonnes)* in 2023, reaching a new record of 37.4 billion tonnes (IRENA, COP30 and GRA, 2025). This means that the world is far from the trajectory that requires an order of magnitude higher reductions in annual emissions to limit warming to 1.5–2°C compared to pre-industrial levels.

Global CO_2 emissions continue to rise, indicating a structural gap between decarbonization targets and the actual capabilities of power systems

Global energy demand is growing faster than the introduction of new RE capacity. In 2024, demand increased by 2.2%, while the average for the previous decade was around 1.3%. The gap is being covered by all available sources, including coal and natural gas, which has led to a new historical record in greenhouse gas emissions. The energy transition is essentially taking place not by replacing fossil fuels, but by their coexisting with new technologies.

↓ Figure 2. Global electricity generation mix, billion kWh



Source: Ember (2025).

Nevertheless, most countries have officially recognized the need for an energy transition. As of 2024, 107 countries (*including all five Central Asian countries — Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan*), which account for 82% of global greenhouse gas emissions, have announced targets to achieve carbon neutrality by the middle of the 21st century (UNEP, 2024). These declarations are an important step, but there is a gap between them and current policy. *The nationally determined contributions (NDCs)* set out in the Paris Agreement for all signatory countries do not, taken together, put the world on track to meet the 1.5°C target: according to UNEP estimates, if current commitments are met, temperatures are expected to rise by 2.5–2.7°C by 2100. Thus, if the commitments made under the NDCs are fulfilled, RE capacity could reach 5.4 TW by 2030, which is half of the 11.2 TW required under the 1.5°C scenario (IEA, IRENA, UN, World Bank, and WHO, 2025).

One of the key tasks of the energy transition, along with reducing emissions, is the implementation of SDG 7 — universal access to affordable, reliable, and modern energy services by 2030. Progress on this goal is also uneven. According to the joint report by the IEA, IRENA, the World Bank, and the UN, *Tracking SDG7: Energy Progress Report 2025* (IEA, IRENA, UN, World Bank, and WHO, 2025), in 2023, the share of the global population with access to electricity reached 92%, while 666 million people still live without electrification (*958 million people in 2015*). Progress in environmental sustainability is also insufficient. The share of renewable sources in global final energy consumption has grown from 15.6% (2015) to 17.9% (2023) — a very modest increase, given the need to double the share of renewable energy (RE) sources by 2030. Energy efficiency, measured by the reduction in energy intensity of GDP, is improving too slowly — 3.87 megajoules/USD in 2022 (4.26 MJ/USD in 2015). This is about 1% per year, while the required rate to achieve the goals is 3% per year. In other words, the world is not on track to achieve any of the SDG 7 indicators if current rates are maintained.

To achieve global goals, including the SDG 7, IEA and IRENA estimate annual investments related to the energy transition at 4.2–4.5 trillion USD (IEA, IRENA, UN, World Bank, and WHO, 2025) (*1.8 trillion in 2023)*. The WEF estimates these needs at 5–5.6 trillion USD (WEF, 2025). Mobilizing such volumes will require unprecedented efforts by international institutions, development banks, and the private sector. Developing countries have significant needs in this regard. International financial flows to support clean energy in developing countries remain insufficient and are concentrated in only a few regions. In 2023, public financing for RE projects in developing countries amounted to only 21.6 billion USD, with 80% of these funds going to just 25 countries. As a result of the uneven distribution of investment, the most vulnerable countries risk falling behind in the transition due to a lack of capital and technology.

International organizations are calling for more action: we need to speed up the electrification of remote and rural areas, increase funding for clean energy projects in the least developed countries, and integrate access goals with decarbonization goals, among other things. (IEA, IRENA, UN, World Bank, and WHO, 2025). The last of these is particularly important: energy security and climate sustainability must be addressed jointly, not at the expense of each other. The concept of "leaving no one behind" implies that the transition to green energy must be universal — if some regions remain dependent on dirty or expensive sources, global goals will not be achieved.

The energy crisis of 2021–2022 revealed a contradiction between the energy transition and the sustainability of energy systems. The recovery of the global economy after COVID-19, geopolitical conflicts, and extreme weather events have led to an unprecedented surge in energy prices. Natural gas prices rose particularly sharply in Europe, with spot prices soaring to the equivalent of 250–300 USD per MWh, making gas-fired electricity the most expensive on the market. On average, in 2022 gas in Europe cost seven times more than historical levels, causing a reduction in gas generation and a return to coal where possible. Faced with the threat of rolling blackouts and gas unavailability, even developed countries were forced to resort to emergency measures: Japan restarted mothballed coal units, while Germany temporarily extended the operation of coal-fired power plants.

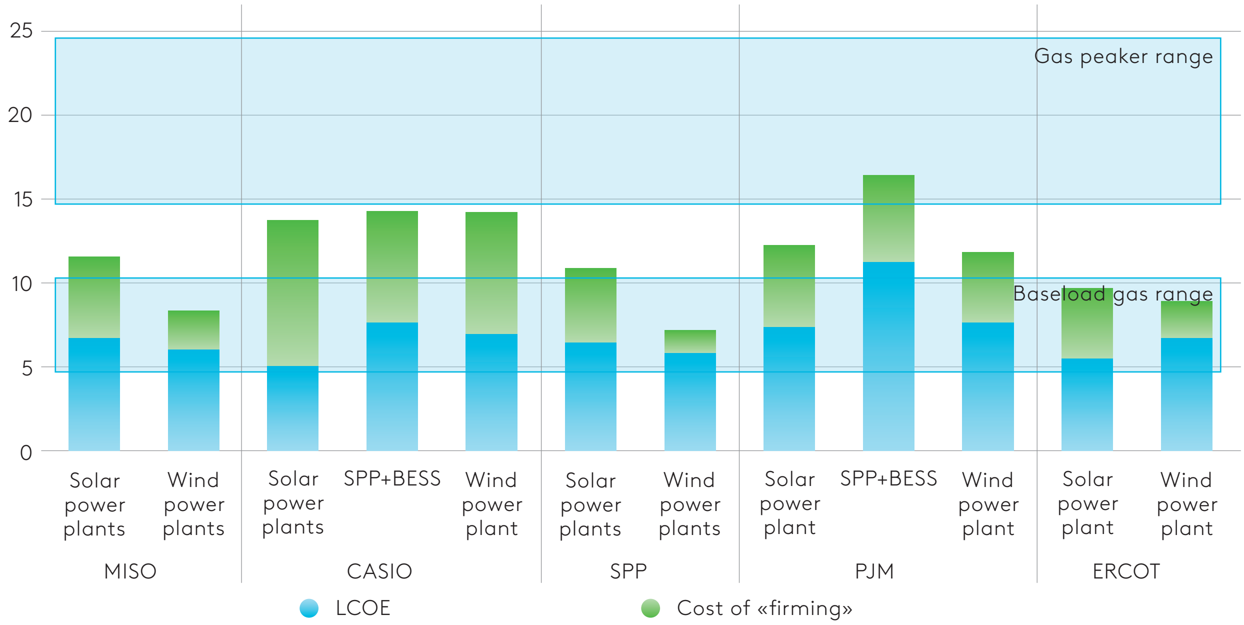
This crisis highlighted the vulnerability of biased strategies. Europe, which for decades had relied on imported pipeline gas as a "bridge" to a low-carbon system, faced a crisis in energy security. High prices have hit the affordability of energy for consumers, causing socio-economic consequences (*rising inflation, household and industrial costs)*. At the same time, in order to supply power and heating, countries have had to increase their use of coal — a step backwards for environmental sustainability. The IEA noted that without droughts (*which reduced hydropower generation)* and the associated additional emissions, the global electricity sector could have reduced emissions in 2023; however, by compensating for the decline in hydropower with fossil fuels, the world received 170 million tonnes of additional CO_2 emissions. This situation clearly demonstrated that the power system is a fragile organism and that a successful transition must be resilient to external shocks. Achieving reliability, accessibility, and environmental neutrality simultaneously is a practical condition for the energy security of states.

Solar and wind electricity have become cost-competitive in most countries worldwide

The global energy transition is entering a new phase. The first stage, focused on reducing the cost of RE sources, has largely been completed: today, solar and wind energy have become the most competitive new sources of electricity in many countries (IRENA, COP30 and GRA, 2025). However, these energy sources are variable, uncertain, location constrained, and inverter-based, bringing new challenges to system operation. The challenges are systemic in nature — integration of RE into grids, additional reservation of capacity and storage, modernization of infrastructure, and investment attraction, especially in developing markets.

To ensure a stable round-the-clock energy supply, in addition to RE sources, "insurance" is required in the form of duplicate capacity, which will be utilized less but is necessary in the event of planned or unplanned changes in the output of RE sources. The economics of these reserve capacities are characterized by high unit costs due to low utilization rates. Overall, this translates into higher end costs for power systems and consumers. These costs are unique to each power system, but the complexity lies in the fact that traditional indicators such as levelized cost of electricity (LCOE) cannot fully capture this effect for a direct comparison of the economic and technological efficiency of different technologies.

↓ Figure 3. RE levelized cost of electricity and cost of 'firming' for network operators in USA, USc/kWh



Source: Lazard, 2025.

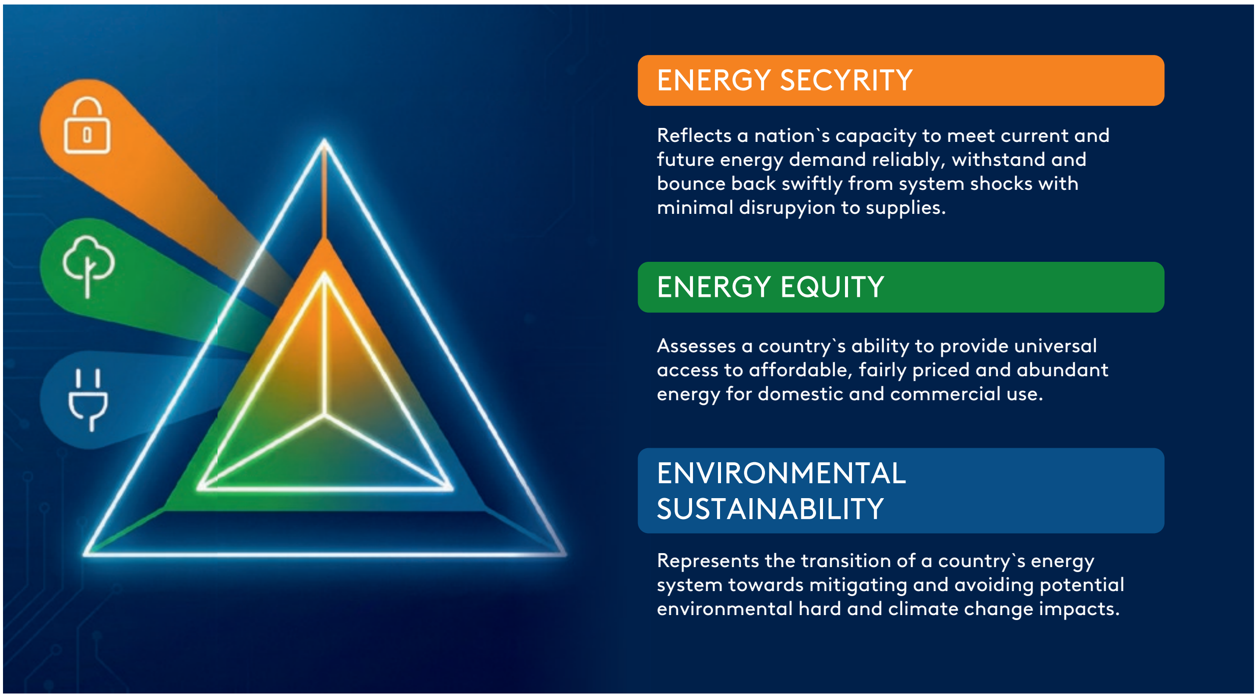
The key constraint of the energy transition is not the electricity cost but the resilience of power systems, including flexible capacity, storage, and digital control tools

There has been a clear shift in focus from reducing the cost of technology to strengthening energy security and overcoming infrastructure constraints. Achieving SDG 7 requires comprehensive efforts, including both accelerating the adoption of clean energy and providing targeted support for energy access and system sustainability. In this context, the concept of the energy trilemma, based on balancing three objectives, is becoming increasingly relevant as a guiding principle for policy.

1.2. The energy trilemma: balancing security, affordability and sustainability

The term "energy trilemma" was introduced by the World Energy Council (WEC) (World Energy Council, 2025) and reflects the idea that a resilient energy system must meet three equally important criteria: *energy security*, *energy equity*, and *environmental sustainability*. This is a kind of "triangle of goals," at the vertices of which are the key priorities of energy policy (see Fig. 4):

↓ Figure 4. The WEC energy trilemma: three equally important goals of an energy system



Source: World Energy Council, 2025.

- **Energy security** refers to the ability of a country or region to reliably meet current and future energy demand, withstand disruptions, and recover quickly from external shocks. This includes diversifying sources and supply routes, developing domestic generation, reserve capacity, and infrastructure reliability (*grids, storage facilities*). High energy security prevents situations where fuel shortages bad weather or accidents disrupt the system.

- **Energy accessibility and equity** mean guaranteed *universal access* to basic energy services at *affordable prices*. This component covers both household (*share of household energy expenditure, tariff policy, subsidies for vulnerable groups*) and commercial/industrial accessibility. In a global context, this includes the elimination of energy poverty — the electrification of remote regions, the transition to clean fuels for cooking, and the levelling of disparities between countries.

- **Environmental sustainability** requires minimizing the negative impact of energy generation and consumption on the environment and climate. This primarily involves reducing greenhouse gas emissions (*mitigating climate change*), abandoning fuels with the largest carbon footprint, as well as preventing local pollution (*smog, acid rain*) and preserving ecosystems (*e.g., in hydropower construction or resource extraction*). The transition to renewable and low-carbon sources and improving energy efficiency are key elements of this dimension.

The energy trilemma that balances security, affordability, and sustainability is a useful framework for assessing energy policy in Central Asian countries

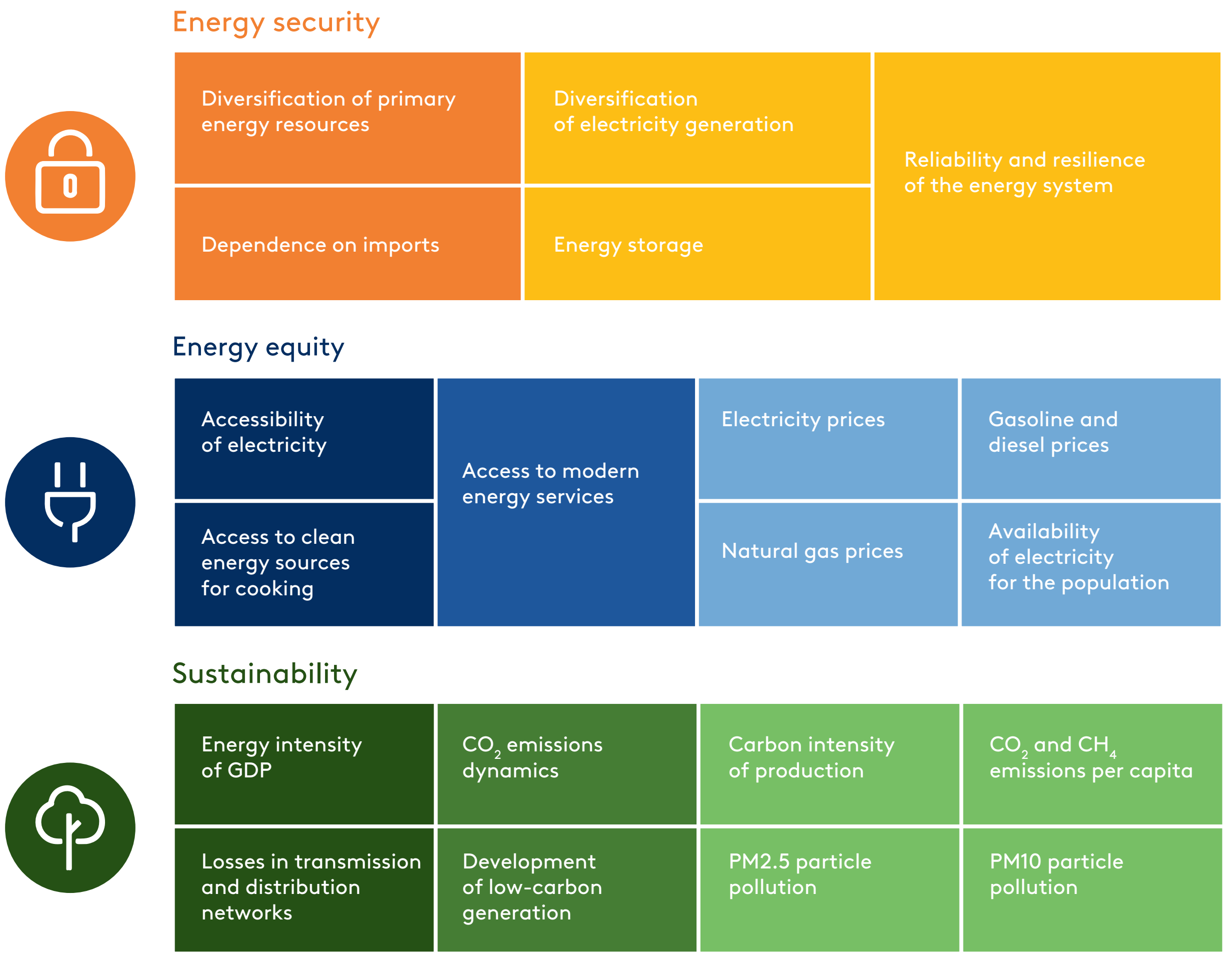
The main feature of the trilemma is that these three goals often conflict with each other, and a unilateral pursuit of one of them can undermine the others. Policies that ignore at least one of the components are unsustainable in the long term.

For example, if a country focuses exclusively on the environmental aspect — introducing strict restrictions on fossil fuels and a rapid transition to RE sources — but does not take into account reliability and costs, it may face energy shortages and social discontent due to high tariffs. An example of this is the difficulties experienced by the energy systems of certain European countries in recent years: the aggressive closure of coal and nuclear power plants, which was not synchronized with the introduction of sufficient reliable capacity, led to increased dependence on gas imports and, as a result, vulnerability to price shocks.

The opposite situation — prioritizing affordability (*cheap energy*) — is usually reflected in the maintenance of fossil fuel subsidies and postponement of the introduction of environmental standards, which over time leads to pollution, deterioration in public health, and a high carbon footprint for the economy. Countries that keep domestic petrol or electricity prices artificially low often face budget overspending and a lack of incentives for energy efficiency, while their energy companies face underfunding, which ultimately undermines the reliability of supply.

Another case may be an exaggerated emphasis on security. Under the slogan of energy independence, countries may focus on maximizing the use of local and cheap resources, even if this involves the most polluting and outdated technologies (*e.g., low-grade coal*). In the short term, this increases autonomy, but it risks technological backwardness and, in the long term, poses environmental and economic risks (*carbon taxes, border carbon regulation, and loss of markets*). The imbalance in this component can also be expressed in a policy of isolationism from neighbors under the banner of "energy security and independence." Thus, a sustainable course requires a compromise among the three objectives. The WEC notes that successful energy systems are managed through a "careful balance" among security, affordability, and sustainability, without "passive trade-offs" where one priority is sacrificed for another.

↓ Figure 5. Structure of the Energy Trilemma Index



Source: adapted from World Energy Council, 2025.

At the political level, the concept of a "just transition" is gaining traction globally: decarbonization should ensure social justice and protect vulnerable groups and workers employed in traditional industries. International climate finance mechanisms, such as *the Initiative for Energy Transition (JETPs)* for South Africa, Indonesia, and Vietnam, are designed to help developing countries close coal-fired power stations while investing in alternatives and supporting employment — in other words, to address environmental and socio-economic challenges simultaneously.

Few countries manage to achieve high results across all components of the trilemma at the same time. The top 10 and top 20 countries in the WEC ranking are consistently dominated by developed countries with high per capita incomes. According to the 2024 index, the leaders were Denmark, Sweden, Finland, Switzerland, Canada, Austria, France, Germany, Estonia, the United Kingdom, and others (see Table 1).

↓ **Table 1. Comparison of country ratings according to the Energy Trilemma Index, SDGs, and WEF Energy Transition Index**

Country	WEC 2025 (rank out of 99 countries)	UN SDG 2025 (rank out of 167 countries)	WEF ETI 2025 (ranked out of 118 countries)
Denmark	1	3	3
Sweden	1	2	1
Finland	2	1	2
Switzerland	3	26	5
Canada	4	25	33
Austria	5	6	6
France	6	5	14
Estonia	7	17	11
Germany	7	4	9
United Kingdom	8	11	16
Norway	8	7	4
New Zealand	9	28	24
United States	10	44	17
Russia	39	51	Not ranked
Kazakhstan	**51**	**70**	**94**
Armenia	58	50	65
Tajikistan	**69**	**88**	**95**
Kyrgyzstan	**Not ranked**	**47**	**78**
Turkmenistan	**Not ranked**	**96**	**Not ranked**
Uzbekistan	**Not ranked**	**62**	**Not ranked**
Belarus	Not ranked	32	Not ranked

Note: CA countries are highlighted in bold.
Source: WEC, UN, WEF.

The leaders of the ratings have the following characteristics:

- **High energy security** is achieved through diversification of sources and imports, developing storage and reserve infrastructure, and regional cooperation. For example, Denmark and Germany are integrated into the pan-European energy network, can import or export electricity as needed, and combine different types of generation (*wind, gas, bioenergy)* for system stability. Canada and Norway have their own vast resources and invest in reliable networks, which puts them at the top in terms of security.

- **Energy accessibility and equity** is ensured in these countries thanks to well-designed social policies and efficient economies. Virtually all residents have access to modern energy services. Although energy prices in Europe are high, there are targeted compensations for the vulnerable and incentives to improve the energy efficiency of housing, which reduces the burden on households. In some leading countries (*e.g., France, Sweden),* the share of household expenditure on energy resources is relatively small due to high incomes and moderate tariffs, which is reflected in a high equity score.

- **Environmental sustainability** is a strong point for most of the leaders in the ranking. European countries have systematically reduced the carbon footprint of their energy sectors by introducing renewable sources, developing nuclear power (*France, Sweden*) and improving energy efficiency. Denmark gets more than 50% of its electricity from wind, Switzerland and France are virtually carbon-free thanks to hydroelectric and nuclear power generation, and New Zealand combines hydroelectric, geothermal and wind power stations. As a result, their sustainability score is close to the maximum.

Leading countries are making progress in all three areas simultaneously. For example, Sweden has significantly increased its share of RE, while strengthening grid integration with its neighbours and maintaining reasonable prices. Denmark, by abandoning coal in favour of wind and gas, has not only reduced emissions but also increased the reliability of supply by connecting to the energy systems of the Scandinavian countries and Germany. It is noteworthy that the countries with the highest scores in the Energy Trilemma Index regularly occupy leading positions in the Sustainable Development Goals (SDG) rankings and the World Economic Forum (WEF) Energy Transition Index (*see* Table 1). This highlights their high performance in energy sustainability, alignment with sustainable development goals, and readiness for energy transition. The high scores of the Scandinavian countries reflect their commitment to addressing broader socio-economic and environmental issues.

However, the energy crisis of 2021–2022, discussed above, must be taken into account in the context of the energy trilemma. Despite its high performance indicators, this crisis, which affected many European countries, demonstrated that attempting to force a “green” transition without sufficient energy security measures can lead to a setback. By 2020, the European Union had achieved notable success in reducing emissions (*–31% from 1990 levels)* and increasing the share of RE sources, but it had failed to diversify gas supplies and expand gas storage. A sharp reduction in usual supply caused a price shock, effectively jeopardizing the climate agenda itself: countries were forced to temporarily increase power generation from coal/fuel oil and subsidize consumer bills by tens of billions of euros to maintain energy affordability. The European Commission has drawn conclusions: the reliability and flexibility of the energy system are now considered an integral part of the “Green Deal”. In particular, a decision was made to accelerate the development of energy storage facilities and modernize networks. After major power outages in 2025, Spain and Portugal publicly acknowledged the need for urgent investment in storage facilities and infrastructure to prevent similar incidents (WEF, 2025).

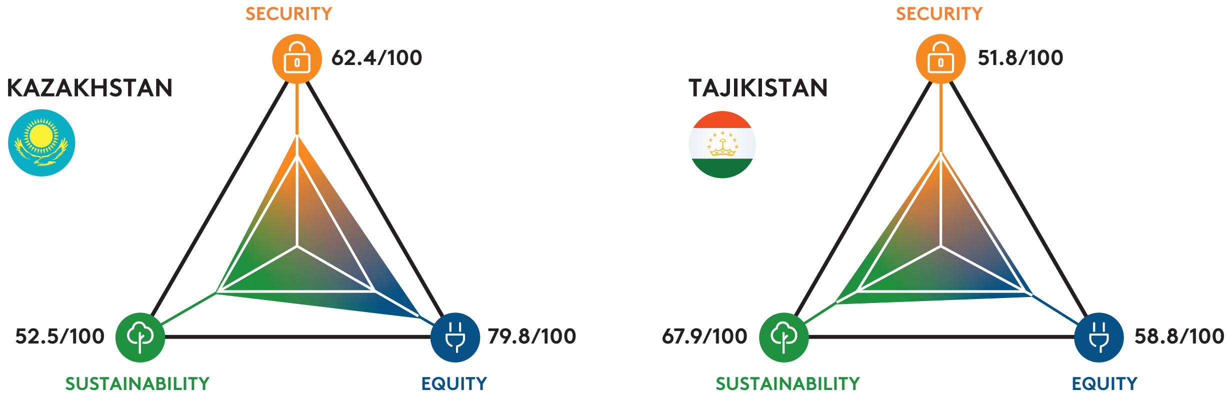
In terms of affordability, the example of a number of developing countries is instructive, where attempts to keep energy prices low have led to financial crises and stagnation in energy sector development. For example, in a number of South Asian countries, long-term subsidies for petrol and electricity have led to chronic underinvestment in generation capacity and networks, electricity shortages and regular blackouts, ultimately affecting both safety and service quality. These countries are now transitioning to market-based pricing mechanisms, while simultaneously introducing targeted support for the most vulnerable segments of the population.

The concept of the energy trilemma is also being adapted to the conditions of the energy transition. The challenges of the new era have broadened the content of each component of the trilemma. The WEC 2024 report notes that energy security now includes the reliability of RE sources, the availability of critical mineral resources, and the resilience of infrastructure to physical threats and cyberattacks. Energy equity also implies a just transition: equal access to clean energy for vulnerable communities, fair distribution of the benefits of the energy transition, and consideration of the interests of workers and industries in the phase-out of fossil fuels. Environmental sustainability has evolved into a broader approach to “planetary health,” including the principles of the circular economy, the water-food-energy nexus, and aligning the pace of decarbonization with the planet’s ecological limits. Thus, the energy trilemma is evolving to reflect humanity’s new ambitions — not a simple reduction in greenhouse emissions, but the creation of more resilient and equitable energy systems.

1.3. The energy sector of Central Asia through the prism of the energy trilemma

The energy sector in Central Asian countries is characterized by pronounced structural polarization, with key states demonstrating various compromises within the energy trilemma. The region is rich in primary energy resources, but their structure predetermines the unevenness of positions in global rankings.

↓ Figure 6. Energy trilemma index for Kazakhstan and Tajikistan



Source: World Energy Council (2025).

Kazakhstan, ranked 51st in the Energy Trilemma Index in 2025, and remains one of the largest producers of fossil fuels in Eurasia. This explains the country with relatively high energy security and affordability indicators, but results in extremely low environmental sustainability. Kazakhstan ranks only 70th in the UN SDG Index and 94th in the WEF Energy Transition Index. These positions highlight the national energy sector's dependence on coal and the critical need for technological modernization, diversification, and accelerated decarbonization of the sector.

Tajikistan demonstrates the opposite structure (*69th place in the Energy Trilemma Index*). Its energy system is almost entirely based on hydropower, which enables "cleaner" energy production. However, the country ranks only 88th in the SDG ranking and 95th in the WEF Energy Transition Index, reflecting weak infrastructure, chronic reserve capacity shortages, and energy supply instability. Despite its low carbon footprint, Tajikistan faces reliability and accessibility issues that limit overall progress towards sustainable development.

For countries not included in the WEC ranking, their position can be assessed using related indices:

- **Kyrgyzstan** ranks 47th in the SDG ranking and 78th in the WEF Energy Transition Index. These results are significantly better than those of Kazakhstan and Tajikistan and indicate gradual progress in sustainable development and energy transition. Although the country's hydro-centric system faces risks of seasonality and limited capacity reserves, Kyrgyzstan demonstrates balanced development towards sustainability.

- **Uzbekistan** ranks 62nd in the SDG. Its energy structure remains dependent on natural gas, but the active introduction of solar and wind power plants, the modernization of thermal power plants, and the creation of flexible capacity are improving reliability and sustainability indicators. The country is likely moving towards a model with moderately high levels of energy security and accessibility, but still limited sustainability.

- **Turkmenistan** is the most vulnerable country in the region. It ranks 96th in the SDG ranking, the worst indicator among Central Asian countries. Heavy dependence on natural gas exports provides formal energy security, but is accompanied by extremely low environmental sustainability, opaque governance, and weak progress in the energy transition. In terms of the trilemma, Turkmenistan is likely to remain in the category with a weak sustainability rating, despite its significant gas reserves and potential for electricity exports.

Against the backdrop of these differences, the factor of regional energy integration is becoming increasingly important, as it could mitigate the imbalances of the trilemma and increase the overall resilience of systems. The experience of developed countries that lead the energy trilemma index rankings — from the European Union to North America — clearly confirms that inter-system connectivity and mutual energy exchange make it possible to simultaneously strengthen all three components of the trilemma: improving the reliability of supplies through mutual capacity reserves, reducing tariff pressure by optimizing production costs, and increasing the share of RE sources through the integration of weather-dependent sources across larger territories.

The main conclusions of the analysis of the current state of the energy transition and its challenges are as follows:

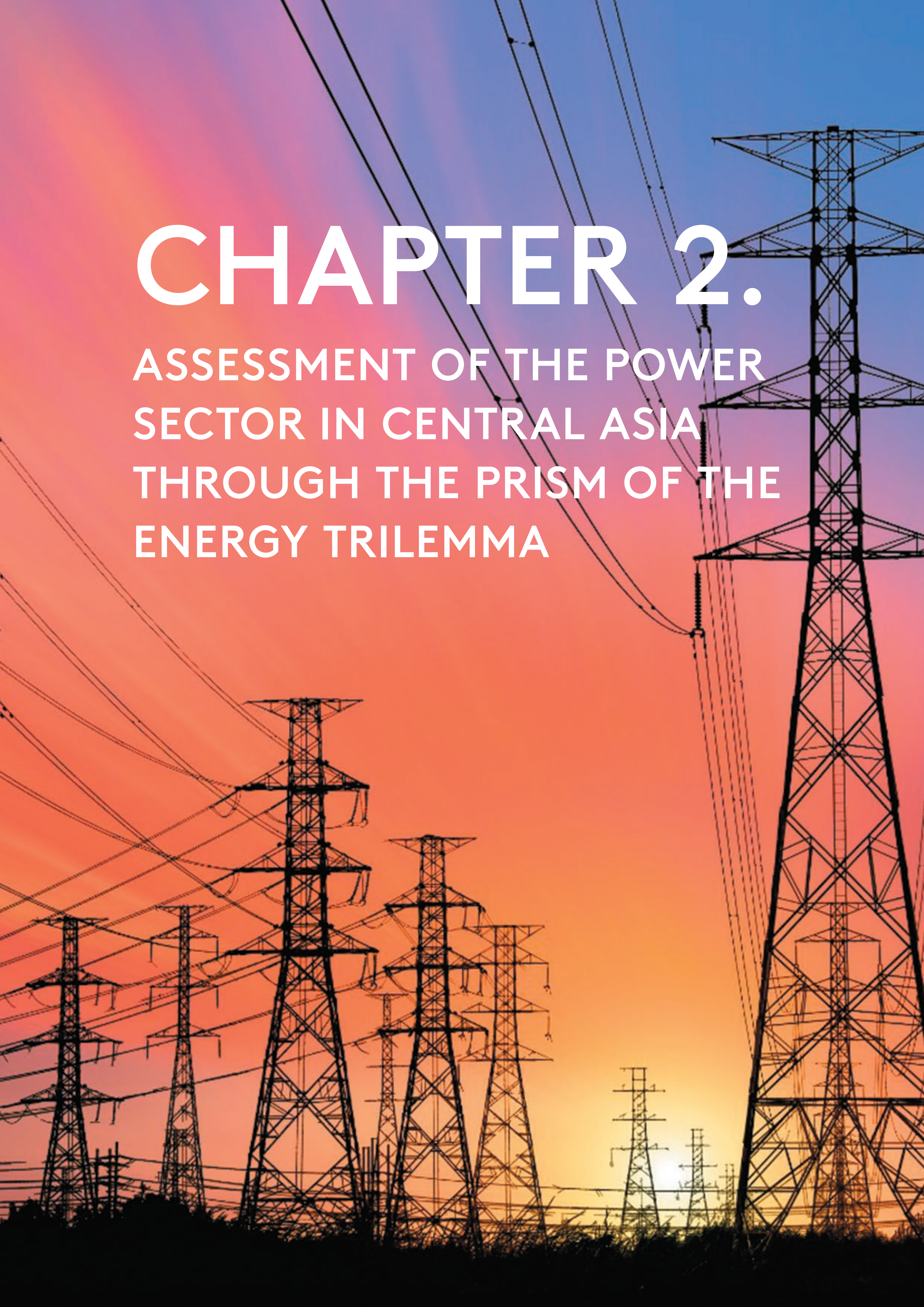
Energy policy should be based on a holistic approach integrating energy security, affordability, and sustainability into a single strategy

- Energy policy must be based on a comprehensive approach, integrating the three goals into a single strategy. This is difficult, requires fine-tuning — for example, when analyzing a new energy technology, we should ask: does it increase the reliability of the system (*or introduce new risks*), is it affordable for large-scale implementation, and how environmentally responsible is it over its entire life cycle? It is this kind of balanced thinking that should form the basis of the approach to energy transition.

- For Central Asia, the development of integration projects could be a catalyst for the transition from fragmented national systems to a regionally balanced model. Connected energy systems increase the resilience of hydropower-dependent countries (*Kyrgyzstan, Tajikistan*) by ensuring exports during periods of surplus and imports during periods of deficit, and for Kazakhstan, Uzbekistan, and Turkmenistan, they create an incentive to diversify generation, add lacking flexibility to the fleet, and make efficient use of gas and renewable resources. Thus, regional energy integration acts as a key positive factor in the trilemma, improving the balance among security, affordability and sustainability and bringing the region closer to the model of energy equilibrium characteristic of more developed economies.

CHAPTER 2.

ASSESSMENT OF THE POWER SECTOR IN CENTRAL ASIA THROUGH THE PRISM OF THE ENERGY TRILEMMA



The power sector in Central Asian countries was formed during the Soviet period as a single Central Asian Energy System (CAES), covering Kazakhstan (*southern part*), Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (Vinokurov et al., 2021). The central dispatch office in Tashkent oversaw and optimized the operation of power generating fleet and water reservoirs in the interests of the entire region: in summer, the upper basin countries (*Kyrgyzstan, Tajikistan)* accumulated water and supplied the lower basin countries with hydroelectric power, and in winter they received electricity and fuel from the lower reaches.

The collapse of the USSR in 1991 led to the destruction of this well-established energy exchange scheme. The regional power system fragmented into national segments, and countries began to pursue only their own interests. Joint management of water resources ceased and led to predictable consequences: Kyrgyzstan and Tajikistan now had to produce more electricity and release more water in winter, to the detriment of summer irrigation in the lower basin countries (Vinokurov et al., 2022). It led to a loss of coordination and chronic imbalances — energy shortages in some seasons, and surpluses in others, which were difficult to export due to limited capacity (Vinokurov et al., 2021).

Despite the significant potential of RE sources and global trends, Central Asia's energy sector remained predominantly "fossil fuel-based" through 2024, with the generation mix having remained virtually unchanged over the past 30 years. This indicates strong inertia and structural barriers: the problem is not only the physical wear and tear of equipment, but also institutional, political, and economic obstacles that slow down the transformation. The region must catch up with global trends in decarbonization and energy efficiency, while operating with critically outdated infrastructure and rapidly growing demand for electricity. This makes the transition to a new energy model particularly challenging, capital-intensive, and urgent.

In this chapter, the analysis of the status quo and challenges of the power sector in Central Asia is structured through the prism of the energy trilemma concept — the balance among three goals: energy security, energy affordability (*equity*), and environmental sustainability. Key aspects of each of these dimensions are examined in turn as they apply to the countries of Central Asia, drawing on data and findings from recent studies. Particular attention is paid to the historical context, fragmentation of the regional system, the state of infrastructure, diversification of generation mix, water-energy nexus, and new challenges — the growth of variable loads, the influence of climatic factors, the need for digitalization, etc.

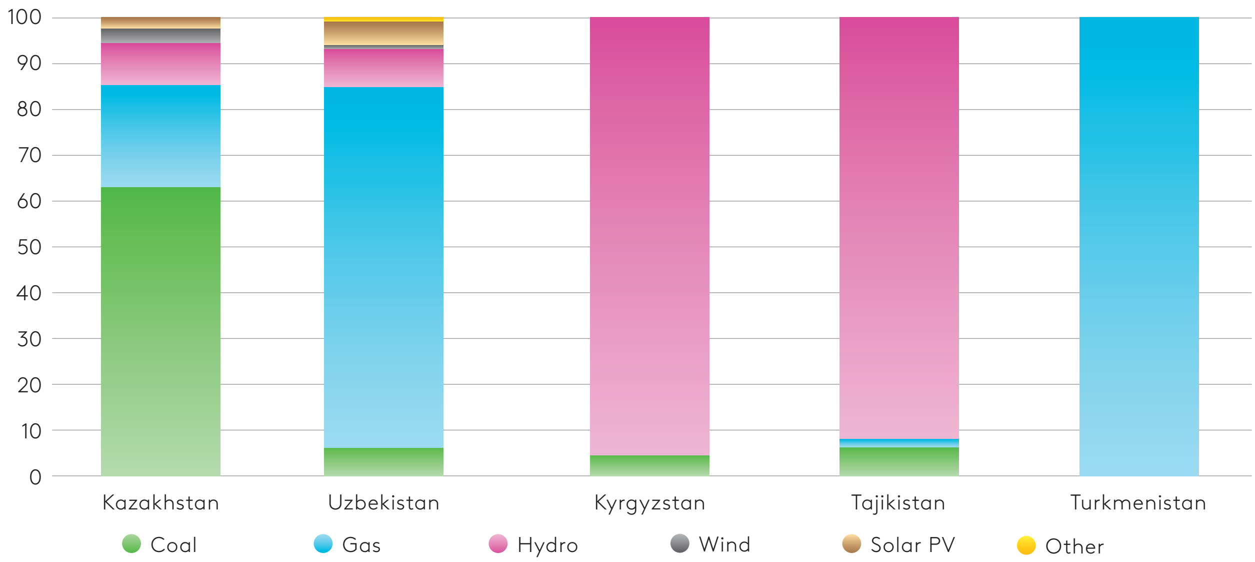
2.1. Energy security

Energy security reflects the ability of a country or region to reliably meet current and future energy needs through diverse sources and resilient infrastructure. For Central Asia, this task is complicated by challenges related to historical fragmentation of the energy system, as well as rapid growth in demand for electricity. Three key aspects of energy security in the region warrant consideration: diversification of energy resources, reliability of energy supply and infrastructure, and flexibility of the energy system under new loads.

Diversification of the resource base and electricity generation

Historically, the fuel and energy mix of the Central Asian republics have varied significantly, reflecting their natural resource base. The countries in the lower Aral Sea basin — Kazakhstan, Uzbekistan, and Turkmenistan — have significant reserves of fossil fuels (*coal, oil and natural gas*), while the countries in the upper basin — Kyrgyzstan and Tajikistan — are almost entirely dependent on hydropower. As a result, generation diversification is low in most countries: for example, in Kazakhstan, 63% of electricity is produced from coal, and in Turkmenistan, 99.9% from gas. Coal and gas also account for the overwhelming majority of Uzbekistan's generation (*80% in total*), while Kyrgyzstan and Tajikistan obtain over 90% of their electricity from hydropower plants. The share of solar and wind power plants is still small — around 3–7% in Kazakhstan and Uzbekistan (*as of the end of 2024*) and less than 1% in the other republics. This concentrated profile creates vulnerabilities: a shortage of any key fuel or unfavourable natural conditions can cause an energy deficit.

↓ Figure 7. Electricity generation mix in Central Asian countries as of beginning of 2025



Sources: Ministry of Energy of the Republic of Kazakhstan, Kyrgyz Energy Settlement Centre, Ministry of Energy and Water Resources of the Republic of Tajikistan, Ember.

Low diversification is already causing problems. Tajikistan and Kyrgyzstan are vulnerable to low water levels: in winter their hydropower plants produce less electricity, and the countries experience acute power shortages. Tajikistan has traditionally been forced to resort to rolling blackouts or increased imports in winter, highlighting the limited nature of its resource base (*limited alternatives to hydropower)*. Kyrgyzstan faced a similar situation: in the winter of 2024, approximately 25% of the necessary electricity was imported from neighbouring countries due to a drop in hydropower generation (IEA, 2024) in the conditions of record consumption. Uzbekistan experienced a major energy crisis in January 2023 due to its excessive reliance on gas-fired thermal power plants: abnormal cold weather triggered a surge in consumption and, simultaneously, a drop in pressure in the gas network, which disabled several power plants. This was followed by massive power outages, demonstrating the danger of insufficiently diversified generation and a lack of reserve capacity. In coal- and gas-rich Kazakhstan and Turkmenistan, the risk is different: although they are self-sufficient in fuel, relying on a single type (*coal or gas)* also creates vulnerability. For example, concentrating generation on coal risks accidents and environmental problems, while relying on gas carries the risk of fuel supply disruptions and price volatility.

60 to 90%

of electricity output comes from a single power generation source, indicating low diversification of the generation mix

↓ Table 2. Installed capacity and electricity generation mix in Central Asian countries as of the beginning of 2025

Country	Installed capacity (MW)	Total generation (billion kWh)	Share in total generation (%)					
			Coal	Gas	Hydro-power	Wind power	Solar power	Other
Kazakhstan	25,314	117.2	63.2	21.9	8.5	3.6	2.5	-
Uzbekistan	21,259	81.5	6.1	73.7	8.5	4.4*	7.3*	0.9
Kyrgyzstan	3,930	14.7	5.7	-	91.9	-	-	2.3
Tajikistan	6,454	22.4	7	1.7	91.3	-	-	0.1
Turkmenistan	6,945	31.6	<0.1%	99.9	-	-	-	-
TOTAL	**63,902**	**267.4**						

Note: * as of mid-2025

Source: Statista, KEGOC JSC, Kyrgyz Energy Settlement Centre OJSC, Ministry of Energy of the Republic of Kazakhstan, Ministry of Energy and Water Resources of the Republic of Tajikistan, Ember.

The cost of electricity from RE in Kazakhstan decreased over the past years, however still significantly higher than the procurement price of conventional generation

Diversification and modernization come at a price, and in recent years, all energy technologies and fuel types have become more expensive. For example, despite the fact that the cost of electricity from RE sources in Kazakhstan has fallen significantly in recent years, it is still several times higher than the purchase price of traditional generation. According to FSC data for 2024, the average purchase price of electricity from thermal power plants was about 12.9 tenge per kWh, while purchases from RE sources cost approximately

34.8 tenge per kWh. The significant gap is explained by the fact that most thermal power plants are already fully depreciated and operate at low cost, which temporarily creates a significant price advantage. At the same time, such thermal power plants still have room for further productivity improvements through reconstruction and modernization, which allows them to extend the service life of equipment and maintain low prices for consumers and the energy system.

To strengthen energy security, all Central Asian countries have announced plans to diversify their energy supply. They have set particularly ambitious targets for developing RE as a means of both decarbonizing and reducing dependence on traditional resources. The main focus is on solar and wind energy, as well as (*in Kazakhstan and Uzbekistan)* nuclear energy and the modernization of existing thermal power generation. The declared energy development targets for 2030–2040 are as follows:

- **Kazakhstan** plans to commission over 26 GW of new capacity by 2035 (*5.5 GW — modernization and expansion of existing thermal power plants; 8.4 GW — RE sources; 12 GW — new coal, gas, and nuclear power plants*). The share of RE sources in total energy mix will reach 15% by 2030 and 50% by 2050, with the ultimate goal of carbon neutrality by 2060. To replace decommissioned coal-fired power plants, there are plans to build nuclear power plants (*the first by 2035)* and adopt 'clean' coal technologies at new thermal power plants (Ministry of Energy, 2024).

- **Uzbekistan** relies on natural gas, but its production has fallen by 27% in six years (*from 60 billion m³ in 2019 to 44 billion m³ in 2024*), which reinforces the need for diversification. According to the *Uzbekistan 2030* strategy, the share of electricity generated from RE sources in the mix should reach 40% by 2030 (*+25 GW of new RE sources)*. In January 2025, the target for new low carbon generation was raised to 54% by 2030 (Website of the President of Uzbekistan, 2025). A package of 50+ green projects worth more than 26 billion USD has been announced to implement these plans.

- **Kyrgyzstan** is focusing on developing its rich hydropower resources (*construction of cascades of hydroelectric power plants, including the 1,860 MW Kambar-Ata-1 megaproject, and new medium and small hydroelectric power plants*). Simultaneously, it plans to increase the share of non-hydro RE sources to 10% of the energy balance by 2040. This goal is likely to be achieved earlier: according to the "Energy Program of the Kyrgyz Republic until 2035", the construction of 3,650 MW of solar power plants, and 400 MW of wind power plants is planned by 2035.

- **Tajikistan** approved the "10/10/10/10" concept for 2030: to increase the installed capacity of power plants to 10 GW, electricity exports to 10 billion kWh, and to reduce network losses to 10% and ensure 10% of generation from alternative sources. The main increase in capacity is planned through the completion of the Rogun HPP (*3,700 MW)* and other HPPs, as well as the construction of 2,000 MW of solar and wind power plants by 2030 (Ministry of Energy and Water Resources of Tajikistan, 2024).

- **Turkmenistan**: due to its huge gas reserves, it is currently diversifying its energy sector to a minimal extent, but plans to commission 300 MW of solar power plants and a pilot 10 MW hybrid plant (*solar + wind*). The main focus is on increasing electricity exports from gas-fired thermal power plants and developing power lines to Afghanistan/Pakistan.

↓ Table 3. Summary of target indicators for the development of the energy sectors of Central Asian countries

Country	Conventional generation targets	RE development targets
Kazakhstan	12 GW of coal and gas generation, nuclear power plants 5.5 GW reconstruction of existing thermal power plants	15% and 50% of electricity generation from RE sources by 2030 and 2050, respectively Commissioning of 8.4 GW of RE sources by 2035
Uzbekistan	Reconstruction of 3 GW of thermal power plants Small modular reactors 330 MW	>25 GW of RE (17 GW of wind power and >8 GW of solar power) and 54% of electricity generation from RE sources by 2030 (including hydropower and nuclear power)
Kyrgyzstan	4.6 GW of new large hydropower plants 80 MW of small hydropower plants Reconstruction of existing hydroelectric power plants	3,650 MW of solar power plants, 400 MW of wind power plants by 2035
Tajikistan	Completion of the Rogun hydropower plant 2 GW of new hydropower plants Reconstruction of existing hydropower plants	2,000 MW of solar and wind power plants by 2030
Turkmenistan	–	300 MW solar power plants 10 MW hybrid power plant

Source: prepared by EDB experts based on strategic documents.

The Central Asian countries recognize the importance of diversification. If these plans are implemented, by the mid-2030s the region's energy balance will become significantly more diverse, reducing dependence on one or two types of fuel/technologies and, consequently, the risks to energy security. However, success depends on attracting investment and resolving the infrastructure issues discussed below.

Energy security and infrastructure

The reliability of energy supply in Central Asia is under serious pressure due to aging generation and transmission & distribution (T&D) infrastructure due to historical underfunding.

A significant part of the generating capacity and networks was commissioned during the Soviet period (1960s–1980s) and has reached the end of its service life. More than 50% of power plants and approximately 70% of power lines in the region have been in operation for over 30–40 years and are approaching the end of their service life (ADB, 2019). In Kazakhstan, the depreciation of thermal power plants reaches 56%, and for coal-fired thermal power plants it is up to 80%, which leads to an increase in accidents and polluting emissions. In Uzbekistan, most large gas-fired plants have been operating for more than 35 years and have low efficiency (25–35% compared to more than 60% for modern counterparts). In Tajikistan and Kyrgyzstan, the high wear and tear on hydropower plants and grids also increases the risk of accidents, especially given the growing load and climate change impacts (glaciers are melting, river regimes are changing) (IEA, 2022).

T&D infrastructure development in Central Asia reflects common challenges of aging infrastructure, growing loads, and the need for integration, but the situation varies from country to country. Kazakhstan relies on extensive legacy grid with high degradation and an imbalance between zones (generation in the north and demand in the south). Limited North-South line capacity leads to the southern zone's dependence on additional flows from Russia. In recent years, Kazakhstan has been modernizing its infrastructure, installing millions of smart meters, strengthening interconnection lines, and implementing the digitalization of grid operations. At the same time, Kazakhstan plays a key role in regional exchanges, taking advantage of grid synchronization with Russia and flows from Kyrgyzstan and Uzbekistan to balance RE sources.

In Uzbekistan and Kyrgyzstan, network development is driven by rapid load growth, high losses, and geographical constraints. In Uzbekistan, the degradation of transformers and power lines, combined with geographical discrepancy of RE generation and load centres, requires large-scale investments in transmission lines and the digitalization of distribution networks. In Kyrgyzstan, the power system has historically been divided by terrain: the construction of the Datka-Kemin line has made it possible to connect the north and south, but distribution networks remain vulnerable and experience high losses. Both countries are actively implementing automatic metering systems to reduce theft and improve payment discipline, while their energy security depends largely on seasonal exchanges with their neighbours.

Tajikistan, which relies almost entirely on hydropower, has reduced the fragmentation of its energy system through the construction of the south-north transmission line and the development of distribution network, although high losses and seasonal deficits remain. The country is actively modernizing its urban networks and expanding its export capabilities (CASA-1000). Turkmenistan, on the other hand, operates almost autonomously, relying on gas generation and its own 500 kV lines. Network losses are relatively low, and the priority is shifting toward expanding export corridors and gradual digitalization. Overall, grid development in the region is moving towards modernization, digital metering, and enhanced cross-border integration, which is necessary to balance the growing share of RE sources and ensure the reliability of energy supply.

Electricity demand in Central Asia could increase by

40%

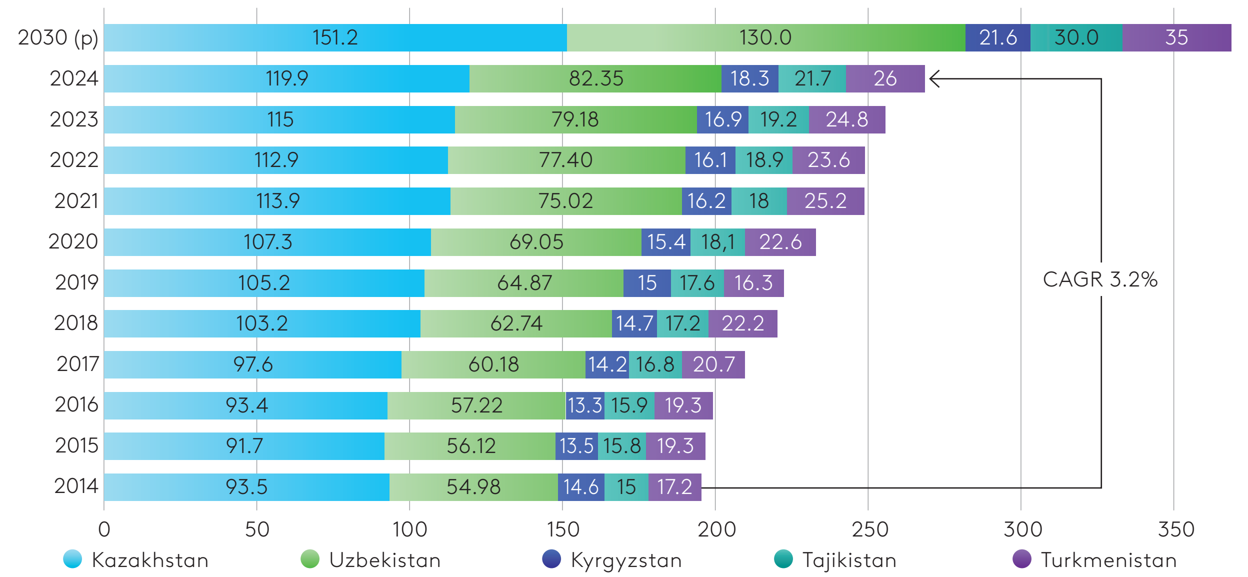
by 2030

Demand for electricity in all Central Asian countries is growing steadily at a rate exceeding global average due to economic growth, industrialization, urbanization, and population growth. In addition, new energy-intensive load centres and consumers are emerging, such as cryptocurrency mining, data centres, and electric vehicles. From 2014 to 2024, the compound annual growth rate of electricity consumption in the region was 3.2%. However, per capita electricity consumption remains below the global average (3,500 kWh per person per year) for most countries in the region (1,800 kWh for Uzbekistan). According to estimates by governments and international organizations, demand could increase by an additional 40% by 2030, from 270 TWh to 370 TWh per year. Past forecasts have systematically underestimated actual demand growth. As a result, power systems are unprepared for increased loads: in many cases, capacity and networks are operating at full capacity.

1,800 kWh/year

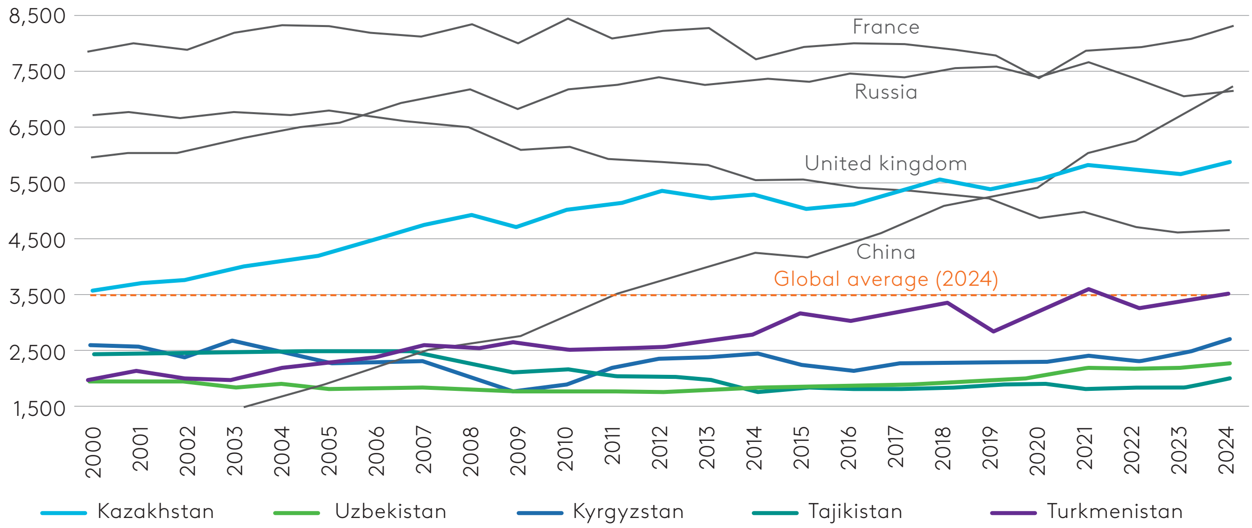
is the average per capita electricity consumption in Uzbekistan — twice below the global average and four times lower than in Russia or France

↓ **Figure 8. Electricity consumption trends and forecasts for Central Asian countries (billion kWh)**



Sources: EDB calculations based on historical data and forecasts from the World Bank and Ministries of Energy.

↓ Figure 9. Electricity consumption per capita, kWh per year



Sources: Ember based on data from EI, EIA, Eurostat, China Electricity Council (CEC), National Bureau of Statistics of China (NBS), Department for Energy Security and Net Zero (DESNZ).

Deteriorating infrastructure leads to high losses and frequent failures. Technical losses of electricity in Central Asian grids reach 15–20%, which is 2–3 times higher than the OECD average (IEA, 2024b). For example, losses in Kazakhstan are estimated at around 11%, and in Tajikistan at up to 20% of transmitted electricity. More than 60% of distribution networks are in need of replacement or major repairs (ADB, 2022). Such losses indicate insufficient reliability of the grid infrastructure and directly affect the quality of supply to consumers. The situation is exacerbated by the fact that tariffs have been kept low for an extended period (*see the section on* Energy Equity), which has left energy companies without sufficient funds to maintain and upgrade their assets. This has resulted in more frequent accidents and outages. In recent years, Kazakhstan and Uzbekistan have experienced power outages during peak hours and emergency shutdowns of power plants on unprecedented scale (KEGOC, 2024). Precise SAIDI/SAIFI (power interruption duration/frequency) reliability indicators by region are not available, but indirect data indicate an unsatisfactory level — in particular, the mountainous regions of Kyrgyzstan and Tajikistan, which are formally electrified, actually receive energy with frequent interruptions and reduced quality.

To improve reliability, large-scale infrastructure modernization is needed. First and foremost, existing power plants require major repairs and technical re-equipment. In the short term, priority should be given to facilities where the impact is greatest: repairing the most deteriorated components of generating assets and T&D lines with the highest losses. In Kazakhstan and Uzbekistan, this means modernizing existing coal- and gas-fired power plants — installing new boilers, turbines, and flue gas cleaning systems — to increase efficiency and extend service life without increasing accident rates. Simultaneously, it is advisable to accelerate the upgrading of networks: replacing old transformers, strengthening overloaded lines and adopting digital control and monitoring systems. Without grid upgrades, the region will face further growth in outages and restrictions, especially during peak loads.

Emergency measures are also being implemented: for example, after the rolling blackouts of 2022, governments began to regulate mining farms and new energy-intensive industries more strictly, requiring them to register and limiting their consumption during peak hours. In November 2025, an energy crisis was declared in Kyrgyzstan: electricity shortages forced the authorities to impose restrictions on the operation of some establishments (in particular, restaurants) after 10 p.m., and citizens were urged to save electricity. However, without a systematic upgrade of capital assets and changes in tariff policy, the reliability problem cannot be solved.

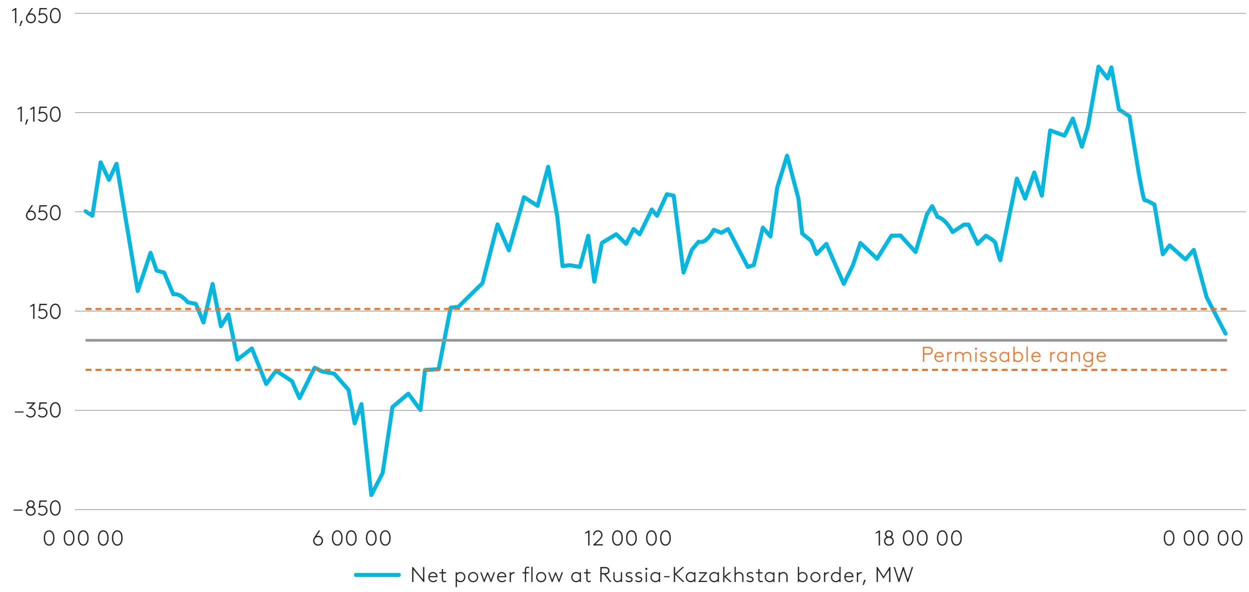
Power system resilience and flexibility

The flexibility of an power system reflects its ability to adapt to sudden changes in load, emergencies, and long-term changes. In Central Asia, the resilience of power systems is at risk due to a lack of flexible capacity, limited grid capacity, and new challenges from variable generation and new types of consumers.

One of the main problems is the low flexibility of the generating fleet. Many of the region's large power plants — outdated thermal power plants — are designed for a baseload operation. They cannot quickly change their output to cover daily consumption peaks or fluctuations in RE generation. In Kazakhstan and Uzbekistan, where the share of solar and wind power plants is growing fast, significantly more flexible capacity will be needed in the coming years to balance the systems. Estimates show that with a share of variable RE sources above 20% (*this level is expected to be reached by 2030 in Kazakhstan and Uzbekistan)*, there will be a need for additional reserves, flexible gas turbines, energy storage facilities, and demand management systems (IEA, 2024a). Otherwise, there will be an increased risk of grid overloads, RE curtailment, and even power shortages during peak hours, especially in winter during severe frosts and when little wind/sun is available.

The rigidity of power system is illustrated below by the case of Kazakhstan: significant imbalances in power flows are being recorded on the border with Russia, repeatedly exceeding the permissible range of ±150 MW. In other words, when generation and demand regularly diverge, system deviations were offset by emergency flows from Russia that help to maintain frequency. With the growth of the share of RE sources, this situation may worsen if means of domestic balancing are not developed. Despite the significant potential of hydropower in Kyrgyzstan and Tajikistan, today their HPPs only partially fulfil the role of flexible generation — their operation is mainly dictated by seasonal schedules for irrigation reservoirs. For hydropower plants to actively participate in intra-day balancing, equipment modernization and new institutional mechanisms are needed — ancillary services markets, coordination of water and energy regimes, and closer integration with neighbouring power systems. In the future, existing hydropower plants, especially in combination with energy storage facilities, could flexibly cover peaks and troughs in RE generation.

↓ Figure 10. Typical power imbalances (24h) at the Kazakhstan-Russia border, MW



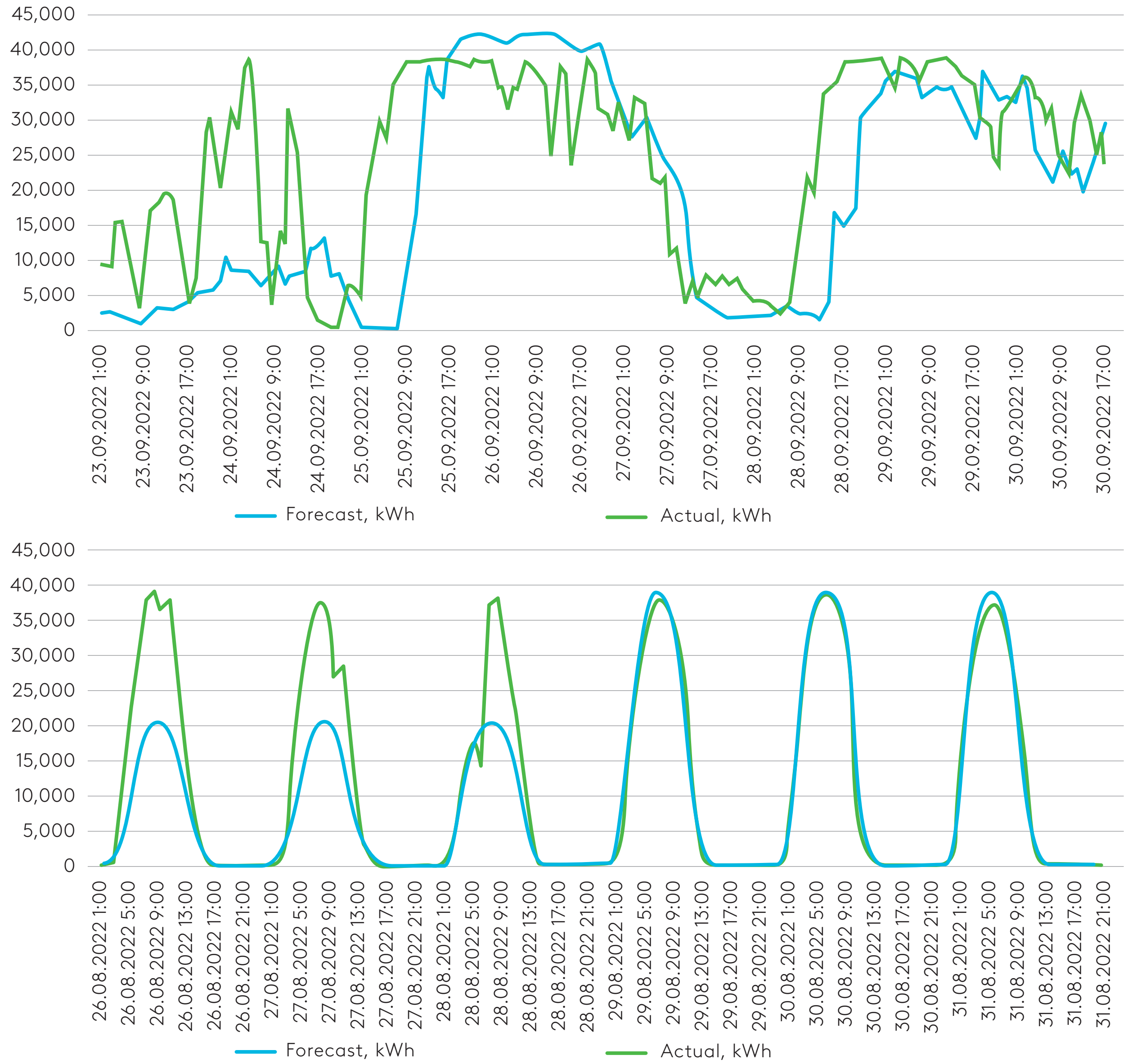
Source: QazaqGreen, Huawei (2025).

A separate issue is an accuracy of forecasting RE generation. With the increase in the share of solar and wind power plants, accurate generation forecasts and error compensation tools are needed. Currently, the accuracy of forecasts are not up to task. For example, in Kazakhstan, over the first nine months of 2022, the deviation between actual and forecast RE generation reached 1,751 million kWh, with a total volume of RE generation of 3,504 million kWh. In other words, half of the RE produced was accompanied by significant forecasting errors, indicating a lack of effective forecasting systems and incentives to accurately follow the schedule. If the situation does not improve, in the coming years this will lead to increased systemic imbalances in the balancing market, and financial risks for operators and participants in the RE market.

In the future, the combination of Dunkelflaute, high seasonality, forecast inaccuracies may pose systemic risks unless adequate reserves, storage, and regional integration are developed

An important task is to adapt power systems with an increasing share of RE sources to the Dunkelflaute, a weather phenomenon characterized by low solar radiation and reduced wind potential. In Europe, there are 2–10 such events per year lasting more than 24 hours. Sometimes these periods last from 3 to 5 days (Li et al., 2021). Such periods are particularly critical in winter, when the load on the grid increases and generation from solar and wind sources drops sharply. For Central Asia, the problem may become extremely acute when significant RE source capacities are reached in the system due to the low flexibility of the systems and the high geographical concentration of RE sources, which increases the correlation between RE facilities and makes them more vulnerable to concurrent weather fluctuations. The Dunkelflaute creates the risk of simultaneous generation reductions across large parts of the grid for periods exceeding the current capacity of battery energy storage systems. Countries in the region need to build up significant reserves, develop seasonal storage, strengthen regional interconnections, and account for forecast and past statistics on adverse weather periods.

↓ Figure 11. Deviations between planned and actual wind and solar power generation in Kazakhstan, kWh



Source: Qazaq Green (2024).

In addition to extreme events, Central Asia experiences pronounced seasonal variability in RE generation. The countries in the region have one of the highest seasonal amplitudes of solar radiation, with solar power plant generation significantly higher in summer than in winter. In Kazakhstan and Uzbekistan, solar power generation peaks in May–July, when the capacity factor reaches 22–25%, while in December–January it falls 4-fold (SolarGIS, 2020). Wind generation has the opposite seasonality — an average of 20% in summer and 40–45% in winter — but does not fully compensate for the decline in solar output. As a result, in winter, when the load is at its highest, the total contribution of RE sources may turn out minimal. Such differences increase the reserve requirements and require power exchange between countries: some have a surplus in summer, while others — in winter. It is estimated that with a share of variable RE sources >20% (*which is expected in Kazakhstan and Uzbekistan by 2030*), significantly more reserve capacity, flexible gas plants, storage systems, demand management, accurate forecasting and, most importantly, regional energy exchange will be required (IEA, 2024a).

Another challenge is unexpected surges in demand from new types of consumers. Previous planning was based on a smooth increase in load, but in the recent years new energy-intensive centres have emerged: crypto mining farms, data centres, and electric vehicles. Their impact is already being felt. For example, the migration of crypto miners to Kazakhstan after the ban on such mining in China in 2021 led to an 8% jump in electricity consumption in just one year, overloading the distribution networks and contributing to the emergency blackout in January 2022. The mass adoption of electric vehicles also brings new peaks in demand: for example, sales of electric vehicles in Kazakhstan grew 36-fold in 2024 thanks to imports of cheap models from China. If many cars are charged in the evenings, this will overload transformers and lines locally, requiring costly infrastructure upgrades (KPMG, 2024). Large data centres can consume tens of MW each: plans have already been announced to build a 200 MW data centre in Kazakhstan and several centres in Uzbekistan. Given that most data center capacity is planned in the US, China, and Europe, overall growth in the region may be limited, but for the relatively small power systems of Central Asian countries, the new loads could be significant (similar to cryptomining). These new loads could undermine the stability of power systems even if sufficient generation is available: distribution networks and operational power reserves will become the weak link.

Regional fragmentation exacerbates the reliability problem. After the collapse of the Central Asian Unified Energy System in the 1990s, countries lost their coordination and mutual assistance mechanisms. Now each state is forced to maintain its own reserve capacity during excessive peaks and emergencies, instead of sharing reserves with its neighbours. This duplicative approach is less efficient and more expensive. The limited capacity of inter-state/inter-regional lines (*for example, the only North-South corridor in Kazakhstan can transmit only 2,100 MW)* does not allow for free power exchanges within the region. Without grid upgrades, resilience remains low: local accidents or natural disasters lead to blackouts across entire regions, since the ability to quickly redistribute power across borders is limited.

Fragmentation of the regional power system led to a decline in cross-border exchanges

to 10%

of previous levels and intensified seasonal imbalances

Conclusion on energy security

Central Asia has a rich resource base, legacy energy system, and is developing new areas of generation, but structural changes are needed to ensure energy security. It is necessary to diversify generation mix — to develop RE sources, hydro and nuclear power, decentralized sources — and not to rely excessively on one type of resource. It is critically important to modernize aging infrastructure, otherwise the accident rate will increase, threatening the reliability of supply. Finally, to increase the resilience of the energy system, it is advisable to introduce flexible capacity (*flexible gas-fired power plants, storage systems*), digital grid control systems, and to restore regional integration and mutual assistance mechanisms. Without these measures, Central Asian countries risk facing growing shortages and disruptions, especially in the context of climate change and increasing demand volatility.

2.2. Energy accessibility (equity)

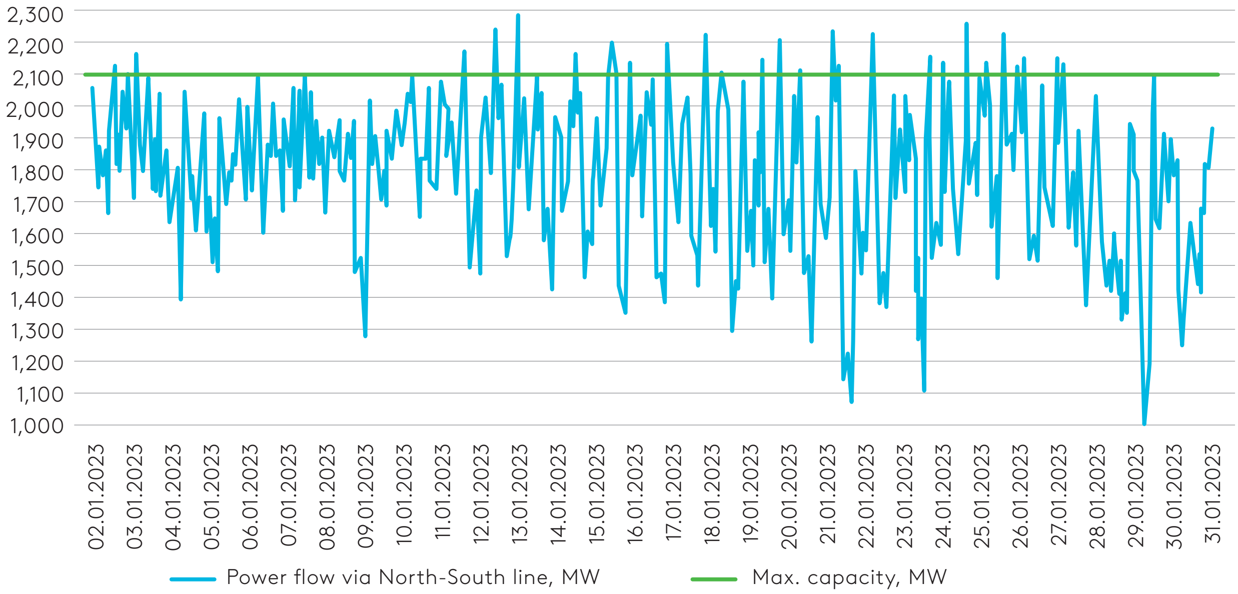
Energy accessibility and equity refer to guaranteed access for all segments of the population to modern energy services at an affordable price, as well as the fair distribution of the benefits and costs of the energy transition. In the context of Central Asia, three sub-aspects can be identified: physical access to electricity (*universal electrification and quality of supply*), affordability (*tariff policy, subsidies*), and social justice during the transition (*minimizing the impacts of decarbonization on vulnerable groups and regions*).

Accessibility and quality of energy supply

The Central Asian countries inherited from Soviet times a relatively high level of electrification. Formally, almost all settlements in the region have electricity, and the share of the population with access to electricity is close to 100% (World Bank, 2023). However, nominal accessibility is not always equivalent to actual accessibility. In remote rural areas, there are interruptions and a reduced quality of energy supply, especially in winter. For example, in the mountain villages of Tajikistan and Kyrgyzstan, poorly developed networks lead to frequent power cuts during cold spells. People are forced to limit their consumption for basic needs, despite the availability of power lines. Thus, energy poverty in the region manifests itself not so much in the lack of connection as in the unreliability of services and the inability of some households to source enough energy for a comfortable life.

The problems begin with the geographical gap between generation and consumption centres. Historically, large power plants in Central Asia were not located where most consumption is concentrated. The remoteness of generation areas from loads leads to increased transmission losses, network overloads, and hinders the integration of new RE capacities. Sometimes, electricity simply does not reach consumers in the required volume and quality. For example, in Kazakhstan, the power system is effectively divided into three isolated zones: North, South, and West. The connections between them are weak: the capacity of the North-South trunk line is limited to 2,100 MW. As a result, there is a chronic shortage of power in the south of the country, while there is a surplus in the north (*where large coal-fired power plants are located*). In Uzbekistan, most new solar and wind power plants are being built in the sunny south and west (*Navoi, Bukhara, and Surkhandarya regions*), while the main load centres are in the northeast (*Tashkent and the Fergana Valley*). The situation is similar in Kyrgyzstan and Tajikistan: most of the hydroelectric power plants are in the south, while most of the consumption is in the north; energy transmission between regions is hampered by mountainous terrain and seasonal fluctuations in water flow. Promising sites for solar and wind farms are also located far from existing grids and cities, requiring the construction of new power lines.

↓ Figure 12. Typical load on the North-South transmission line in January in Kazakhstan, MW



Sources: QazaqGreen, Huawei (2025).

Governments are aware of the problem and are taking steps to improve the quality of supply. Kazakhstan is implementing a program to modernize distribution networks and install smart meters, aimed at reducing interruptions and losses (KEGOC, 2025). In Uzbekistan, following the 2020–2022 energy crisis, investments are being made to expand network capacity in the Fergana energy hub and southern regions. Kyrgyzstan and Tajikistan, with the support of international financial institutions, are upgrading transformers and power lines to reduce the gaps between southern generators and northern loads. In addition, the development of decentralized generation is seen as a way to improve access: the construction of small hydropower plants and solar stations near remote consumers reduces dependence on long networks. The adoption of rooftop solar panels, small hydropower plants, and hybrid energy systems for rural areas has begun on a pilot basis (UNDP, 2022a).

Nevertheless, significant differences in supply reliability between urban and rural areas remain. To achieve energy equity, Central Asian countries need to ensure that every consumer has not only a connection to the grid, but also a sustainable energy supply with sufficient capacity. Addressing the issue of quality is particularly important given the region's extreme temperatures: reliable heating in winter and air conditioning in summer are a matter of survival. This implies further upgrading of local networks, adequate power backup (*e.g., with diesel generators or battery systems in isolated areas)* and the development of microgrids.

Energy affordability and tariff policy

The electricity sector is considered a socially significant sector, and tariffs often are kept artificially low in order to ensure affordability. Central Asia has some of the lowest electricity prices in the world: for example, the average tariff for households in Kazakhstan in 2024 was around 4 US cents/kWh, while the global average was 17 US cents/kWh. In Tajikistan and Kyrgyzstan, tariffs for the population are even lower. These measures ensure high energy affordability and minimize household energy costs. Up to 2017 in Turkmenistan, electricity, along with gas and petrol, was provided to the population free of charge. These policies ensured high affordability: the share of household energy expenditure was minimal, and electricity was accessible to all. According to the WEC Energy Trilemma Index, Kazakhstan and Tajikistan, which are included in the ranking, received high scores for the Equity (*affordability*) component, precisely because of low prices and widespread electrification.

↓ **Table 4. Average electricity tariffs for the population in Central Asia, cents/kWh**

Country	Average tariff*	Comment
Kazakhstan	2.0	Differentiation by zone
Uzbekistan	4.8–7.7	Subsidized; gradual adjustment underway
Kyrgyzstan	1.6–2.0	One of the lowest tariffs in the world
Tajikistan	3	
Turkmenistan	<1.0	Electricity is practically free

Note: * as of July 2025
Source: EDB estimate based on public data.

Despite rising costs of power generation (*both renewable and conventional*) and the need for large-scale investments in grid modernization, Central Asian countries maintain relatively low tariffs for the population thanks to the high share of depreciated legacy power plants. Most thermal power plants built during the Soviet period have already fully recouped capital costs, so their current production costs are limited to fuel prices and operating expenses. This allows wholesale prices to be kept at around ten tenge per kWh, which is significantly lower than the unit cost of new gas, coal, or RE generation plant. The values presented in Table 5 reflect this effect: depreciated infrastructure forms the basis for cheap electricity, temporarily easing pressure on tariffs, although in the long term, the capacity of such stations will be insufficient and their upgrade will inevitably lead to an increase in costs.

↓ Table 5. Average wholesale electricity price of conventional and RE generation plants in Kazakhstan in 2024

	Volume electricity procured, bln kWh	Costs, bln KZT	Wholesale price, KZT/kWh
Conventional	68,5	882,8	**12,89**
RE	6,6	232,1	**34,80**

Source: "Financial settlement center for renewable energy sources" LLP.

The downside of the low tariff policy has been chronic underfunding of the industry and distortion of price signals. Strict tariff regulation and cross-subsidization — where losses from cheap electricity for the population are covered by other types of consumers — has led to the accumulation of debt by energy companies and the postponement of investments in modernization. Tariff revenues often cover only 40–60% of the cost of services in Central Asia. In Kazakhstan, energy companies have indicated that current prices do not provide a return on investment, with the result that approximately half of the infrastructure is being operated beyond its useful life without the necessary upgrades.

Tariffs below cost recovery level remain a key barrier: low electricity tariffs undermine the sector's investment attractiveness

The lack of funds leads to infrastructure degradation and increased accidents. Moreover, distorted prices have encouraged irrational consumption: when electricity is cheap, consumers have no incentive to conserve it, and the load on the grid grows excessively. In Turkmenistan, where energy was free for an extended period, per capita consumption was abnormally high, with some of the world's highest grid losses. Such developments have undermined the financial stability of the sector, which has exhausted the reserves built up during the Soviet era and is now forced to modernize urgently, requiring huge investments and a return on those investments. Non-market regulation reduces the attractiveness of the sector for investors and donors.

In recent years, Central Asian countries have been taking steps to reform the tariff and institutional architecture of the power sector. Most countries in the region have set out in their strategic documents the goal of gradually establishing competitive electricity markets. A competitive model has the potential to contribute to the formation of more transparent price signals, which allow the generation expansion and network infrastructure to be synchronized with changing supply and demand structures.

During the transition period, a number of countries in the region are using centralized electricity procurement mechanisms, including a single buyer model. Such mechanisms tend to play a stabilizing role during the reform of the industry, smoothing out price fluctuations and reducing the short-term social risks associated with the introduction of new capital-intensive generating capacities. In addition, centralized models can help reduce investment risks in the early stages of developing new technologies, including RE sources.

The experience of Kazakhstan and Uzbekistan (Website of the President of Uzbekistan, 2022) shows that centralized electricity procurement models can ensure the controlled integration of new generation sources and help maintain the predictability of tariff dynamics. At the same time, international experience shows that the long-term dominance of centralized schemes can limit the formation of market price benchmarks and reduce the transparency of the cost structure in the power sector. In the context of growing investment needs, including the development of flexible capacity, energy storage, and grid infrastructure modernization, the availability of clear price signals is particularly important for investment decisions.

In the Kyrgyz Republic, the formation of centralized mechanisms to support renewable energy sources is in its early stages and is aimed at reducing payment risks and stimulating private investment in new generation projects. Such instruments can play an important role in market development, but in the long term, their effectiveness will largely depend on their ability to integrate into a broader competitive market model.

As the complexity of the region's energy systems increases and the share of variable generation grows, the importance of competitive markets tends to increase. The development of bilateral contracts, electricity exchange trading, balancing markets, and independent tariff regulation potentially contributes to a more efficient allocation of investment resources. In such conditions, market prices can serve as an indicator of capacity shortages or surpluses, creating economic incentives for the development of new generation facilities, energy storage technologies, and demand management solutions.

Competitive markets can play a special role in the context of RE integration. International experience shows that the introduction of dynamic pricing elements that reflect changes in load and generation costs at different times can increase the efficiency of existing capacity utilization and stimulate adoption of demand response technologies. At the same time, the success of such reforms largely depends on the consistency of their implementation, the level of institutional maturity of the sector, and the availability of effective consumer protection mechanisms.

Overall, the move towards economically feasible tariffs has begun, but is progressing cautiously. For energy equity, it is important to find a balance: to ensure the financial sustainability of the sector (without which it will not be able to reliably supply consumers in the future) and maintain the affordability of energy for the people. This can be achieved through targeted social policies — support for specific groups, rather than universal subsidies. In the long term, transparent tariff regulation, independent regulators, and competition in the markets should bring prices to market levels, while the share of household expenditure on electricity will remain acceptable thanks to income growth and support measures. The experience of European countries shows that high nominal tariffs can co-exist with high energy equity if targeted subsidy mechanisms and energy efficiency improvements are implemented.

Just Transition and social aspects

The concept of a "just energy transition" (*known as Just Transition*) is becoming increasingly important for Central Asia as decarbonization progresses. Regional economies, especially Kazakhstan and Uzbekistan, are heavily dependent on the extraction and export of fossil fuels — the fuel and energy sector accounts for up to 15–20% of GDP and is a main source of foreign exchange inflow. A rapid phase-out of coal, oil, and gas without a well-thought-out alternative threatens social upheaval: job losses, falling incomes in company towns, loss of budget revenues, and even a decline in energy security. Therefore, the transition to low-carbon energy must take social justice into account — that is, the costs should be borne primarily by those who are better able to bear them, and vulnerable groups should receive support.

For Central Asian countries, a just transition means supporting the workforce and regions that depend on the fossil fuel and adjacent industries. In Kazakhstan, for example, coal mines and thermal power plants are concentrated in the Karaganda and Pavlodar regions; thousands of people in these regions are employed in the coal industry. Decarbonization plans envisage the gradual closure of inefficient coal-fired power plants. Pilot projects under the Just Transition program are already being implemented. These include developing plans to diversify the economies of company towns, creating new industries beyond coal mining, and stimulating small and medium-sized businesses in these areas. A mandatory element is the retraining of workers: miners and energy workers should be trained in new vocations that are in demand in new economy. Such retraining is supported by both the state and international organizations. It provides coal regions with vocational training programs and tools to support local small and medium-sized businesses (microloans, small grants, incubation), which contributes to economic diversification and the creation of new jobs (World Bank, 2021; ILO, 2024).

Another aspect is the protection of vulnerable consumers during reforms. As noted, tariff increases are inevitable for the sector's sustainability, but it is important that low-income households are not left without the energy they need. A just transition involves targeted subsidies for electricity and heating, low-interest loans for the installation of energy-efficient equipment, assistance in replacing coal stoves with electric or gas heating, etc. (UNDP, 2022b). Such measures are already being implemented: Uzbekistan, in addition to social norms for electricity, provides preferential loans to the population for solar water heaters and home insulation; Kazakhstan is developing a voucher mechanism for low-income families. These tools make it possible to carry out reforms without worsening the basic living conditions of the most vulnerable groups.

Finally, equity also applies to the distribution of benefits from economic activity. Large energy projects (*hydroelectric power plants, resource extraction sites, large solar/wind farms*) must be implemented with the interests of local communities in mind. The international principle of FPIC (*free, prior, and informed consent)* is increasingly mentioned in the context of investments in RE: the construction of large solar plants or wind farms should bring jobs and infrastructure development at the local level, not just electricity to the central grid. In Central Asia, little attention has been paid to this so far, but there are some early examples: in Kazakhstan, some foreign RE investors are financing social projects for the local population in the areas where the plants are located (EBRD, 2022).

Conclusion on energy equity

Central Asian countries have managed to maintain high formal energy accessibility for the population, but at the cost of financial instability in the sector and uneven service quality. The task for the future is to ensure a reliable energy supply to all consumers, while bringing prices to an economically justified level. This requires a delicate balancing act: tariff reforms should be accompanied by targeted social support, and the energy transition by development program for the affected regions and workers. Only in this case will the transition to a new energy model be socially sustainable and receive public support instead of resistance.

2.3. Environmental sustainability

Environmental sustainability in energy sector means the ability to meet energy needs while minimizing negative impacts on the environment — locally (*air, water, and landscape pollution*) and globally (*greenhouse gas emissions*). The environmental aspect is particularly relevant for Central Asia: on the one hand, the region is suffering from the effects of climate change (*rising temperatures, more frequent droughts, melting glaciers, etc.)*, and on the other, it itself contributes significantly to global CO_2 emissions due to the predominance of carbon-intensive industries. Within the environmental component, we will consider four aspects: decarbonization (*reduction of greenhouse gas emissions)*, development of low-carbon generation (*RE sources, nuclear power, etc.)*, improvement of energy efficiency and adaptation to climate change, and the water-energy balance.

Decarbonization and emission reduction

The power sector remains the largest source of GHG emissions making it critical for achieving climate goals

The energy sector in Central Asia has historically been focused on fossil fuels, which is why the economies are highly carbon-intensive. Kazakhstan and Uzbekistan are among the largest CO_2 emitters in Eurasia due to the burning of coal and gas in the power and industrial sectors. Kazakhstan's CO_2 emissions per unit of GDP are among the highest in the world, largely because around 65% of its electricity is generated from coal. In Uzbekistan, electricity and heat generation are based on fossil gas, and equipment is inefficient, leading to high CO_2 and methane emissions. Turkmenistan, with its vast natural gas reserves, has poor control over methane leaks during extraction and transportation — according to the IEA, the country is in the top 5 in terms of CH_4 emissions, which dramatically increases its GHG footprint. Kyrgyzstan and Tajikistan have almost carbon-free electricity generation (*thanks to hydropower*), but coal (*for heating homes*) and petroleum products still play a major role in the final energy consumption of these countries, resulting in significant emissions in the non-power sector.

The decarbonization of the energy sector in Central Asia is a multi-level, long-term process closely linked to the economic structure of the countries. For decades, coal, oil, and gas have been the basis of electricity and heat supply as well as key contributors to the economy (*a significant part of GDP, exports, and employment*). In Kazakhstan and Uzbekistan, coal and gas generation provide 70–80% of electricity, and in large cities, centralized heat supply from combined heat and power (CHP) plants covers 60–80% of heat demand (KAZENERGY, 2019). Given the harsh climate and high energy intensity of the economy, there are currently no mature and affordable alternatives to such cogeneration systems. In addition, Central Asian countries are entering the energy transition with a low baseline for RE, limited access to capital, and worn-out infrastructure (IRENA, 2023a). Low tariff policies, which have kept electricity and heat prices low, are hindering modernization and the adoption of energy-efficient technologies.

In such conditions, a realistic decarbonization strategy could envisage the development of all available energy solutions. This means combining the modernization of conventional generation along with the expansion of new clean generation. On the one hand, there is a need to upgrade existing coal and gas power plants, to increase their efficiency, equip them with modern purification systems and, where possible, prepare them for possible adoption of CO_2 capture and storage (CCS) technologies. This will make it possible to reduce the specific emissions of existing facilities during the transition phase without closing them down immediately. On the other hand, large-scale investments are needed in RE sources — solar and wind power plants, as well as hydropower where resources are available. Technological pluralism is the key to reducing carbon intensity without threatening energy security.

Excessively rapid and forceful decarbonization poses risks of tariff increases, job losses, and reduced energy security, especially in extractive regions (UNESCAP, 2021). At the same time, delays in decarbonization are associated with external and internal costs. One of the external factors is the adoption of the EU's Carbon Border Adjustment Mechanism (*CBAM)*, which should affect exports of energy-intensive goods from Central Asia (*steel, ferroalloys, cement, aluminium)*. Without reducing the carbon intensity of production, countries in the region risk losing their competitiveness and access to European markets (European Commission, 2024). In addition, slow progress deprives them of advantages: it limits access to green investments, climate funds, and new financial instruments (*e.g., green bonds)* (EBRD, 2024).

A successful transition to low-carbon energy requires balanced and equitable policies that combine climate goals with economic and social realities. Practical steps towards decarbonization in Central Asia focus on several areas: modernizing existing power plants, gradual phase-out of coal, developing low-carbon technologies and developing an emissions trading system. Modernization involves reducing specific emissions at existing thermal power plants by installing more efficient boilers and turbines, flue gas cleaning systems, and improving combustion control. These measures make it possible to reduce CO_2 emissions per unit of output and reduce air pollution (SO_2, NO_x, *dust)*, which is important for public health. A complete phase-out of coal as a fuel is a more distant prospect. IEA scenarios envisage the end of coal combustion in developed countries by 2030–2040, but such a rapid phase-out is unrealistic for Kazakhstan and Uzbekistan (IEA, 2021). Instead, the plan is to decommission the oldest and most inefficient coal-fired power plants by 2035–2040, replacing them with gas and RE sources. Kazakhstan intends to reduce the share of coal in electricity generation to 34% by 2035.

Decarbonization in Central Asia should be seen as a gradual transformation of the energy and economic landscape. Success will require maintaining a balance between climate commitments, energy security, and social accountability, without sacrificing one for the sake of another. Implementing an equitable and gradual transition model will enable countries to reduce emissions while increasing competitiveness, attracting investment in new technologies, and ensuring sustainable development.

Low-carbon generation

Expanding RE is central to improving environmental sustainability. Central Asia has enormous RE potential: the steppes and deserts of southern Kazakhstan and Uzbekistan have high solar insolation; the mountainous regions of Kyrgyzstan and Tajikistan have significant untapped hydropower resources; and the Caspian coast of Turkmenistan and Kazakhstan has strong winds. Awareness of this potential has come relatively recently, and now all Central Asian countries are setting ambitious targets for the adoption of RE sources.

The development of RE is already yielding results. In Kazakhstan, the installed capacity of solar and wind power plants has grown from zero in the 2010s to 3.2 GW in 2025 and continues to increase. The share of RE in electricity production has reached 6–7%. Uzbekistan, which started later, is showing rapid growth: in 2023–2024, the first large solar farms were commissioned with the participation of foreign investors, and wind farms are being built on the plateau near Nukus and in the Jizzakh region. In the first half of 2025, RE sources generated over 22% of Uzbekistan's electricity (*of which solar and wind power accounted for approximately 12%)*. Kyrgyzstan and Tajikistan are actively developing the RE sector: the Rogun HPP (*3,700 MW)* is being completed, Kambar-Ata-1 (*1,860 MW)* is planned, and hundreds of MW of solar power plants have been announced for the near future. Turkmenistan has begun construction of its first large solar power plant (*100 MW)* and is exploring wind potential on the coast. Thus, over the past ten years, RE sources have come to play a significant role in the energy systems of these countries.

The main obstacles to the large-scale deployment of RE sources are infrastructural and institutional constraints. First, there are problems with integrating RE sources into the grid: the variable generation of solar and wind power plants requires higher flexibility in power systems, which is currently difficult to achieve in Central Asia. Without grid modernization, a share of RE sources exceeding 20% could cause interruptions. Many of the best sites for RE sources are located far from load centres (*for example, the desert regions of Uzbekistan are far from Tashkent, and Kazakhstan's wind locations are far from industrial centres)*. New power lines are needed; otherwise, RE capacity will be of limited use. The investment climate and market mechanisms require constant government support. The examples of Kazakhstan and Uzbekistan with their auction mechanism and power purchase agreements (PPAs) has proven effective in scaling up RE. Kyrgyzstan and Tajikistan are still shaping a regulatory framework for RE as an interest in investing is emerging.

Central Asia is only at the beginning of its journey to unlock the full potential of RE. A several-fold increase in solar and wind power capacity is expected in all countries over the next decade. This will significantly improve the power sector's environmental performance, but will require immediate investments in grids and storage facilities, as well as regional cooperation. If the scaling materializes, RE will become a driver of sustainable development. It will provide clean energy for economic growth and universal access to electricity even in remote areas, and reduce greenhouse gas emissions.

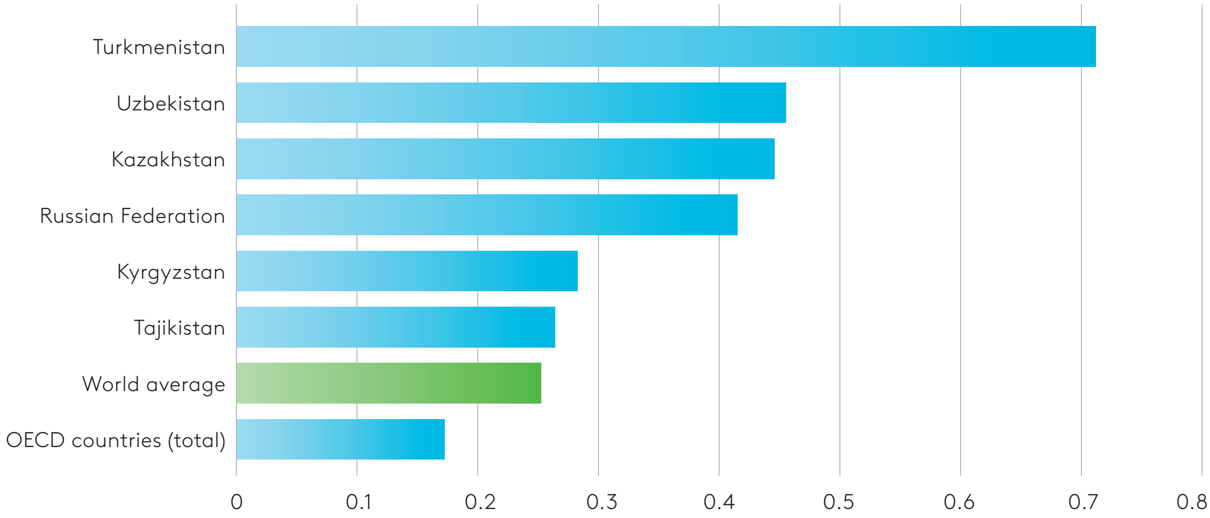
Energy efficiency

The energy profile of Central Asia is characterized by extremely high energy intensity of the GDP, which on average exceeds global and OECD averages by 2–3 times (IEA, 2024b). The gap is largely attributed to outdated, Soviet-era generation and distribution infrastructure, where network losses can reach 20%. The situation is exacerbated by historically low, subsidized electricity tariffs, which have served as a social support tool for decades while erasing the incentives for modernization and energy saving. In the residential sector and heavy industry, the absence of market-price signals discourages improvement of thermal insulation and introduction of energy-saving technologies. Thus, the region has encountered an "inefficiency trap": economic growth requires a disproportionate increase in energy production, which, given the degradation of generation assets, creates critical risks for energy security.

Amid rapid population growth and climate change (*in particular, water shortages, which are critical for hydropower in Kyrgyzstan and Tajikistan*), Central Asian countries are forced to shift from extensive capacity expansion to intensive energy saving. So the region's energy efficiency strategy is being transformed from a peripheral environmental issue into a key factor in macroeconomic stability. Kazakhstan has approved new standards for building insulation, and state-funded housing modernization programmes are being implemented in large cities. In 2022, Uzbekistan passed a law on rational energy use and introduced mandatory energy audits for large enterprises and budgetary organizations. In Kyrgyzstan and Tajikistan, with the support of the EBRD, credit lines are available to small businesses and households for the purchase of energy-efficient equipment. However, reports emphasize that the measures used so far cover only a small part of the potential opportunities (Copenhagen Centre on Energy Efficiency, 2015). Barriers include a lack of funding, weak enforcement of regulations, and a lack of energy service companies. Climate funds and international loans are essential for advancing the initiatives.

Measures to improve efficiency at relatively low cost have a rapid environmental impact. The main areas of focus are: modernization of heating systems, insulation of buildings, and adoption of energy efficiency standards and equipment in enterprises. In Central Asia, a significant proportion of energy is used for heating (*cold winters, old heating infrastructure*), so the upgrade of heating networks, replacement of old boiler houses, and installation of metering and temperature control devices can reduce heat loss by 20–30%. In the residential sector, insulating apartment buildings, installing energy-efficient windows, switching to LED lighting and A-rated household appliances can yield significant savings. For example, UNDP pilot projects in Uzbekistan have shown that comprehensive thermal modernization of a single apartment building reduces its energy consumption by 30–40%.

↓ **Figure 13. Emissions intensity per unit of GDP, kgCO_2/USD**



Source: UNECE, 2024.

In industry, many factories (*metals, chemicals, cement*) lag behind global benchmarks for energy efficiency by 20–50%. Their phased modernization — installation of new energy-saving equipment, waste heat recovery, process optimization — can significantly reduce the load on the power system and reduce emissions.

The next key element in improving efficiency is reducing electricity losses in T&D networks. According to IEA (2024b) estimates, approximately 60% of the region's networks are outdated, which is confirmed by the level of losses: from 11% in Kazakhstan to 20% in Tajikistan, which is 2–3 times higher than the average for OECD countries. In Kazakhstan, depreciation of T&D lines is estimated at 66% (Министерство энергетики РК, 2022), while in Uzbekistan there are more than 33,000 obsolete transformers and 122,000 km of networks, where annual losses reach 14 billion kWh (Kun.uz, 2023). Massive equipment depreciation leads to an increase in accidents and the risk of outages, which in turn requires backup generation and limits the efficiency of power systems.

Electricity losses in the region reach up **to 20%,** increasing sector's costs and GHG emissions and inhibiting the energy transition

↓ **Table 6. Losses in electricity transmission and distribution network in Central Asia (2023–2024)**

Country	Year of data	T&D losses, %	Estimated losses, billion kWh	OECD average,%
Uzbekistan	2023	17.8	14	6.3%
Tajikistan	2024	20	4.5	
Kyrgyzstan	2024	15	2.6	
Kazakhstan	2024	11.2	13.5	

Sources: National Statistical Committee of the Kyrgyz Republic, Ministry of Energy and Water Resources of the Republic of Tajikistan, EU SECCA, Ministry of Energy of the Republic of Kazakhstan.

High losses are a common and critical challenge for all countries in the region. They directly affect the availability of energy and increase the need to build new power plants, effectively acting as a hidden barrier to the energy transition. Reducing losses is often the cheapest and most environmentally responsible source of energy, as every kilowatt-hour saved is essentially "green": it reduces the need for additional generation and emissions. Therefore, combating losses is one of the priority ways to improve the energy efficiency and sustainability of the Central Asian energy sector. Energy efficiency is also fundamental to the integration of RE sources: without reducing baseline consumption and upgrading networks, large-scale deployment of solar and wind power will not be able to cover the region's projected energy deficit.

The impact of climate change and the water-energy nexus

Central Asia is among the regions most vulnerable to the effects of climate change, which are occurring there faster than the global average (Vinokurov et al., 2022b). A key risk is the exacerbation of the water-energy nexus: climate change affects water resources, that in turn affect energy infrastructure (*hydroelectric power generation, cooling of thermal power plants)* and agriculture in these countries.

Water shortages due to warming are already becoming a reality (Vinokurov et al., 2023). Rising temperatures and changing precipitation patterns are leading to more frequent droughts and reduced river flows, which may directly affect hydropower generation.

Climate change may increase the volatility of hydrological resources, raising risks for countries with a high share of hydropower generation

Another effect of climate change is the increase in the temperature of rivers and reservoirs needed to cool thermal power plants. For example, in the summer of 2025, Switzerland shut down the reactors at the Beznau nuclear power plant, and France reduced the capacity of the Golfech nuclear power plant due to excessively high river water temperatures that violated environmental cooling standards.

A World Bank study (2024) modelled how the output of the largest hydropower plants in Central Asia will change under different climate scenarios. The results showed an overall negative trend: for most reservoirs (*Toktogul, Kambarata, Nurek, etc.),* a decrease in available water volumes and, accordingly, electricity generation is expected in almost all scenarios, especially in conditions of severe warming and drought. Even in the optimistic scenario (*a wetter and warmer climate*), most facilities continue to show a downward trend in production. The data highlights the climate vulnerability of the hydropower infrastructure in Central Asia: the decline in reservoir levels reduces the ability to accumulate runoff in winter and distribute water evenly in summer.

↓ **Figure 14. Change in electricity generation from hydropower plants of the corresponding reservoirs depending on climate change scenarios, GWh**

Reservoirs	1 Current	Arid	Central	Hot_dry	Warm/wet	Warm/wet+
All Reservoirs	33,847	–31%	–23%	–28%	–21%	–5%
Andijan Reservoir	316	–52%	–38%	–46%	–37%	–37%
Baipaza cascade	4,684	–35%	–29%	–29%	–27%	4%
Charvak reservoir	3,013	–29%	–13%	–27%	–16%	–16%
Chirchik_cascade	1,135	–14%	–9%	–13%	–11%	–11%
Farkhad reservoir	574	–35%	–23%	–33%	–24%	–23%
Kambarata_II	527	–61%	–50%	–65%	–33%	–33%
Kayrakkum reservoir	485	–25%	–18%	–25%	–17%	–17%
Kurpsaiskaja	2,639	–28%	–20%	–31%	–17%	–17%
Nurek reservoir	11,002	–28%	–23%	–21%	–22%	13%
Shrdara reservoir	621	–17%	–12%	–18%	–12%	–12%
Tashkumyrskaja_cascade	3,082	–28%	–19%	–30%	–16%	–16%
Toktogul reservoir	4,595	–35%	–28%	–39%	–21%	–21%
Tyuyamuyun reservoir	1,009	–40%	–32%	–36%	–26%	–11%

Source: World Bank (2014).

One of the solutions is to develop RE sources as a way to reduce tensions in the water-energy nexus. If the downstream countries (*Uzbekistan, Kazakhstan, Turkmenistan)* become less dependent on hydropower from the upper basins in summer by generating their own solar and wind power, and the countries in the upper basins (*Kyrgyzstan, Tajikistan)* obtain alternative sources of energy in winter (*when hydropower generation falls)*, this will help to balance interests. USAID modelling (2024) has shown that cooperation and investment in irrigation modernization can significantly reduce water shortages in the lower basin of the Amu Darya River, while scenarios for achieving national RE targets would cover projected electricity demand and reduce CO_2 emissions by 40% by 2050, with RE accounting for 30–35% of the total. It means that the development of RE and regional cooperation can partially ease tensions and change the dynamics of relations. To achieve this, however, it is necessary to move from bilateral agreements to the creation of a supranational regulator with powers to coordinate and manage water and energy resources.

In addition to collective efforts, each country is taking steps to adapt its energy sector to climate risks. In the upstream countries (*Kyrgyzstan, Tajikistan),* it is critically important to have backup energy sources in case of low water levels; this means building flexible power plants (*e.g., gas-fired*), solar/wind power plants along with energy storage. If they manage to partially replace hydropower production in winter with new RE sources or gas plants, they will not have to release as much water for power generation. In turn, Kazakhstan and Uzbekistan can actively develop small scale RE sources and improve water efficiency (*reduce losses in irrigation networks, adopt drip irrigation)* to reduce their dependence on summer river flows.

Conclusion on environmental sustainability

The environmental sustainability of Central Asia's energy sector can only be achieved through a comprehensive approach: gradual decarbonization, wide adoption of RE sources, large-scale energy efficiency improvements, and adaptation to inevitable climate change. The region has all the necessary resources — solar, wind, water, and technological solutions — to transition to a more sustainable energy model. However, success will depend on political will and cooperation: the environment knows no borders, and problems such as melting glaciers or dust storms affect several countries at once. A sustainable energy future for Central Asia is only possible if countries jointly balance the key components of the energy trilemma — security, equity, and the environment — without sacrificing one for the other, but rather developing coordinated development strategies.

CHAPTER 3.

TECHNOLOGICAL SOLUTIONS FOR A BALANCED ENERGY TRANSITION

(prepared with support of IRENA)

The energy transition from fossil fuels to low-carbon generation and RE is becoming crucial for Central Asian countries. The region still relies heavily on fossil fuel resources. Simultaneously, global trends point to rapid growth in the share of clean energy: the combined share of low carbon generation (*renewables and nuclear)* reached 41% of global electricity production in 2024 (IEA, 2025b). Wind and solar energy have become very cost-competitive sources of new generation, shifting the focus of energy transition issues from the cost of technologies to systemic constraints — insufficient grid infrastructure and energy system reliability. These challenges are also relevant for Central Asia: deteriorating grids, limited flexibility, and dependence on water resources complicate the integration of new energy sources.

In these conditions, a balanced energy transition in Central Asia requires a comprehensive approach that takes into account the specific characteristics of each country. The region includes both major fossil fuel exporters (*Kazakhstan, Turkmenistan)* and countries with predominantly hydropower (*Tajikistan, Kyrgyzstan)* and others with rapidly growing demand for electricity (*Uzbekistan)*. There is no single universal solution: a rational combination of technical and technological options is needed to simultaneously ensure energy security, sustainable development, and the fulfilment of climate commitments.

This chapter examines current status and trends for main energy technologies — from coal, gas, and nuclear generation to renewable sources (*solar, wind and hydro energy*) — as well as new technologies such as hydrogen, bioenergy and carbon capture. Special attention is paid to tools for increasing the flexibility of energy systems — energy storage systems, electric vehicles, and demand management. The analysis of global trends in each of these areas is supplemented by an assessment of the applicability and prospects of technologies in Central Asian countries (*Kazakhstan, Uzbekistan, Tajikistan, Turkmenistan, and Kyrgyzstan)*, taking into account their resources and needs.

The energy technologies are analyzed through the lens of global trends, capital and operating costs, as well as environmental and technological risks. A comprehensive analysis provides a holistic understanding of global trends and allows to assess applicability of individual solutions in Central Asia.

Such analysis should help to identify the most rational trajectories for diversifying the energy balance, balancing the development of conventional and low-carbon generation, and assessing which public policy instruments would be most effective in stimulating investment and reducing systemic risks.

↓ **Table 7. Average parameters for various generation technologies**

Technology/ Fuel	Total installation cost, USD/kW	LCOE, USc/kWh	GHG emission factor, gCO_2/kWh	Balancing capability
Onshore wind energy	1000	3.4	12	No
Solar energy	700	4.3	46	No
Offshore wind energy	2,800	7.9	12	No
Bioenergy	3,200	8.7	18	Low
Geothermal energy	4,000	6	45	Low
Natural gas	2,400	5–11	469	High
Oil (ICE)	2,200	7–15	840	High
Coal	4,000	7–17	1,001	Low
Nuclear power plant	6,000	8–25	16	Low

Sources: IRENA, 2025a; IPCC, 2011; EDB estimate.

3.1. Dispatchable generation

Dispatchable sources of electricity are those plants whose output can be quickly adjusted in line with the load schedule. Such plants are capable of supplying electricity on demand, thereby maintaining supply-demand balance in the power system. Traditionally, these include coal- and gas-fired thermal power plants, as well as hydropower and nuclear power plants. In recent decades, this category has come to include certain renewable and alternative technologies capable of providing constant or controllable generation, such as geothermal power plants and bioenergy. Below is an overview of each of these types of generation, their current status, development trends, and significance for the energy transition.

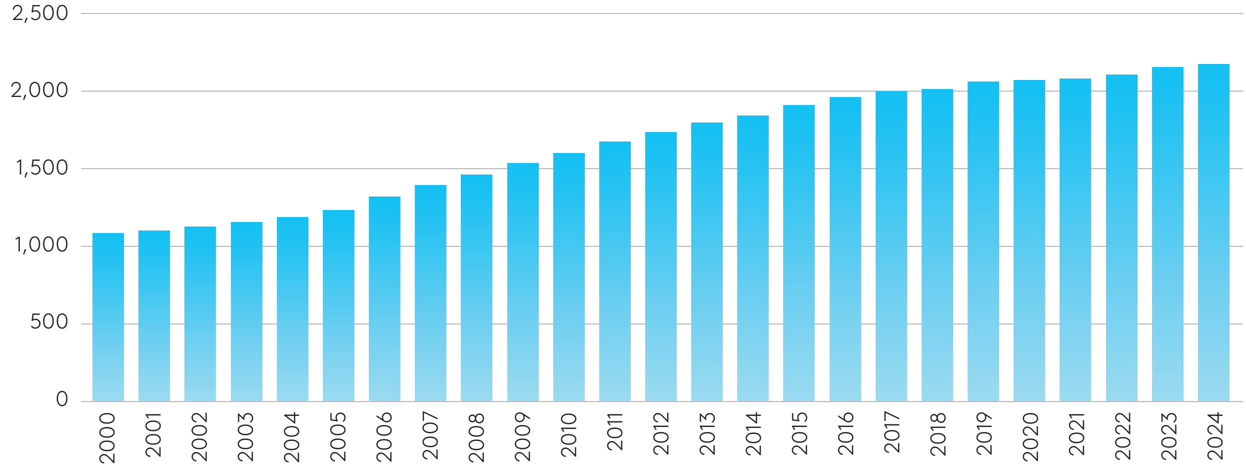
Coal-fired generation

Total coal-fired power capacity worldwide is stagnating since 2018 if China is excluded

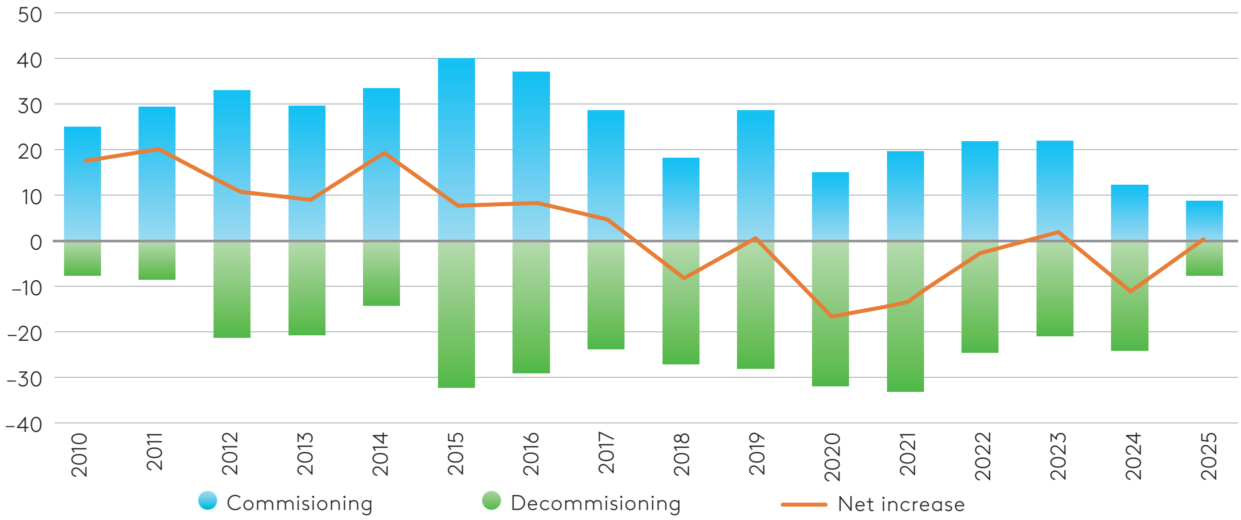
Coal-fired power plants have traditionally been one of the largest sources of electricity in the world. As of early 2025, coal accounted for approximately 33% of global electricity production, but in the first half of 2025, it lost its leading position to total combined RE generation (Ember, 2025). Coal generation has lost its growth momentum: the global installed capacity of coal-fired power plants is at 2,175 GW (*24% of total capacity)* and stagnating. The increase in new coal capacity in Asia is offset by the mass decommissioning of old plants in the Western countries. From 2015 to 2024, global coal-fired power plant capacity grew by only 13%, and in 2023, growth was only 2% — the lowest in decades. Excluding China, total global coal capacity has not increased since 2018 and has even declined in some cases. The largest economies (*the US, the EU, the UK*) are deliberately phasing out coal: for example, in the US, 9.7 GW of coal-fired units will be closed in 2023, and the largest energy companies have announced a complete phase-out of coal by 2035. In Europe, 4.2 GW were phased out in 2023, and a number of countries have completely closed coal-fired power plants or approved phase-out deadlines (*Germany — by 2038, Poland — 2049*). Simultaneously, Asian countries continue to operate and even build coal-fired power plants to meet growing demand and ensure energy security, primarily China (*>1,000 GW of installed capacity*) and India (*250 GW*). Nevertheless, global investment interest in coal is declining: international No New Coal initiatives have reduced the global project portfolio by 68% since 2015, indicating a growing consensus against new coal.

Modernization of existing coal, gas, and hydropower plants can be more cost-effective than their premature decommisioning

↓ Figure 15. Trends in installed capacity of coal-fired power plants in the world, GW



↓ Figure 16. Net increase in coal-fired generation capacity globally (excl. China), GW



Source: Global Energy Monitor, 2025.

Coal-fired power generation is characterized by high fuel consumption and the largest carbon footprint. The construction of modern ultra-supercritical coal-fired power plants costs approximately 4,000–5,000 USD per 1 kW of installed capacity. High CAPEX and carbon costs mean that the average LCOE for new coal-fired power plants is around 7–17 cents/kWh (*depending on the region and technology)* — significantly higher than that of RE sources. For example, the LCOE for solar and wind farms is currently in the range of 3–8 cents/kWh, meaning that coal energy is already more expensive (Lazard, 2025). The addition of carbon capture and storage (CCS) systems doubles the cost of projects: installing CCS with 90% efficiency increases the capital costs of a coal-fired power plant from approximately 4,500 to 7,500 USD/kW. In addition, CCS increases operating costs (*fixed O&M costs rise to 67 USD/kW per year)*. In regions with emissions charges, coal-fired power plants also incur carbon costs: at a CO_2 price of €80–90/tonne, the cost of generation increases by 30–40 USD/MWh (+3–4 USc/kWh), undermining the competitiveness of coal. Environmentally, coal is the most polluting source: total specific emissions exceed 1,000 gCO_2/kWh (*for comparison, gas has 469 g/kWh and wind has 12 g/kWh)*. These factors, as well as decarbonization policies, are forcing countries to gradually abandon coal, despite its role in energy security. Nevertheless, coal retains its position in the short term: in times of crisis (*e.g., gas price spikes)*, many countries have temporarily increased coal production to avoid energy shortages.

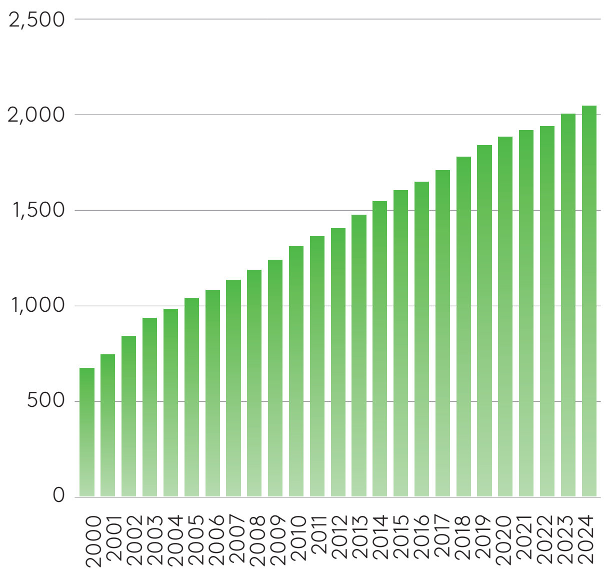
Despite the global trend towards reducing the role of coal, in many Asian countries it remains key to the stability of the energy system and the availability of electricity. In Central Asia, coal continues to play a significant role, especially in Kazakhstan, where coal-fired power generation has historically been developed for domestic needs and electricity exports. Simultaneously, there is growing interest in reducing the carbon footprint. Technologies for co-firing biomass at existing thermal power plants could provide a transitional path: partially replacing coal with biofuel allows emissions to be reduced without completely decommissioning the plants. Another approach is to equip some relatively new coal-fired units with CO_2 capture systems, which could potentially enable climate targets to be met without shutting down the plant. However, such projects require significant investment and effective support mechanisms (*carbon pricing, subsidies for "clean coal")*. For Central Asian countries, a more realistic scenario would be the gradual replacement of outdated coal-fired capacity with gas and renewables, while retaining some coal-fired generation as a reserve and modernizing the most efficient ones.

Gas-fired generation

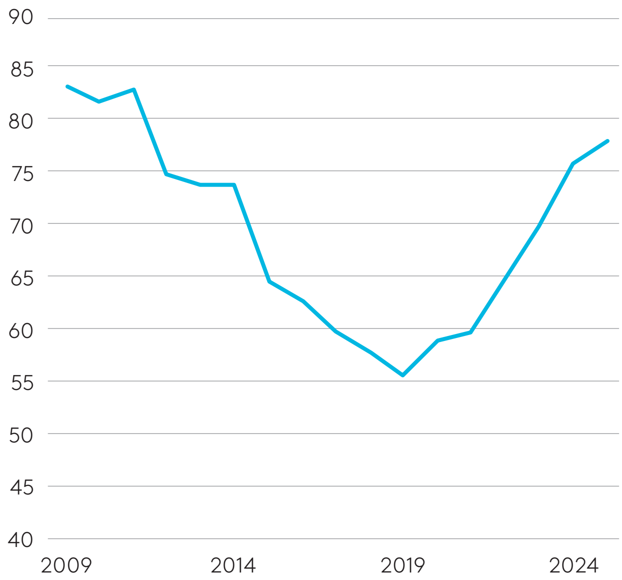
Natural gas power plants rank second in the world in terms of electricity generation, accounting for 22–24% of global generation. The total installed capacity of gas generation is estimated at 2,170–2,200 GW, which is comparable to coal. Gas plant are widespread due to their lower carbon footprint compared to coal, high flexibility, and relatively quick roll-out. In 2025, global gas-fired power generation continues to set records, although growth rates are moderate *(1–1.5% per year)*. Many countries view natural gas as a transitional fuel for the energy transition: with its help, coal emissions can be reduced and variable RE sources — be balanced.

The global geography of gas generation is shifting: most of the capacity growth is occurring in Asia, the Middle East, and developing economies, where gas-fired power plants are being built to replace coal and meet growing demand. For example, China has increased its gas fleet to 130–150 GW in recent years and has the largest portfolio of projects (*another +150 GW is planned)*. Southeast Asian countries are replacing cancelled coal projects with LNG plants. Gas dominates in the Middle East: Qatar, the UAE, and Kuwait generate more than 90% of their electricity from gas, and Saudi Arabia plans to increase the share of gas in energy mix to 70% by 2030. In developed economies, the growth of gas-fired generation is limited — it plays an increasingly auxiliary, peak-shaving role. In the EU, following the 2022 crisis, gas is seen as a potential source of reserve capacity: for example, Germany has planned 17 GW of new H_2-ready gas-fired units by 2030 to replace coal (Enerdata, 2023). In the US and the UK, gas-fired power plants are operating fewer hours per year, mainly coming online during peak loads. The trend is that by 2030, the average annual capacity factor of gas-fired power plants worldwide could decline by another 20–30%, reflecting their transition from base load to balancing sources.

↓ Figure 17. Trends in installed capacity of gas power plants worldwide, GW



↓ Figure 18. Trends in the LCOE of gas-fired electricity generation, USD/MWh



Source: Global Energy Monitor (April 2025), Lazard (2025).

The advantage of gas-fired generation is relatively low investment costs, high operational flexibility and quick deployment. Historically, the construction of combined cycle gas turbine *(CCGT)* units cost 1,100–1,300 USD/kW, while simple cycle gas turbine *(OCGT)* units cost 650–1,000 USD/kW, which is almost four times cheaper than equivalent coal-fired power plants. However, costs have risen in recent years: equipment shortages and inflation have pushed the CAPEX of new gas plants to 2,000–2,400 USD/kW in some regions (IEEFA, 2025). Against the backdrop of rising construction costs, the economics of gas projects are increasingly dependent on the fuel component. Gas prices can be highly volatile, as demonstrated by the 2021–2022 energy crisis, when spot prices in Europe soared to the equivalent of 250–300 EUR/MWh, making gas-fired electricity briefly the most expensive on the market. On average, gas prices in Europe rose more than sevenfold in 2022 relative to normal levels, leading to a decline in gas-fired generation and a temporary return to coal. Nevertheless, at moderate prices, gas-fired generation is competitive: the average LCOE of a new CCGT plant is estimated at 50–110 USD/MWh (*5–11 cents/kWh*), which is comparable to or lower than that of coal (*70–170 USD/MWh*). In addition, gas turbines have technical advantages for flexible operation: low minimum loads and fast start-up. Modern installations can reach full capacity in tens of minutes, which is extremely important when there are fluctuations in RE generation or sudden changes in demand. Gas plants provide valuable system services — inertia, frequency regulation, reserve capacity, and voltage support.

Natural gas remains the main source of flexible capacity in power systems with a high share of renewables

Gas turbines are the main source of balancing power in systems with high levels of solar and wind generation. Alternatives for covering peaks are still limited: hydropower is effective but geographically tied to rivers; battery storage is rapidly becoming cheaper, but its scale and storage duration are still inadequate; and demand management is in its infancy. Therefore, according to forecasts, by 2050, global fast-response resources must grow fourfold to compensate for the variability of RE sources. Until then, gas-fired power plants will remain a critical element of energy systems. A rapid abandonment of gas without ready alternatives carries the risk of a deficit in balancing capacity and problems with the reliability of electricity supply.

For Central Asian countries, natural gas is a key component of the energy system and a potential bridge to a low-carbon future. Gas-fired generation will remain important for the reliability of energy systems and for covering peaks, especially as the share of variable RE sources increases. Priorities could include improving the efficiency of gas-fired power plants (*CCGT with an efficiency of 55–60% and above*), reducing methane leaks during transportation, and integrating gas capacity into hybrid energy systems (*e.g., combining gas-fired power plants with renewables and storage facilities, where gas is used only for peak shaving and emergency backup*). These plants will become a kind of "insurance policy", ensuring reliability when there is no sun or wind. Kazakhstan, Uzbekistan, and Turkmenistan have significant natural gas reserves, which enables them to modernize and expand gas-fired plants relatively inexpensively to replace more polluting coal and ensure flexibility. New CCGT projects are being implemented in these countries, often with the support of financial institutions seeking to reduce the carbon intensity of regional energy systems.

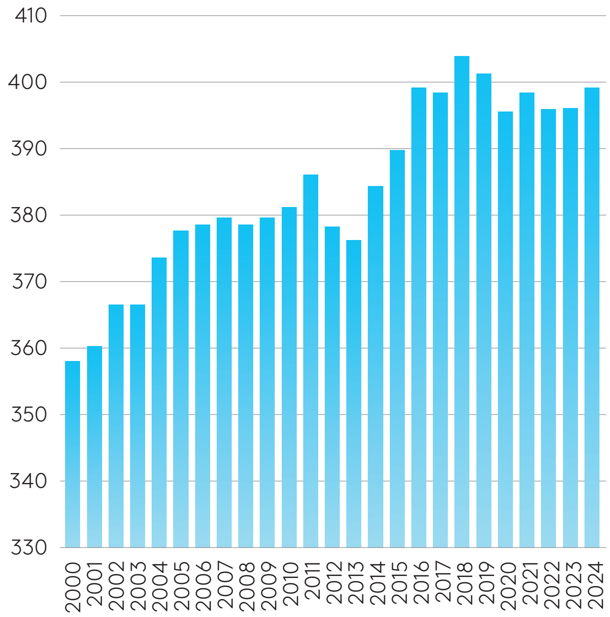
However, in the long-term (*2040–2050s*), it is necessary to take into account that gas is also a fossil fuel and its emissions may have to be reduced. Global experience shows that plants are being designed with the possibility of subsequent CCS installation or transition to hydrogen fuel. Here, Central Asian countries should pay attention to these technologies. For example, the Keadby-3 CCGT project is being implemented in the UK with a view to subsequently connecting a CCS infrastructure.

Nuclear energy

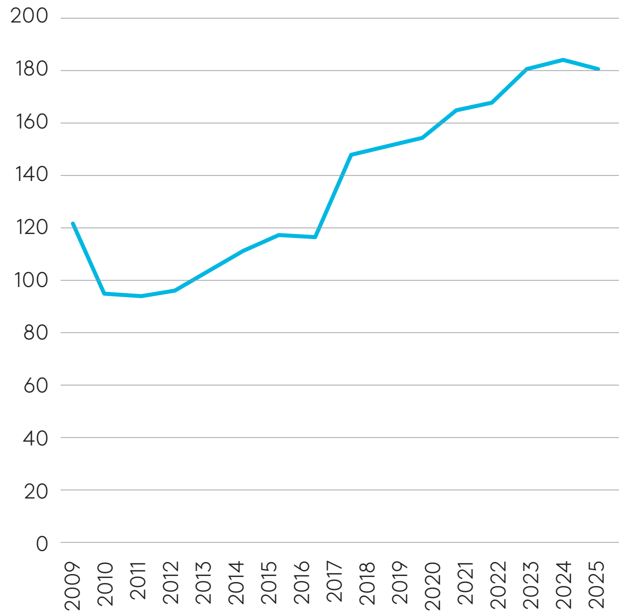
Since 2025, nuclear power is experiencing an institutional renaissance: there is growing interest from IFIs in the context of decarbonization, energy security, and power system resilience

Nuclear energy plays an important role in the global energy system today, remaining the second largest source of low-carbon electricity after hydropower. As of 2025, 31 countries operate approximately 440 power reactors with a total capacity of 400 GW, which accounts for approximately 9% of global electricity production. In 2024, nuclear power plants generated 2,778 billion kWh (Ember, 2025). Fourteen countries obtain more than 25% of their electricity from nuclear power plants; in France, this share reaches 70%, and in Slovakia and Hungary, around 50%.

↓ Figure 19. Trends in installed capacity of nuclear power plants worldwide, GW



↓ Figure 20. Trends in the nuclear power LCOE, USD/MWh



Source: Ember Electricity Data Explorer (2025), Lazard (2025).

The United States, France, China, Russia, and the Republic of Korea are the world leaders in nuclear power generation, accounting for over 70% of installed nuclear power capacity. The United States has the largest fleet (*94 reactors, 95 GW*) and produces about 30% of the world's nuclear power. France (*57 reactors, 63 GW*) generates 65% of its electricity from nuclear power plants. China is showing the highest growth rates:

since 1991, it has commissioned 57 reactors, with another 28 units (*near 30 GW)* under construction; once they are commissioned, China's installed capacity will exceed that of France. Thus, the nuclear industry is globally concentrated in a limited number of countries, although more than 30 states operate nuclear power plants.

Nuclear power generation is characterized by very high capital costs and a long construction cycle, but low specific operating costs and virtually zero emissions during operation. A modern turnkey high-capacity reactor costs an average of 4,000–8,000 USD per kW (*4–8 billion USD per 1 GW)* in developed countries. This amount includes design, equipment, construction, and commissioning, as well as financing costs (*interest on long-term loans)*. The cost of capital and the duration of the project are the key factors in the economics of nuclear power plants. With affordable borrowing costs, nuclear energy can be competitive: for example, at a discount rate of 3% per annum, the estimated LCOE of nuclear power plants is lower than that of any other source. But at 10% per annum, the cost of nuclear generation increases significantly. With a 10% discount rate, the average LCOE of new nuclear power plants is estimated at 60–110 EUR/MWh for China, the Republic of Korea, and Russia (where projects are cheaper) and exceed 100–150 EUR/MWh for the United States, Japan, and Europe (OECD/NEA, 2020). This corresponds to a range of 8–18 cents/kWh, which at the upper end significantly exceeds the cost of wind and solar energy under the same financing conditions.

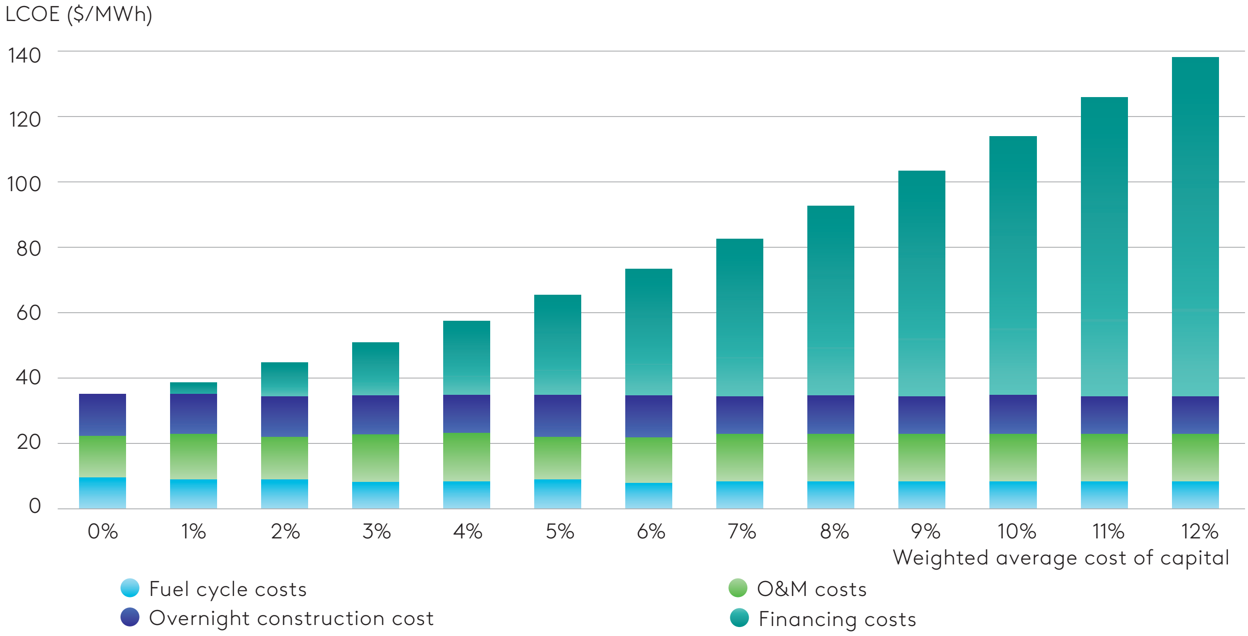
Nuclear projects are most viable where the state shares the risks of construction or where an industrial base for serial reactor construction has been preserved. For example, South Korea introduced a series of identical reactors in the 1990s and 2000s, managing to reduce the estimated cost to 2,000–3,000 USD/kW and the average construction time to 4–5 years. China also achieved a 15% reduction in cost for each subsequent reactor through serial production and localization. In contrast, individual projects in countries that had not built nuclear power plants for a long time (*European EPRs in France and Finland, American AP1000s)* faced cost overruns and delays, raising specific investments to 8,000–10,000 USD per kW. Thus, nuclear power generation today is competitive only under conditions of special political and economic support. Several countries are introducing mechanisms to offset market risks: for example, in the UK, the Hinkley Point C nuclear power plant currently under construction has been awarded a 35-year CFD contract at a fixed price of 92.5 GBP/MWh (in *2012 prices),* which guarantees investors a return on their investment.

Nuclear energy has high start-up costs, but once successfully launched, it provides stable and relatively cheap power generation for decades. Reactor fuel has high energy density and accounts for a small share in the cost structure. Unlike gas-fired power plants, where 60–70% of the cost is the fuel cost, at nuclear power plants, fuel accounts for only about 10–15% of the LCOE. Nuclear fuel is cheap per kWh and relatively stable in price, which gives nuclear generation the advantage of cost predictability (*Kazakhstan is a global leader in uranium production*). With increasing environmental restrictions, nuclear energy is becoming more attractive compared to carbon-based generation, particularly when taking into account the total cost to the energy system. However, for a new round of development in the nuclear industry, it is necessary to reduce CAPEX and construction risks. International efforts are focused on standardizing designs, introducing small modular reactors (*SMRs*) and mass-producing components, which should reduce the time and cost of building nuclear power plants. If these initiatives are successful, after 2030 nuclear energy may not only increase in volume but also improve its economic performance, once again strengthening its position among competitive energy sources.

There are currently no operational nuclear power plants in Central Asia, but several are under development. Kazakhstan is the regional leader in terms of technological potential in the nuclear sector: the country has the world's largest uranium reserves and a well-developed uranium mining industry. During the Soviet era, a small BN-350 reactor operated in Kazakhstan, which was closed in 1999, having accumulated experience in the operation and handling of nuclear fuel. Construction has now begun in Kazakhstan on the first 2.4 GW nuclear power plant in the Zhambyl district of the Almaty region, with Russia's Rosatom acting as the general contractor. The planned commissioning date for the plant is 2035–2036. The possibility of building two more is being considered. Construction of a nuclear power plant has begun in Uzbekistan: both a small (*two RITM-200N reactors)* and a large (*two VVER-1200 reactors)* nuclear power plant will be built on the same site. The first small nuclear power plant is scheduled to be commissioned in 2029, with the overall launch of both types of plants scheduled for 2029–2035. The project is a joint venture with Russia. Other Central Asian countries have no plans for nuclear power plants in the near future. However, there is potential interest in small modular reactors (SMRs): SMRs with a capacity of 50–100 MW could provide a stable energy supply to remote areas or large industrial facilities.

For Central Asia, nuclear energy could be a valuable element of a balanced energy transition, but only with careful planning, international support, and adherence to the highest safety standards. Nuclear power plants provide predictable baseload power with zero emissions, which is particularly important for Kyrgyzstan and Uzbekistan, which experience a shortage of clean electricity in winter when hydro and solar power generation declines. A single nuclear power plant can replace a significant portion of coal-fired generation and reduce CO_2 emissions by millions of tonnes per year. Their role is to carry a base load and winter demand coverage when solar generation is minimal and consumption is high. Among the key challenges are the extremely high cost, construction risks and duration of the project, which will require several billion dollars in investment, most likely under an intergovernmental agreement. In addition, nuclear infrastructure needs to be developed: a regulatory body needs to be established, personnel need to be trained, and a radioactive waste management system needs to be put in place.

↓ **Figure 21. Nuclear power LCOE estimate depending on capital cost, USD/MWh**



Source: World Nuclear Association, 2024.

Hydropower

Hydropower is the oldest and largest source of renewable electricity generation in the world. Large hydropower plants account for 16% of global electricity production, making hydropower the largest source of low-carbon generation (*about 39% of all carbon-free electricity*). The total installed capacity of hydropower plants worldwide exceeds 1,300 GW. The largest producers of hydropower are China, Brazil, Canada, the United States, Russia, and a number of developing countries with significant rivers (*India, Paraguay, Turkey, and others*). Hydropower is valuable for its ability to provide flexibility: unlike solar and wind power, hydroelectric power plants with reservoirs can store water and generate electricity on demand, covering peak loads and providing system reserves. Many hydropower plants serve as a backbone for the reliability of power grids, providing inertia, frequency regulation, and emergency reserve.

As power systems integrate growing volumes of variable renewable energy (VRE), hydropower is increasingly required to provide flexibility rather than baseload generation. Many existing hydropower plants were designed for steady operation and now face more frequent start-stop cycles, partial load operation, and faster ramping requirements. Enhancing the flexibility of aging hydropower assets has therefore become a critical system priority.

As the share of variable renewables grows, hydropower increasingly shifts toward providing system flexibility rather than baseload generation

Targeted modernization offers a cost-effective pathway to address these challenges. Equipment upgrades and advanced control systems can expand operating ranges, improve efficiency, and reduce mechanical stress. Digital solutions, including real-time monitoring, digital twins, and predictive maintenance, further increase plant availability and operational reliability. Additional flexibility can be achieved through hybridization with pumped storage, battery systems, and co-located solar or wind generation. Overall, modernizing existing hydropower plants can significantly strengthen power system flexibility and support reliable integration of variable renewables without large-scale new capacity additions (IRENA, 2023b).

The potential for expanding traditional hydro generation is limited by geography and environmental considerations. The best sites for large hydropower plants have already been used in many countries. The construction of new dams faces challenges such as resettlement, land flooding, and changes to river ecosystems. Climate change also has an impact: melting glaciers and changing precipitation patterns are causing uncertainty about future river flows, especially in regions that depend on seasonal runoff. Some large rivers may reduce hydropower output in dry years, which requires this risk to be taken into account in planning. There are opportunities for the development of small hydropower plants (*on tributaries and canals)*, the modernization of existing plants (*increasing turbine efficiency, adding additional generators, introducing digital control systems, and monitoring dams and equipment for preventive maintenance).* The modernization of old hydropower plants is of great interest: in many cases, upgrading turbines and generators can increase the capacity of a plant and extend its service life with less investment than building a new plant. In addition, the concept of pumped storage hydropower (PSH) is being developed — a hybrid of hydro and storage technology that allows excess energy to be stored (*see the section on PSH below*).

For Central Asia, hydropower is a pillar of balanced development, but one that requires regional consensus. The Amu Darya and Syr Darya rivers are transboundary, so the use of their waters for energy generation and irrigation is subject to intergovernmental agreements. Hydropower, together with energy storage facilities and gas-fired capacity, could become the basis for the integration of huge arrays of solar and wind power plants. Hydropower plants have unique flexibility — they can increase generation by hundreds of MW in minutes, compensating for fluctuations in wind or solar power. According to estimates, large hydropower plants in Central Asia still have reserve capacity that can be used for wider range balancing. However, environmental factors must be taken into account: changes in the hydrological cycle due to warming may require adjustments to the operating modes of reservoirs. For example, to prevent the Aral Sea from drying up, the Amu Darya and Syr Darya releases must remain sufficient, which imposes restrictions on the complete autonomy of water regimes for energy purposes. Balancing the interests of energy and irrigation is crucial for sustainable development. The governments of Central Asia, with the support of regional organizations, are working on agreements on the joint management of water and energy resources. This is fraught with political difficulties, but the progress made in recent years gives cause for cautious optimism.

In summary, hydropower is a kind of anchor for the energy transition in Central Asia, providing clean and cheap electricity on which further decarbonization efforts may be built. Maximizing its potential (especially in Tajikistan and Kyrgyzstan) and its closer integration with other power systems will enable the region to reduce flexibility deficits and reduce its carbon footprint simultaneously. With sound management, hydropower will become the cornerstone of a sustainable energy mix alongside solar, wind, and gas-fired generation.

Small-scale hydropower

Small-scale hydropower plants are a flexible and renewable source of energy, particularly relevant for mountainous regions in Central Asia. Unlike large hydropower plants, small plants typically operate on small rivers or irrigation canal spillways, usually without large dams, which reduces their environmental impact. Small hydropower can provide electricity to remote communities, reducing the need for long transmission lines. In global practice, small hydropower plants are considered a key element of a decentralized energy system: their modularity and relative simplicity allow for rapid capacity expansion where needed, and their production costs are often competitive with diesel generators and other local sources. For Central Asian countries with significant hydropower potential, the development of small hydropower plants is a logical complement to large projects: they increase the reliability of energy supply in peripheral regions while utilizing a renewable resource. According to the classification in the region, “small” usually refers to hydroelectric power plants with a single capacity ranging from hundreds of kilowatts to 10–30 MW. Such facilities can partially regulate power output within a daily cycle thanks to small reservoirs or flow regulation, although to a lesser extent than large hydropower plants. Small hydropower plants are not subject to fuel risks and have a long service life with minimal operating costs. Their disadvantages — seasonal flow (decreased output in winter for flood-fed rivers) and relatively high capital costs per unit of capacity — are offset by their local significance and environmentally responsible generation.

Kyrgyzstan and Tajikistan, which have many mountain rivers and a shortage of electricity in remote areas, are placing the greatest emphasis on the development of small hydropower plants. In recent years, Kyrgyzstan has adopted a state program to support small hydropower. There has been a real boom in recent years: in 2023–2024 alone, 14 small hydropower plants with a total capacity of about 40 MW were commissioned, and in 2025, another 18 new mini-hydropower plants were planned to be launched. It is expected that by 2028, dozens of new facilities with a total capacity of over 200 MW will be built. Tajikistan also has great potential for small hydropower — hundreds of mountain rivers and canals can be used for generation. In the 2000s, there were about 20 small hydropower plants in operation in the country, mainly built during the Soviet era, but their technical condition remained unsatisfactory. In recent years, with the support of international donors, new projects have been implemented. A landmark event was the construction of the 11 MW Sebzor HPP in the Pamir region, with funding from international partners in 2025. In other countries in the region, small hydropower is developing on a smaller scale and in a more selective manner.

Small hydropower plants could become a "hidden reserve" for Central Asian power sector: their total potential is estimated at several gigawatts. Their ability to operate in isolation is particularly valuable, since where there is no grid coverage, small hydropower plants can become the basis for local microgrids. These can be used to create isolated power systems supplied by a combination of small hydropower plants, solar stations, and energy storage devices. This approach makes it possible to provide round-the-clock power to small villages without connecting them to central grid.

Bioenergy

Bioenergy encompasses the production of energy from biomass: solid biofuels (*wood, agricultural waste, pellets, bagasse*), biogas, and biofuels (*bioethanol, biodiesel*). In power sector, the main application is the combustion of biomass or biogas in power plants to generate electricity and often heat (*cogeneration)*.

Bioenergy can play an important role in a global energy transition, as it provides dispatchable generation that complements variable RE sources and contributes to efficiency gains in industry and heat supply through cogeneration. In power systems dominated by solar and wind power plants, the addition of biogenic sources capable of delivering power on schedule increases the flexibility and reliability of the grid. In addition, bioenergy can be used as a transitional solution at coal-fired power plants — co-firing biomass with coal is already practiced in several countries, allowing for a reduction in carbon footprint without immediately abandoning coal altogether. For example, replacing 10–20% of coal with wood chips or pellets in a boiler reduces CO_2 emissions accordingly, with virtually no reduction in the plant's output. Combined with carbon capture and storage, bioenergy can also deliver negative net emissions, making it a strategic tool for achieving long-term climate goals (IRENA, 2022b). Finally, biomass can be converted into liquid biofuels for use outside the power sector: for example, bioethanol and biodiesel are widely used in transport as additives or substitutes for fossil fuels, reducing carbon emissions and providing an additional market for the agricultural sector.

The generation of electricity from biomass depends on the availability of raw materials, conversion technology, and fuel delivery logistics. Costs can vary significantly across regions and types of plants. On average, over the past decade, the total cost of installing bioenergy power plants has ranged from 2,000 to 3,450 USD per kW. The LCOE for bioenergy has remained relatively stable at 0.06–0.087 USD/kWh (6–8.7 cents), which is slightly higher than for solar and wind power plants, but often lower than for new coal-fired power plants when power plant emissions charges are taken into account (IRENA, 2025a).

Global installed bioenergy capacity continues to grow, reaching 151 GW in 2024. Geographically, bioenergy is developed in Europe (*especially in Scandinavia, the United Kingdom, and Germany, due to coal decarbonization policies and support for pellets*), North America, and countries with developed agriculture (*Brazil — bagasse at sugar mill CHP plants, Southeast Asia — use of palm oil waste, rice husks, etc.)*. China is also actively expanding its waste-to-energy and waste incineration plants. The lion's share (84%) of this capacity runs on solid biofuel — wood chips, wood pellets, and agricultural residues such as bagasse (*sugar cane pulp)*. About 15% comes from renewable municipal waste (*from waste incineration plants)* and less than 1% from biogas power plants (IRENA, 2025b). This reflects the fact that the most economical form of bioenergy remains the combustion of cheap solid bio-resources in large boilers, often with combined heat and power generation.

Although bioenergy is close to carbon neutral in terms of CO_2 balance, there are environmental concerns: the large-scale use of wood can lead to deforestation if logging exceeds forest regeneration. Therefore, international protocols (*e.g., the EU*) require confirmation of the sustainable origin of biofuels. Logistics are also critical: transporting biomass over long distances is unprofitable due to its low energy density, so it is better to locate bioelectric power plants close to raw material sources or industrial facilities (*sawmills, sugar factories)*. Otherwise, transport costs and associated emissions may negate the benefits.

Bioenergy is still underdeveloped in Central Asian countries. In some rural areas, small biogas plants are traditionally used to supply farms with gas and electricity from livestock waste, but utility-scale bio-power plants are virtually non-existent. Nevertheless, the potential exists: significant agricultural residues (*straw, cotton husks, manure)* can be collected and used either for direct combustion or for biogas production. For example, in Uzbekistan and Kazakhstan, large agricultural holdings have begun to introduce biogas complexes to generate electricity from poultry and livestock manure, which simultaneously solves the problem of waste and provides local energy. Another opportunity could be the adoption of biomass co-firing at existing thermal power plants. In Kazakhstan, where there are many coal-fired thermal power plants, it is possible to experimentally replace part of the coal with local waste. This would reduce emissions without significant investment, although technical modifications to boilers would be required. In the context of a balanced energy transition in Central Asia, bioenergy can only make a limited contribution to decentralization and decarbonization.

Geothermal energy

Geothermal energy uses the heat of the Earth's interior to generate electricity and heating. Its contribution to global electricity production is still modest but stable. At the end of 2024, the total installed capacity of geothermal power plants was about 15.4 GW, equivalent to 0.35% of the total world renewable generation capacity (IRENA, 2025a). The main countries operating geothermal power plants are the United States (*California, Nevada)*, Indonesia, the Philippines, Turkey, New Zealand, Iceland, Mexico, Kenya, and others — mainly those with access to high-temperature geothermal reservoirs (*in areas of tectonic activity*). Despite its small share, geothermal generation is valuable because it is not dependent on the weather and provides almost constant baseload power.

There are different technologies: classic geothermal power plants with steam turbines use steam/hot water from wells (*usually at temperatures above 150–200°C*), while binary plants (*Organic Rankine Cycle*) allow electricity to be generated even from medium- and low-temperature resources (*100–150°C*) through heat exchange with a working fluid. On average, the cost of building geothermal power plants has changed little over the past decade and ranges from 2,000 to 4,000 USD per kW. According to IRENA, it peaked at 4,909 USD/kW in 2018 and fell to 4,015 USD/kW by 2024. These values are comparable to other sources of generation and are attractive given the continuity of operation they provide (*the capacity factor of geothermal power plants can exceed 80–90%*).

From 2015 to 2024, global installed geothermal capacity grew slowly but steadily. Growth is constrained by several factors: geothermal resources are unevenly distributed and tied to geology; exploration and drilling require significant initial investment with uncertain outcomes (there is no guarantee that an exploratory well will yield sufficient hot water flow). Nevertheless, in recent years, the sector has gained new momentum thanks to technological advances. Geological exploration methods are improving — seismic exploration, 3D modelling of reservoir structures — which increases the likelihood of successful drilling. Advances in drilling technology are reducing drilling costs and allowing deeper penetration into hot layers. Simultaneously, interest in direct applications of geothermal heat — for district heating, greenhouses, industrial processes — is growing, stimulated by rising fossil fuel prices and the desire for sustainable heat supply. The use of geothermal heating and cooling systems has expanded significantly: since 2015, their total thermal capacity has increased by 50%, reaching 110,000 GWh of heat generation in 2022 (IRENA, 2023c). The main growth has been in low- and medium-temperature resources available in many regions that were not previously considered for geothermal energy.

An innovative concept is EGS (Enhanced Geothermal Systems) — the creation of artificial geothermal reservoirs in hot deep rocks through hydraulic fracturing and water injection. EGS technology has the potential to expand the geography of geothermal generation, but is still in its early stages and requires further research.

Although the Central Asian region as a whole does not have high-temperature geothermal sources suitable for utility-scale power generation, it does have significant low-temperature geothermal resources (World Bank, 2019). For example, Kazakhstan, Uzbekistan, and Tajikistan have known thermal water outlets (*with temperatures of 40–80°C and above*) that can be used for heating, aquaculture, greenhouse heating, and balneological needs. According to World Bank estimates, the use of these resources could contribute to reducing emissions and fossil fuel consumption in heat supply. In the future, with the development of heat pump technologies, even resources with temperatures of 50–70°C could be effectively used for district heating. This is particularly relevant for Central Asia, given the high potential for replacing coal-fired boilers and stove heating with environmentally responsible geothermal heat. Geothermal generation will not be a key element of a balanced energy transition for Central Asia, but geothermal heat supply can make a useful contribution to improving energy efficiency and reducing emissions.

3.2. Variable energy resources

RE integration without expanding energy storage and flexible capacity is not sustainable and increases system risks and the likelihood of emergency outages

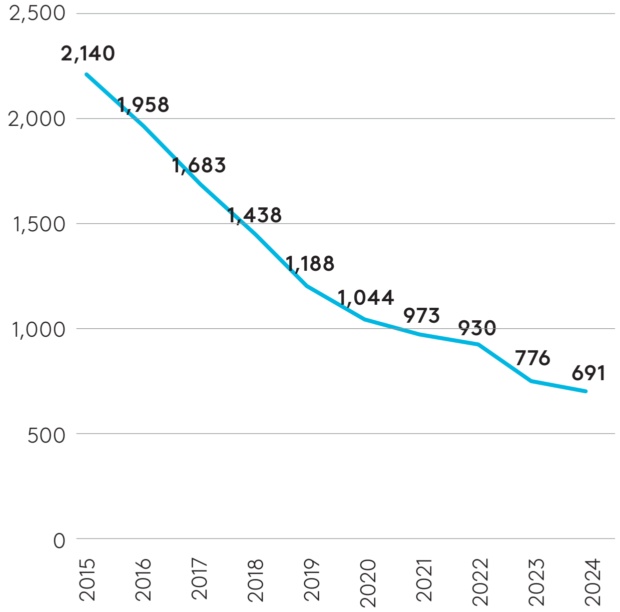
Variable RE resources are primarily solar and wind energy, which cannot be supplied strictly according to schedule, as their output depends on natural conditions — solar radiation and wind speed. The share of such RE sources is growing rapidly worldwide thanks to their falling cost and decarbonization policies. However, due to the variability and uncertainty of generation, these sources pose new challenges for the power system. They cannot be directly dispatched, as they cannot be increased on command by the dispatcher when demand increases. In addition, solar and wind installations are typically asynchronous — connected via inverters and lacking their own rotating inertia, which means that without special measures, their contributions to the stability of the power system can be limited. With a small share of RE sources, these problems are manageable, but as their share grows, more attention needs to be paid to integration issues such as securing adequate reserves, upgrading grids, introducing energy storage, and digital control methods.

Solar photovoltaic energy

Solar photovoltaic (PV) energy is a rapidly developing RE technology due to its cost reduction, modularity, and versatility in both off-grid and grid-scale applications. Utility-scale photovoltaic energy refers to large grid-connected power plants, typically with a capacity of more than 5 MW, which use inverter systems to convert direct current from photovoltaic modules into alternating current with the correct voltage and frequency for direct feed-in to the grid (NREL, 2024a).

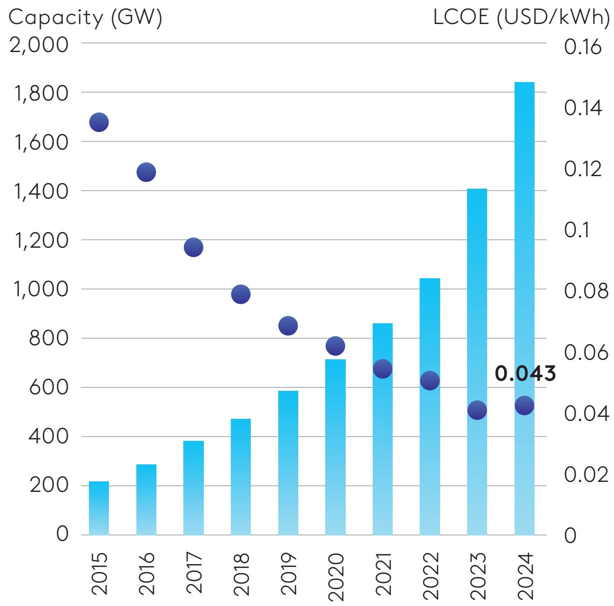
Over the past decade, the cost of solar power has fallen by more than 3 times. By 2024, the average LCOE of an industrial solar power plant was 4.3 cents/kWh, which is approximately 70% lower than in 2015. Solar generation has become a highly competitive source: on average, it is 41% cheaper than the cheapest fossil fuel generation options (IRENA, 2025a). The price of solar modules sold in Europe fell by 97% between 2010 and 2024, while the total installed cost for utility-scale projects fell by 87% from 2010 levels. Efficiency has also improved: the weighted average capacity factor of solar power plants worldwide has reached 17.4% thanks to improvements in inverters, maximum power point tracking, and increased module efficiency. The average commissioning time is only 2.3 years in OECD countries, while in non-OECD countries it is 1.6 years (Gumber, Zana, & Steffen, 2024).

↓ **Figure 22. Trends in total installed cost of solar PV power plants, USD/kW**



Source: IRENA, 2025a.

↓ **Figure 23. Trends in total installed capacity of solar PV and its LCOE**



Source: IRENA, 2025a and IRENA, 2025b.

4.3 UScents/kWh is the weighted-average LCOE for solar PV in 2024

Due to lower prices and shorter commissioning times, the solar energy sector has experienced rapid growth over the past decade. According to IRENA, by the end of 2024, the total installed capacity of solar PV systems reached 1,859 GW worldwide. In 2024 alone, a record 452 GW of new solar capacity was commissioned. Of this increase, 58% *(262 GW)* came from utility-scale PV power plants with a capacity of more than 5 MW, and the remaining 42% came from distributed installations *(rooftop, commercial, etc.)* (IRENA, 2025b). Solar energy has become a global phenomenon: large projects are being implemented in China, India, the United States, the Middle East, Latin America, and Africa.

Utility-scale PV plants are connected to the grid via inverters that convert the direct current from the panels into alternating current with the required parameters. To ensure reliability in regions with a high proportion of solar generation, hybrid schemes are increasingly being used: solar plants are combined with battery energy storage systems (BESS). Such combinations allow power output fluctuations to be smoothed out and electricity to be supplied during peak demand hours after sunset. For example, the Bugesera project has been implemented in Rwanda: 60 MW of solar PV + 60 MWh of storage, providing power to the new airport. In Egypt, the International Finance Corporation (IFC) is financing the installation of 300 MWh of batteries at the 500 MW Kom Ombo solar farm. In the US, such combinations are becoming more frequent: in 2023, three-quarters of all new solar projects in the US were planned with batteries to ensure flexibility.

The large-scale adoption of solar energy is leading to the emergence of new mode of operation. In order to understand it, it is important to introduce the term "net load", the total load minus generation from the sun and wind. As the share of solar energy grows, the net load curve takes on a characteristic "duck profile" shape: at noon, the load on traditional generation plummets (*thanks to solar generation)*, and when the sun goes down, there is a sharp increase in net load. There is a need to quickly increase the output of remaining capacity in the evening hours. The effect is being observed globally. The solution is a set of flexible measures: the introduction of energy storage, the expansion of interconnections, the development of gas peakers, and the diversification of RE sources (*geographically and by type)*. Another aspect is the increasing frequency of negative prices on the wholesale electricity market during hours of low demand and high solar generation. Negative prices mean that producers pay consumers for taking energy, which happens when there is an excess of cheap solar electricity. Such cases are rare and localized, but their occurrence highlights the importance of increasing system flexibility (*storage, demand management)* for the integration of large volumes of RE sources.

Electricity grids could become a constraint for the growth of solar energy. In regions with limited interconnection capacity, surplus solar energy often has to be curtailed because it cannot be transmitted to consumers. A well-connected transmission network, especially cross-border interconnections, can greatly facilitate the integration of RE sources. Reliable interconnections allow power systems to exchange electricity in real time, smoothing out local fluctuations in generation/load and increasing the overall stability of the system. An example is the Energy Imbalance Market (EIM) in the western United States: expanding the CAISO operator's balancing zone through a regional market has allowed California to export surplus solar energy to its neighbors and reduce forced curtailment of RE (NREL, 2019). Between 2014 and 2018, the EIM helped avoid a reduction of 715 million kWh of RE (*≈0.5% of CAISO's RE production)* (IRENA, 2019).

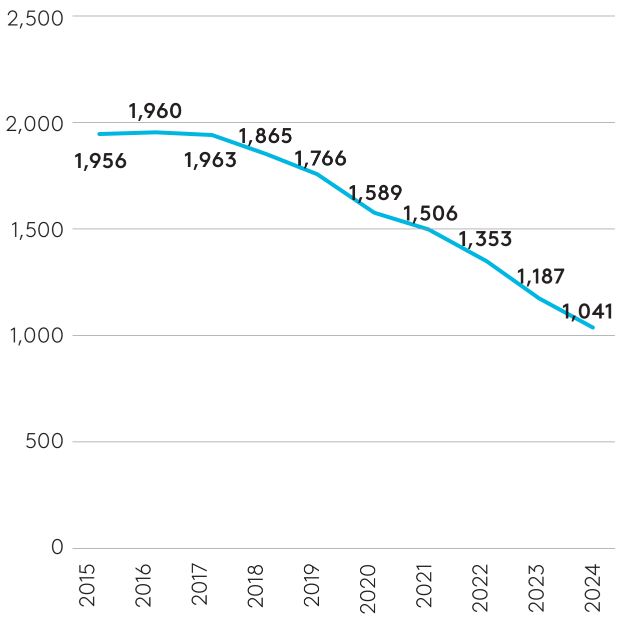
In Central Asia, the issues of RE integration and grid development are also relevant. Historically, the energy systems of the Central Asian republics were interconnected, but now there are restrictions and insufficient transmission capacity between countries. Given the prospects for large solar parks in southern Kazakhstan, Uzbekistan, and Turkmenistan, regional cooperation and grid modernization could play a crucial role in enabling the exchange of surplus solar energy and ensuring balance. For example, solar generation could be exported to the hydropower systems of Kyrgyzstan and Tajikistan during the day, while in the evening, hydropower plants would help meet the needs of their neighbours. Such schemes require investment in power lines, harmonization of market mechanisms, and trust between countries, but the potential benefits are significant: the creation of a balanced and sustainable regional energy system.

In conclusion, solar PV has already become one of the cheapest and fastest-growing sources on a global scale. It represents a huge opportunity for Central Asia, as the region has some of the best solar resources in the world (*a large number of sunny days per year, vast flat territories*). Solar power can significantly diversify the energy balance of Central Asia, reduce dependence on fossil fuels, and provide electricity to remote areas through decentralized installations. The main challenges are to ensure system balance and reliability, which requires integration with other technologies, as discussed.

Wind energy

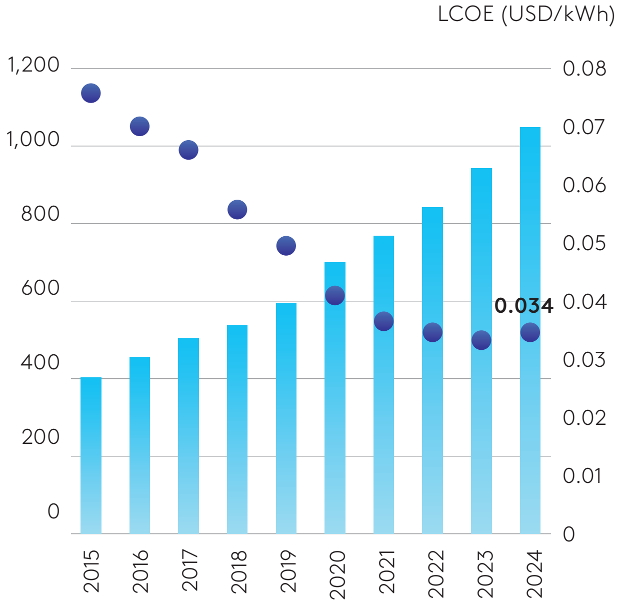
Onshore wind energy is currently one of the most mature and cost-effective RE technologies. Wind farms play a key role in reducing carbon emissions and supporting the global energy transition. Over the past decade and a half, onshore wind energy has gone from being relatively expensive to one of the most cost-competitive forms of electricity generation.

↓ Figure 24. Trends in total installed cost of onshore wind power plants, USD/kW



Source: IRENA, 2025a.

↓ Figure 25. Trends in total installed capacity of onshore wind energy and its LCOE



Source: IRENA, 2025a, IRENA 2025b.

From 2015 to 2024, capital costs for onshore wind farms fell sharply, almost by half. The average total cost of installing a wind farm fell from 2,000 USD/kW to 1,040 USD/kW (IRENA, 2025a). Accordingly, the LCOE of wind energy has also decreased: by 55% over the decade, stabilizing over the last three years at around 3.4 cents/kWh. This puts onshore wind farms among the most cost-competitive sources of electricity, alongside solar farms. The fall in prices is due to technological advances and economies of scale: leading turbine manufacturers have increased production volumes, reducing costs, and the turbines themselves have become much more powerful and efficient.

One of the key improvements is the increase in turbine size. Between 2010 and 2024, the average rotor diameter of a wind turbine in China increased from 75 to 188 metres, and the average rated capacity — from 1.5 MW to 5.6 MW (IRENA, 2025a). Taller towers and larger diameters allow for more efficient and stable wind capture (*at higher altitudes, the wind is stronger and more consistent*). As a result, the capacity factor of onshore wind farms has increased from 27% in 2010 to 34% in 2024. A modern 4–5 MW turbine generates significantly more electricity per year than several previous-generation turbines with a similar total capacity.

All these achievements have led to rapid growth in installed wind power capacity. By 2024, the total capacity of onshore wind farms worldwide exceeded 1,000 GW. Large-scale projects are being implemented on virtually every continent. In 2023 and the first half of 2024, there was a slight slowdown in growth due to supply problems and rising costs, but overall the trend remains positive.

3.4

UScents/kWh

is the weighted-average LCOE for wind power in 2024

Onshore wind energy is expected to continue to grow in the coming years due to the construction of new facilities, the completion of projects delayed by the pandemic, and the modernization of aging wind farms. Many of the first wind farms built in the 1990s and 2000s are approaching 20–25 years of operation. Instead of complete dismantling, it is often profitable to repower them, to replace old turbines with new, more powerful ones at the same sites with good wind potential. This allows for increased output at already developed sites and the efficient use of existing network. The concept of hybrid RE systems is also emerging: the installation of solar panels and batteries on the territory of a wind farm for joint operation. Wind and solar profiles often complement each other (*solar generation during the day, wind often at night or at other times*), and batteries allow residual fluctuations to be smoothed out and a more stable total power output to be achieved.

Hybridization offers significant economic advantages. Shared use of infrastructure (*substations, power lines, roads*) reduces connection, land, construction, operation and maintenance costs for each type of generation. The total investment in a hybrid facility may be lower than if wind, solar, and batteries were built separately, due to optimized financing and risk sharing. According to SolarPower Europe, such synergies reduce the LCOE for each component, making hybrid projects more attractive than single-type systems (SolarPower Europe, 2025).

Onshore wind energy is of great interest to Central Asian countries, especially Kazakhstan and Uzbekistan, which have vast steppes with good wind resources. This energy can provide a large-scale supply of inexpensive energy, especially in the autumn and winter, complementing the summer peak of solar generation. In combination with hydro and gas power plants, wind farms will help the region achieve a more balanced, diverse, and environmentally responsible energy system. To make this a reality, transparent auction mechanisms, improvements to the grid infrastructure for power transmission, and solutions to smooth out variability (*storage facilities, gas-fired peaking plants, HPPs, import-export)* are required. Given the experience of other countries, it is important to prepare public opinion in advance (*education about the safety and environmental responsibility of wind farms)* and the workforce (*staff training is required for maintenance).*

Offshore wind energy is also of interest to Central Asia in relation to the Caspian Sea: the technical potential here is estimated at 845 GW within 200 km of the coast. Almost half of this is in the Kazakh sector (*418 GW, of which 265 GW is for fixed turbines in shallow water)* and 73 GW is in the Turkmen sector (ESMAP, n.d.). Over the past decade, offshore technologies have made tremendous strides, reducing installation costs by more than half (*average — 2,850 USD/kW in 2024, 6,265 USD/kW in 2015)* and LCOE (*to 7.9 cents/kWh)* (IRENA, 2025a). Wind resources at sea are often more stable, and large turbines (*15–20 MW new models)* are capable of generating more energy. Climate conditions pose a serious challenge to the development of this potential: in the northern part of the Caspian Sea, winter icing hinders the operation of turbines. The areas of the Middle Caspian Sea with less ice are more promising. Although offshore projects in the Caspian Sea are a matter for the distant future, the very existence of such resources broadens horizons of energy transition.

3.3. Energy storage systems

As the share of variable renewable sources in the energy system increases and load patterns change, the need for energy storage systems grows. Energy storage systems play a key role in the energy transition, smoothing out imbalances between generation and consumption, providing backup, and increasing grid flexibility. They can absorb excess energy during periods of low demand or peak RE production and release it when demand is high or generation is insufficient. Energy storage systems are also capable of providing system services such as frequency regulation, operational reserve, and black start, similar to flexible gas turbines.

Currently, battery energy storage systems, especially those based on lithium-ion technology, are undergoing the most rapid development. Thanks to falling prices, they are being adopted both at the energy system level (*utility-scale battery storage*) and at the distributed energy level (*home batteries, electric vehicle batteries*). In addition, there are well-established pumped storage power plants, which provide large-scale storage by pumping water between reservoirs. Looking ahead, much attention is being paid to hydrogen as a means of storing energy in chemical form (*through electrolysis and subsequent use of hydrogen for generation or in other sectors).*

Battery Energy Storage Systems (BESS)

Utility-scale BESS have become one of the symbols of modern energy. They allow energy to be redistributed over time, helping to balance supply and demand as an increasing share of RE sources is integrated.

Lithium-ion battery energy storage systems have become the fastest growing segment of storage. Between 2015 and 2024, the average unit cost of installing a BESS fell by almost 88% — from 1,544 to 192 USD per kWh (IRENA, 2025a). This reduction in cost has been made possible by technological advances in energy density, cycle life, and economies of scale associated with the mass production of electric vehicle batteries. In parallel with the fall in prices, BESS deployment has doubled annually, especially between 2020 and 2024. China and the United States have become the largest markets, accounting for about 75% of capacity growth. In China, the adoption of BESS is driven by government mandates, such as the mandatory installation of storage devices in the construction of RE facilities. In the US, a powerful stimulus was provided by the federal Inflation Reduction Act (*IRA*), which provided a 30% tax credit for autonomous storage devices. Europe, India, and Australia are also increasing their capacity, albeit at a more moderate pace.

–88% is the change in BESS costs over 10 years. It made a journey from an expensive experiment to a mature tool that enables higher RE penetration without additional risks

BESS are used both for peak load management and for providing grid ancillary services. Modern industrial battery systems are capable of replacing gas peakers, participating in frequency regulation and smoothing the solar generation profile, especially in the 1–4-hour range. Although short-duration systems dominate today, interest in long-duration energy storage is growing rapidly. Projects with a discharge duration of 6–10 hours are being implemented in the United States and Australia. Long-duration storage systems are critical for deep integration of RE sources, as they can cover not only daily but also multi-day generation gaps. New technologies are emerging that are more suitable for long-term operation, such as sodium-ion, liquid flow batteries, and others.

BESS has already proven its economic efficiency and resilience to climate events in practice. In the winter of 2024, during a storm in Texas, battery storage systems saved the power grid approximately 750 million USD by freeing up to 3 GW of gas generation and providing reserves. In the summer of 2023, batteries provided electricity to more than 430,000 homes during extreme heat. 87% of BESS operators' revenues in Texas comes from the ancillary services market, where battery speed is a key competitive advantage. Nevertheless, at the global level, the main driver remains the possibility of energy arbitrage — charging during low-price hours and discharging during peak demand hours. Market and regulatory reforms are needed for further scaling. The experience of Texas has shown that recognizing BESS as an independent market participant capable of buying and selling energy and participating in capacity and reserve auctions can lead to explosive growth — from zero to 7.5 GW between 2020 and 2024.

In Central Asia, the use of BESS is still limited to pilot projects, but interest is growing rapidly. Kazakhstan, Uzbekistan, and other countries are including plans in their strategies to deploy large storage systems to support new solar and wind power plants. International experience shows that regulatory changes are needed to accelerate this process. The case of ERCOT (*Electric Reliability Council of Texas)* with its 7.5 GW BESS fleet can be helpful. It set clear rules for storage participation in energy and service markets, eliminated uncertainties and double tariffing (*when a battery pays the grid for both consumption and generation)*. But the prerequisite for these changes is the recognition of storage facilities as a separate entity (*neither generation nor load, but a dual entity)* with its own grid connection rules and tariffs. In the Central Asia region, where energy markets are just emerging, it is easier to implement the rules from scratch.

Pumped storage hydropower plants

Pumped storage hydropower (PSH) plants remain the most mature technology for large-scale energy storage. Their principle is based on pumping water between two reservoirs located at different heights. During periods of excess energy, water is pumped uphill, and during periods of shortage, it flows downhill through turbines, generating electricity. PSHs allow for not only daily but also weekly load balancing, ensuring long-term storage and supporting system stability. In 2024, the total installed capacity of PSH plants worldwide was approximately 189 GW, of which 8.4 GW was commissioned in 2024 alone (IHA, 2025). This technology accounts for 94% of all long-term energy storage capacity and more than 90% of the total energy stored worldwide.

PSH plants play an important role in ensuring system inertia and providing reserves. Their cyclic efficiency reaches 75–80%, and their service life can exceed 50 years. According to IRENA, storage costs range from 1.8 to 50 USD per MWh, and short-term storage costs range from 370 to 600 USD per kW of installed capacity, taking into account the costs of the dam, tunnel, turbine, generator, earthworks, and land (IRENA, 2020), depending on the topography and design of the station. China is the undisputed world leader in this field: in 2024, the world's largest pumped storage power plant, Fengning, with a power capacity of 3.6 GW and a storage capacity of up to 40 GWh was launched. China plans to build up to 200 GW of new pumped storage hydroelectric power plants, which will significantly exceed the national target of 120 GW by 2030.

The main limitations of PSH plants are geographical and environmental. The location requires a significant difference in elevation, reliable geological conditions, and the availability of water. In densely populated and flat areas, such facilities often encounter resistance. Construction takes 5–10 years and requires significant capital investment in the initial stage. However, the operating costs of pumped storage power plants are low and the efficiency is high. Political and financial support measures are needed to realize the potential of this technology, ranging from arrangement of payments for system and grid services to simplification of permitting procedures.

There are currently no fully operational PSH plants in Central Asia, but promising projects are under discussion. These include the use of mountain lakes in the Almaty region of Kazakhstan and the creation of regional storage facilities in the mountains of Tajikistan and Kyrgyzstan. The main purpose of PSH plants in the context of Central Asia may be to accumulate excess hydroelectric and solar energy in the summer for use in the winter, as well as to balance daily solar generation and evening peak demand. However, there are obstacles in the form of financing and international coordination. Regional PSH projects could potentially be a part of this cooperation.

Hydrogen

Hydrogen is considered a universal energy carrier capable of linking the electricity sector, industry, and transport. "Green" hydrogen is produced by electrolysis of water using RE and does not emit CO_2. In the future, it could be used in the steel and chemical industries, in heavy transport (*trucks, ships, aviation),* and as a seasonal energy storage medium. According to IRENA's 1.5°C scenario, hydrogen and its derivatives could account for up to 12% of global CO_2 emissions reductions by 2050 (IRENA, 2023a). Today, the share of "green" hydrogen is extremely small — less than 1% of the 94 million tonnes of global annual production (IEA, 2024a). The bulk of production is "grey" hydrogen, produced from natural gas or coal, which is accompanied by significant emissions — 8–12 kg of CO_2 per kilogram of hydrogen.

Despite its low current share, green hydrogen production is expected to grow rapidly. Many countries have launched electrolysis projects with a capacity of tens of gigawatts, particularly in the EU, China, Australia, and the US. IRENA estimates that by 2050, up to 94% of hydrogen should be produced by electrolysis (IRENA, 2024). The main barriers remain high cost — 3–6 USD per kg of H_2 compared to 1–2 USD for grey hydrogen — and storage difficulties. Producing 1 kg of hydrogen requires 50–55 kWh of electricity, so competitiveness depends on the cost of RE sources — preferably below 20 USD/MWh. Capital costs for electrolyzers are expected to fall by 70–80% with mass deployment. As of 2024, more than 50 countries have published national hydrogen strategies, setting targets for electrolyzer capacity of 113.5 GW by 2030 and 287 GW by 2050 (IRENA, 2024).

From a storage perspective, hydrogen is interesting as a means of long-term and even seasonal energy storage. It can be stored in tanks or underground caverns for weeks and months, bridging seasonal generation imbalances — for example, between summer sunshine and winter demand. This makes hydrogen a unique complement to batteries and pumped storage hydroelectricity.

For Central Asian countries with extensive wind and solar resources, green hydrogen could become an export commodity. Currently, Kazakhstan is implementing the Svevind project to produce GW-scale green hydrogen/ammonia for supply to Europe. At the same time, hydrogen can also be used within the region — for example, to decarbonize metallurgy or fertilizer production. However, this requires support from the state: standards, safety, incentives, and participation in international supply chains. As long as the cost remains high, it is too early for Central Asian countries to adopt hydrogen on a large scale. Hydrogen can become a universal energy link for a zero-emission economy. It connects the electricity sector with transport and industry and could become a global commodity, like oil and gas today. A balanced energy transition requires hydrogen to be included in Central Asia's long-term strategy in order to turn this resource into an export product of the future, while maintaining its role in global energy markets.

Energy storage systems, demand response, and hybrid power plants are becoming a core element of a resilient power system, not an optional add-on

Battery systems, pumped storage plants, and hydrogen are three pillars of the future energy sector. Each technology has its advantages and limitations, but their competent combination will make it possible to build a sustainable energy system capable of safely integrating high shares of RE sources and coping with changing demand conditions.

3.4. Energy decentralization and aggregation

The energy sector is undergoing a structural transformation. The model of the past — centralized generation from large thermal, hydro, and nuclear power plants and transmission networks — is giving way to a more complex architecture based on decentralization. With the adoption of small-scale distributed generation, consumer storage systems, flexible loads, and digital control, the energy sector is being transformed into a network with thousands of active nodes. These distributed energy resources (DER) create new opportunities for flexibility, reliability, and sustainability, but at the same time require a radical change in system management methods.

Smart grids are a key element of the new decentralized model. These are power grids equipped with digital devices, sensors, smart meters, and automated control systems. They allow real-time monitoring of the grid status, forecasting of consumption and generation, and dynamic grid management in response to fluctuations and failures. Smart grids provide two-way communication between consumers and operators, adapt to a high share of RE sources, and allow for the optimal integration of electric vehicles, heat pumps, and other new loads. The development of smart grids requires investment in digital infrastructure, data exchange standards, and new pricing models that enable flexible real-time management of supply and demand (ISGAN, 2025).

Virtual power plants (VPPs) play a special role in digitalization. These are aggregated and centrally managed associations of many small objects: solar panels, home and industrial batteries, electric vehicles, heat pumps, etc. Through a software and hardware platform, aggregators manage thousands of distributed resources as a single unit capable of participating in electricity markets as a conventional power plant. For example, Tesla Powerwall batteries, combined in a VPP in Australia, participate in frequency regulation and power reserve, providing up to several megawatts of flexible power on command. In the US, aggregators combine millions of devices — from boilers to electric vehicle chargers — into rapid response reserves, providing a total response in seconds.

In the longer term, demand response programs can free up capacity comparable to large power plants, without capital expenditures on generation

The economic potential of VPPs is significant: DERs, which are passive on their own, become sources of income by participating in wholesale and ancillary markets. In Germany and Denmark, VPPs combine hundreds of biogas and wind installations, selling capacity on the market. The success of virtual power plants requires regulatory conditions: market access for aggregators, DER management standards, fair tariffs and transparent compensation mechanisms. For Central Asia with its growth of RE sources and the emergence of EVs, the adoption of VPPs will allow consumers to be involved in the energy system, reducing the load on central power plants and grids.

At the local level, **microgrids** play an important role. These are autonomous energy systems capable of operating both in synchronous mode with the external grid and in isolation. A microgrid combines local generation (solar panels, small wind turbines, diesel generators), storage systems, and flexible loads. It can serve individual buildings (e.g., a hospital) as well as entire neighbourhoods or villages. In the event of an accident or external grid outage, the microgrid switches to island mode, ensuring uninterrupted supply with minimal loss of energy quality.

The global microgrid market is estimated at 12.8 billion USD (*as of 2023*) and is growing rapidly (REN21, 2024). In developing countries, they are becoming a solution for the electrification of remote areas without access to a centralized grid. In developed countries, they are used to improve the reliability of power supply to critical facilities, including data centres, military bases, and university campuses. Microgrids are also used as corporate solutions: companies create local generation and storage facilities to optimize costs and provide backup power. In Central Asia, microgrids can be useful in both rural and urban settings: from projects in mountain villages to ensuring the sustainability of hospitals and campuses in Almaty or Tashkent. They are becoming a testing ground for advanced technologies: control systems, load prediction algorithms, and self-learning controller models. Their development requires regulatory recognition, simplified connection procedures, and flexible tariff policies.

Finally, **carbon capture, utilization, and storage (CCUS)** occupies a special place in the new energy paradigm. Although this technology is not directly related to decentralization, it is important for offsetting emissions in sectors where full electrification is impossible or slow. By 2050, IRENA's 1.5°C scenario will require the removal of about 7 billion tonnes of CO_2 annually, accounting for up to 19% of the total emissions reductions needed (IRENA, 2023a). The main areas of application for CCUS are the retrofitting of existing coal and gas-fired power plants, as well as industrial sectors such as cement, steel, and chemicals, where emissions are process-related and difficult to eliminate by other means.

However, CCUS remains an expensive technology. The average cost of capturing one tonne of CO_2 is 50–100 USD with traditional installations, and even higher with more complex applications. Without high carbon taxes, subsidies, or contracts for difference, the introduction of CCS for business remains unlikely. According to data for 2023, there are about 30 large CCS projects in operation worldwide with a total capacity of 40 million tonnes of CO_2 per year, which is less than 0.1% of global emissions. However, incentives adopted in the US (45Q credit — 85/t CO_2), EU support, and national strategies in a number of countries are launching a new wave of projects. Central Asia has the potential to pilot CCUS in the oil and gas and metallurgical sectors, especially in Kazakhstan and Uzbekistan, where CO_2 can be injected into depleted fields (for enhanced oil recovery) with a double effect: carbon storage and increased oil production. However, the regional priority remains the development of RE and energy efficiency, and CCUS can be considered as a backup option as part of a balanced transition.

Decentralized generation sources, smart grids, virtual power plants, microgrids, and carbon storage technologies form a multi-layered infrastructure for the energy sector of the future. Their joint implementation allows for the construction of flexible, sustainable, and climate-neutral energy systems. For Central Asian countries seeking to integrate RE sources and achieve sustainable development, decentralization, and digitalization open the way to modernizing the energy sector without the need for large-scale centralized investment, attracting flexible resources on the consumer side.

3.5. Demand management and digital adaptation: the basis for sustainable consumption

The energy transition requires a transformation not only in generation but also in consumption. **Demand side management (DSM)** is becoming an integral part of a balanced energy system, allowing consumer behaviour to be adapted to the needs of the grid. DSM includes measures to improve energy efficiency, smooth out peaks, shift loads to off-peak hours, and encourage response to price and grid signals. When implemented correctly, demand management reduces the need for the construction of new power plants and power lines, facilitates the integration of RE sources, and increases the reliability of energy supply.

New consumer trends, including the growth in the number of electric vehicles, the development of data centres and mining, and the electrification of industry, have a dual effect. On one hand, they increase the load on the grid, especially at certain times of the day. On the other, there is additional potential for flexibility. Electric car charging can be optimized in terms of time; data centres can redistribute the load; and production processes can be adjusted depending on the state of the grid. All this is made possible by automation and digital technologies.

A key technology of the new demand model is **automated demand response (ADR)**. Unlike traditional DSM programmes based on tariff signals, ADR allows real-time management of electricity consumption by customers, both residential and industrial, without human intervention. Controllers and IoT devices receive signals from the power system and automatically adjust the operation of equipment: they reduce the heating temperature of boilers, temporarily turn off air conditioners, and shift the operating cycles of refrigeration equipment or electric vehicle charging. This allows hundreds of megawatts of load to be reduced instantly, preventing overloads and accidents. In California, for example, OhmConnect connects tens of thousands of homes to an ADR network, reducing peak load at the operator's command.

The ADR infrastructure operates through protocols (such as OpenADR), allowing the system to automatically interact with smart devices. The main benefits are speed, scale, and accuracy. Millions of actions can be coordinated in real time: disconnecting 1–2 kW from thousands of users, thereby freeing up capacity equivalent to that of a large power plant. The economic benefits are reflected in reduced reserve costs, increased reliability, and reduced emissions. At the same time, user comfort is virtually unaffected — the systems are configured to minimize interference with everyday life (OpenADR Alliance, 2019).

Intelligent algorithms and **artificial intelligence (AI)** could bring considerable benefits in the energy sector. AI could potentially analyze historical consumption, weather conditions and consumer behaviour and predict optimal management strategies. It could also play a role in predictive equipment analytics, RE generation forecasting, and power line load optimization. AI could help to understand when it is best to charge batteries, how to redistribute the load during hot weather, and how to minimize losses. The scale of the tasks (*data from millions of sensors and consumers in real time*) can make AI a critical element of the energy systems of the future.

An additional digitalization technology is **the digital twin (DT)** — a virtual model of a physical object or system that is updated in real time and reflects the current behaviour of the object. In the energy sector, digital twins are used at two levels: as a digital twin prototype (DTP) at the design stage — for example, to model a future network or power plant — and as a digital twin instance (DTI) — a model of existing equipment that is updated based on sensor data. Within the framework of DTI, a digital twin can, for example, monitor the operation of a turbine, predict possible breakdowns, or suggest optimal settings for current conditions.

For the power system operator, the digital twin is a powerful analytical tool. It allows various scenarios to be tested: for example, simulating the behaviour of the grid in the event of a sharp increase in load, generator failure or a sharp drop in RE generation. This makes it possible to prepare for crises before they occur. An example is the national control system in Kazakhstan: a digital twin of the entire KEGOC network can display flow distribution in real time, identify deviations, and suggest the best strategies to operators.

Large-scale implementation of digital twins requires advanced telemetry, IoT infrastructure, and computing power. However, as smart meters and controllers become more widespread, these technologies are becoming more accessible. In 2024, the International Electrotechnical Commission (IEC) recognized digital twins as a priority for the development of smart energy systems. They pave the way for a transition from reactive to preventive management — from "firefighting" to continuous digital diagnostics and optimization.

For Central Asian countries, the potential for demand management, automation, and digitalization is high. The problem of summer network overloads due to air conditioners, or uneven loads on thermal power plants in winter, can be addressed with ADR and AI. Simply raising the temperature of air conditioners by 2–3 degrees at the dispatcher's command during peak hours may prevent outages without noticeable discomfort. In industry, metallurgical or chemical enterprises can participate in flexibility programmes by shifting energy-intensive processes to night-time hours. This requires the adoption of smart meters, communications, and, most importantly, economic incentives. If consumers receive real compensation for their response, many will be willing to participate. In the long term, digital twins of the entire energy system — from networks to generation and large consumers — will help optimize investments. Instead of building excess capacity, it is possible to identify bottlenecks in advance, test solutions, and implement only what is necessary. This is especially important for countries with limited resources, when every investment must be as effective as possible.

Demand management, automation, AI, and digital twins are interconnected tools of the new energy sector. They make consumers active participants in the system, transform energy infrastructure into an adaptive and predictable environment, reduce the need for costly reserves and create the basis for the full integration of RE sources. In the global transition to sustainable energy supply, these solutions are no longer an addition: they are becoming an important element of the architecture of the future energy sector.

3.6. Technological solutions for Central Asia

Central Asia faces a challenging but achievable task: to make a balanced energy transition, taking into account its unique resources and needs. Analysis of global trends and technologies shows that there is no single universal solution — success lies in a combination of multiple approaches: modernizing traditional generation, accelerating the development of renewable sources, expanding energy storage systems, and increasing the flexibility of the energy system on both the generation and consumption sides. Interconnection of the systems will also play a crucial role in optimal operation of individual energy sectors. For Central Asian countries, the strategy could include:

- **Rational use of fossil fuel generation**: Coal-fired power plants, which still play a major role in Kazakhstan and, to some extent, in Uzbekistan, should be gradually modernized or phased out, while reducing environmental damage. Gas-fired generation will remain critical for balancing and covering peaks in the coming decades, so the focus is on building modern CCGTs and open cycle GT with high efficiency and low emissions, as well as creating conditions for them to operate in a flexible mode. Drawing on global experience, countries in the region should reform their capacity and services markets so that gas and hydro power plants, and eventually storage facilities, can together ensure the reliability of the system in an economically sustainable manner. The right balance between traditional and new generation will avoid energy shortages as demand grows and at the same time reduce the carbon footprint.

- **Large-scale development of RE sources**: Solar and wind energy are key drivers of the transition, given the rich resources of Central Asia. They have already become the competitive sources of new energy in the world, and foreign and local investments are actively flowing into this sector in the region. However, a high share of RE sources requires a parallel solution to integration issues. Therefore, along with the adoption of hundreds of MW of solar and wind farms, it is necessary to strengthen the electricity grids (*including interconnectors)* and increase flexibility. International experience has shown that timely infrastructure development is key to preventing constraints associated with RE sources. Central Asia can draw on models from neighbouring regions: for example, it could consider creating a common electricity market between countries so that Uzbekistan's surplus solar energy could be exported to Kazakhstan via interconnectors during the day, and in the evening Kazakhstan's hydro or gas capacity could be sent south. Such cooperation would increase the sustainability of all participants and allow for the integration of more RE sources without large expenditures on reserves for each individually.

- **Integration of nuclear energy:** Nuclear generation is more of a prospect of mid-2030s for Central Asia, but preparations should be made now. Nuclear power plants are capable of providing stable carbon-free energy, but require serious institutional efforts. Including the nuclear option in the energy balance of Kazakhstan and Uzbekistan will diversify the generation mix and reduce dependence on the weather, but it is important to maintain a balance of risks.

- **Introduction of energy storage systems and hydrogen solutions**: Energy storage is a game changer for the energy system. In the future, Central Asian countries could try pilot projects involving large BESS at network nodes. The experience of China and the United States shows that even a few hundred MW of BESS can significantly improve the quality of energy supply and save fuel. Storage facilities are particularly promising for Kazakhstan and Uzbekistan, where excess solar energy in the summer can be stored for evening peak demand. Along with batteries, the pumped storage hydroelectric projects may be feasible for mountainous republics (*Kyrgyzstan, Tajikistan)*: with the support of international banks, the construction of pumped storage hydroelectric plants could become a mutually beneficial project, providing the region with long-term energy storage and river flow regulation. As for hydrogen, Central Asia has the potential to become a player in the new green hydrogen market. Within the region, green hydrogen could be used to decarbonize hard-to-abate industries. Central Asia should miss out on the hydrogen trend if it is to avoid remaining dependent solely on traditional hydrocarbon exports at a time when the global market is undergoing transformation.

- **Decentralization and digital innovation**: Central Asian energy systems have historically been centralized, but the transition to a new model requires smart distributed energy. This means encouraging the installation of solar panels on roofs and the creation of local microgrids (*especially in remote rural areas and mountain villages)* — these will help solve the problem of energy accessibility and reduce network losses. At the same time, it is necessary to develop the aggregation of distributed resources — small generators, storage devices and controlled loads combined through virtual power plants to participate in the energy market. This will create new business opportunities for entrepreneurs (*energy service companies, utilities)* and involve consumers in the transition. At the level of transmission lines and large cities, it is advisable to adopt digital twins and advanced management systems. These will allow operators to see bottlenecks in real time, distribute flows efficiently, and quickly find optimal solutions in emergency situations (IRENA, 2025c). In an increasingly complex environment (*dozens of new power plants, thousands of RE sources)*, old dispatching methods are becoming obsolete; investments in digital infrastructure and training staff in digital skills will pay off in increased reliability and savings.

- **Demand management and new consumers**: Balancing the transition is impossible without working on the demand side. Central Asian countries should more actively adopt differentiated tariffs and automatic load management systems, first for large industrial and commercial consumers, then for households as meters are installed. For example, Uzbek cotton-processing enterprises or Kazakh ferroalloy plants could agree to interruptible consumption programmes in exchange for discounts, which would give operators a tool to manage peaks. Electric vehicles and charging infrastructure, which are bound to grow (*especially if Central Asian cities tackle air pollution*), need to be properly integrated into the power system from the outset: slow charging at night, intelligent load distribution at charging stations, consideration of Vehicle-to-Grid pilots where cars can feed power back into the grid during peak hours. New large consumers, such as cryptomining farms and data centres, should be subject to regulation: for example, connection permits should only be issued on condition that a certain proportion of RE is used or that emergency shutdown capabilities are available at the operator's request. The obligation for IT companies to purchase RE is already coming from the market, and it is important to support this at the policy level as it increases international competitiveness — by creating green tariffs and facilitating the registration of PPAs with RE sources for data centres and miners.

- **Government policy and regional cooperation**: Bringing all these technological solutions to life requires appropriate policy instruments. It is important to improve the regulatory framework: guarantee market transparency and non-discriminatory access (*for investors in RE sources, for aggregators*), adopt a carbon price (*for example, Kazakhstan already has an emissions trading system*). It is useful for Central Asian countries to coordinate their policies: to exchange experience from pilot projects and jointly attract funding from international institutions. Geographic proximity also dictates joint technical and economic solutions: the cascades of hydropower plants in Tajikistan and Kyrgyzstan can serve as a "battery" for Uzbekistan's solar parks, but this requires intergovernmental agreements on the operating mode of HPPs (*taking into account both electricity and irrigation*). It is in the interests of all countries to maintain a unified energy network in Central Asia and gradually integrate it with neighbouring power systems, which will expand the market for surplus energy and increase energy security.

Regional power system integration can reduce reserve requirements, optimize investments, and increase the energy security of all Central Asian countries

In summary, a balanced energy transition in Central Asia should be based on a pragmatic mix of technologies: exploiting the region's strengths (*complementarity between availability of generation resources and existing interconnection infrastructure)* and mitigating its weaknesses (*network deterioration, high carbon generation index)* by adopting the best international practices. Such a transition will bring many ancillary benefits: reduced air pollution in cities, new jobs in the RE and IT sectors, and increased resilience of energy supplies to external shocks. Although there are many challenges ahead, from technical to financial, the combined efforts of governments, businesses and international partners can overcome them.

The future of power sector is determined not by a single technology, but by the complex interaction of innovation, market mechanisms, and policy. Central Asia, located at the crossroads of Eurasia, aims to diversify its economy, strengthen its energy independence and take its rightful place in the region's emerging low-carbon economy.

CHAPTER 4.

THE “MIDDLE PATH” IN ENERGY TRANSITION FOR CENTRAL ASIA: BALANCING SECURITY, ACCESSIBILITY, AND SUSTAINABILITY

The global energy transition — a large-scale restructuring of the world's energy sector aimed at decarbonization and sustainable development — faces conflicting demands. Today, the global energy agenda is shaped by various ideological approaches, which can be divided into three groups. The first is "green" maximalism, whose supporters advocate the fastest possible transition to clean energy and often call for a radical rejection of fossil fuels. The second is conservative scepticism, characteristic of defenders of the status quo and supporters of "proven" technologies; this approach focuses on the risks of the energy transition and questions its necessity or feasibility within the stated timeframe.

The "middle path" implies rejecting extremes, both "green maximalism" and conservatism, in favor of a phased and pragmatic transformation

This report explres a pragmatic approach that combines elements of both views: it recognizes the urgency of climate action, but insists on realism, a step-by-step approach, consideration of local specifics, and the use of the full range of technologies. Given the scale of the challenges, this approach is particularly relevant for Central Asian countries. It represents a "middle path" between two extreme positions, a universal strategy that avoids both radical maximalism (immediate abandonment of traditional resources at any cost) and conservative scepticism (denial of the need for change). This approach is based on the principles of the energy trilemma, recognizing that a successful energy transition is only possible if all three of its components are simultaneously ensured: energy security, affordability, and environmental sustainability.

4.1. "Green" maximalism

This point of view stems from the primacy of the environmental threat and asserts that deep decarbonization of the energy sector cannot be delayed. Adherents of green maximalism demand the rapid phase-out of coal, oil, and gas — including moratoriums on new developments and the early closure of existing facilities — replacing them with RE sources and storage technologies. Their arguments are based on scientific data on climate: to keep global warming within 1.5°C, global CO_2 emissions must be reduced by almost half by 2030 and approach zero by 2050. These words reflect the spirit of "green" maximalism at the highest level. Such calls are supported by a number of states and coalitions: for example, several climate-vulnerable countries and social movements are demanding that UN summit agreements include a direct commitment to *a global phase-out of fossil fuels*. At recent COP events, battles unfolded over the wording "phase-out fossil fuels" — some states insisted on its adoption, although it has not yet been enshrined in the final documents due to resistance from other camps.

Maximalists point out that RE sources are already capable of covering most of the demand. The cost of solar and wind energy has fallen to record lows — solar power is now about 41% cheaper than the cheapest fossil fuel alternatives, and onshore wind is one of the most economical sources (*about 3–4 cents/kWh)*. Thus, in their opinion, *there are no economic obstacles* to the rapid expansion of RE sources: the markets themselves are ready to invest in them with the right policies in place. Breakthrough storage technologies (*lithium-ion batteries, which have fallen in price by almost 88% since 2015, Power-to-X, hydrogen)* should solve the problem of the variability of renewable sources. "Green maximalists" are often sceptical about the use of nuclear energy and CCS as allegedly too expensive or slow solutions — instead, they propose focusing on 100% RE and demand management. From a financing perspective, they point to the huge subsidies that oil and gas have received for decades: redirecting these flows to clean energy will enable a leap forward. Political arguments also include the moral dimension: industrialized countries, in their view, bear historical responsibility for emissions and should therefore be the first to abandon hydrocarbons and help the poorest countries transition to clean technologies.

The main feature of this position are an unconditional commitment to climate change mitigation and resource constraints. It sets the bar high and stimulates technological progress. Thanks to this pressure, for example, the Net Zero by 2050 concept, supported by the IEA, was born: its scenario envisages no new oil and gas extraction projects after 2021 and 90% of energy generation from renewable sources by the middle of the century. Until recently, these ideas seemed radical, but today they form the mainstream of strategic planning all over the world (*in the form of legally binding neutrality targets)*. Under the influence of the green lobby, large banks and funds have begun to refuse to finance coal projects. Public opinion, especially among young people, in many countries is leaning towards supporting tougher climate measures, and mass movements are giving politicians a mandate to accelerate the energy transition.

The main risk of this approach is ignoring objective technical and economic constraints. Completely restructuring the energy system in one or two decades without disruption is an extremely difficult task. The infrastructure of power grids, storage systems, and equipment manufacturing simply cannot be scaled up instantly. For example, to ensure 100% renewable electricity supply, huge energy storage capacities are needed to cover night-time and seasonal production shortfalls; long-term storage technologies are not yet mature enough for widespread commercial use. A rapid abandonment of fossil fuels without replacement by alternatives threatens to cause energy shortages, which would undermine security and affordability. Critics also point to the economic costs: the accelerated phase-out of hydrocarbon assets means billions of dollars in write-offs and job losses in the oil and gas sector; without a program of retraining and creation of new jobs, the social consequences could undermine support for the energy transition. Another argument is geopolitical: a unilateral rejection of oil and gas by Europe, for example, may do little to help the climate if other major emitters do not follow suit, but it will weaken the competitiveness of the economy. The categorical rejection of certain technologies (*such as nuclear power or CCS)* is also debatable: *the IPCC* includes significant amounts of nuclear power and carbon capture in its 1.5°C scenarios as necessary elements; without them, it will be much more difficult to limit global warming. Thus, "green" maximalism suffers from a lack of flexibility: it sets a clear goal, but risks not offering a reliable route that takes into account the starting conditions and obstacles.

4.2. Conservative scepticism

The opposite side of the debate is represented by those who either doubt the urgent need for an energy transition or emphasize its *negative aspects*. These may be outright climate sceptics who deny the scale of the threat of global warming, but in contemporary discourse, moderate conservatism is more common: verbal recognition of climate goals while delaying concrete steps or putting forward conditions (*"yes, but not now", "yes, if developed countries pay", etc.)*. The conservative approach focuses on *energy security and the economy,* often contrasting them with the environment. Its supporters point out that fossil fuels have been the basis of industrial progress for decades and that a sudden rejection of them is unrealistic. Particular attention is paid to the risks to energy security: it is argued that the sun and wind cannot provide a 24/7 base load, and therefore the premature closure of coal and gas stations threatens to cause disruptions. The example of Texas (*the 2021 crisis, when wind turbines froze and gas stations shut down, leaving millions without electricity)* is used to illustrate the vulnerability of an energy system with a high share of RE sources without sufficient reserve capacity.

Another argument is the high cost of the transition. Conservatives calculate the estimated costs of rebuilding infrastructure, subsidizing RE sources, and compensating coal-producing regions, and conclude that the trillions of dollars involved would be "better spent on more pressing needs." They warn of rising tariffs for consumers due to the addition of "green" program costs to their bills.

For countries whose economies are heavily dependent on fossil fuel, a conservative approach is natural: it gives them time and opportunities for diversification without immediately collapsing budget revenues. Politically, this position is attractive because it promises to minimize disruption for the population — preserving jobs in traditional industries, moderate price increases, evolution instead of revolution. In international negotiations, this approach sounds like a demand to soften tough targets and allow for flexible timetables, especially for developing countries. They argue that developed economies have been increasing emissions for 150 years and now demand that others reduce them to zero in 30 years, which seems unrealistic without harming development.

The main drawback of this approach is its disregard for climate constraints and its rigidity. Scientists are clear: without rapid and deep emissions reductions, the Paris target will be missed in just a few years. The conservative approach essentially means that emissions will continue to grow or plateau over the next decade. This dramatically increases the risks of catastrophic climate change, which in turn poses economic threats (*crop yields, extreme weather events, migration, and conflicts*). From the economic standpoint, relying on fossil fuels is fraught with missed opportunities. While sceptics believe in "cheap" hydrocarbons and invest in prolonging the life of fossil fuels, other countries can take the lead in new industries — RE, hydrogen, electric mobility — and reap the economic benefits. The world is already moving towards carbon regulation (*for example, the EU is introducing a cross-border carbon tax requiring exporters to pay for their CO_2 emissions*), and countries that do not reduce emissions risk losing access to markets. On the other hand, an excessive focus on hydrocarbons could also undermine energy security: fossil resources are finite, new deposits are more difficult and expensive to extract, and global demand could fall faster than predicted, leading to price instability. One-sided strategies are becoming less and less tolerated by society. People want to see awareness and consideration of so-called "externalities": the side effects of economic activity on people's lives and the environment.

4.3. "Middle path": realism, diversification, and context

The pragmatic approach represents a kind of "middle ground" between the two extremes. Its adherents recognize the urgent need for energy transition and the ultimate goal of carbon neutrality, but propose to achieve it gradually and in a balanced manner, combining different solutions and taking into account the specificities of each country. Today, this "middle path" is largely shared by major international organizations (IEA, World Bank, World Energy Council) and many governments. It is largely based on the concept of the energy trilemma, as evidenced by the shift in narrative: "As energy systems evolve, the agenda is shifting from idealism to pragmatism: reliability, economics and sustainability now equally influence decisions, and the energy system is expected to provide not only clean but also reliable and affordable energy" (WEF, 2025). These words from the WEF 2025 report summarize the essence of the approach: climate goals remain, but are complemented by the priorities of energy security and social acceptability.

The arguments in favour of a "middle path" are based on lessons learned from real-world experience. It takes into account both failures and successes: it recognizes that it is impossible to rely entirely on the "invisible hand of the market"; a political course towards decarbonization is needed; but a purely command-and-control approach without market signals leads to inefficiency. A pragmatic strategy responds flexibly to new data. For example, when it became clear in 2021–2022 that energy security had been underestimated, countries quickly adjusted their plans: Germany built LNG terminals in record time, while accelerating RE and storage programmes. International experts note that the transition has now become multidimensional: not only climate, but also energy independence, technological competition, and grid stability have come to the fore (WEF, 2025). This position is more viable in the political arena, as it reduces polarization; it acknowledges the legitimate concerns of sceptics about reliability and costs, while not rejecting the goals of decarbonization. It is a compromise that is easier to convey to a broad coalition of participants, from businesses to NGOs. It is no coincidence that in recent years the rhetoric of major players has shifted towards the centre. China promises to peak emissions by 2030, but emphasizes energy security and preventing electricity shortages as it moves away from coal.

This approach may be criticized as "vague" and insufficiently ambitious by abovementioned coalitions. There is a risk that, under the banner of "realism," governments may slow down too much, using the need for balance as an excuse to postpone difficult decisions (*for example, continuing to subsidize fossil fuels under the guise of concern for the poor, instead of providing targeted assistance and investing in RE)*. Another risk is the dispersion of efforts: by trying to do everything, priority areas may be underfunded. It is important to set the right priorities here: the "middle path" is a multi-strategy for achieving high goals. While supporting a variety of approaches, the international community must still monitor the final indicators: reduction of emissions, growth in the share of carbon-free energy, and access to energy services for the population. A pragmatic approach is justified as long as it actually leads to progress on all three axes of the trilemma.

Overall, a moderately pragmatic approach dominates official international discourse today. Recent summits have been marked by both accelerated climate action and energy security. For example, a global agreement is expected on a threefold increase in RE capacity by 2030 (*from 3 TW in 2022 to 11 TW)*, but at the same time, measures to increase battery deployment, develop LNG infrastructure, etc. are being discussed. In other words, the world is striving for a balanced deal. In the next section, we formulate the principles of a universal "middle path" strategy on the basis of this consensus.

4.4. Principles of a universal "middle path" strategy

A key element of the strategy is the simultaneous modernization of conventional generation and the development of renewables, not treating them as mutually exclusive

Based on analysis of the global energy transition agenda, the challenges of the energy trilemma and the difficulties in achieving SDG 7 worldwide, a regional diagnosis of the state of the energy sector in Central Asia, and an in-depth overview of modern technological capabilities, a universal "middle path" in energy can be defined as a strategy that *simultaneously* promotes energy security, accessibility, and environmental sustainability by adapting specific technological and institutional solutions to national conditions. Below is a set of key principles and guidelines for such a policy, applicable on a global scale:

1. **Balancing the goals and metrics of the energy trilemma**. National energy policy should set quantitative targets for all three dimensions. Regular monitoring and a system of trilemma indicators will help to identify trade-offs and make timely adjustments. For example, when developing an energy strategy, it is important to ask: how will the plan to phase out coal-fired power plants affect reserve capacity? Are funds allocated for grid modernization to integrate RE sources? How will the poor be protected from possible tariff increases? Developing integrated energy transition plans is the best way to address these issues. Many countries are already moving in this direction: for example, in 2023, Canada passed the Targeted Climate Accountability Act, which requires consideration of the impact of climate measures on jobs and industry.

2. **Diversification and technological pluralism.** A universal approach rejects the extremes of single solutions. Instead of relying on a single category of sources, the energy balance should be diverse, including various low-carbon options: RE (*solar, wind, hydro, geothermal)*, nuclear energy (*in countries where it is acceptable)*, natural gas as a transitional fuel (*to replace coal)*, followed by equipping gas infrastructure with carbon capture technologies. There is no universal share of RE or other resource that is suitable for everyone — each region will find its own optimal trajectory. However, the principle of diversification means that one cannot put all one's eggs in one basket: even if a country is rich in a particular resource, such as gas or sunlight, it should develop additional areas to increase resilience. Diversification also applies to imports: reducing excessive dependence on a single supplier of fuel or equipment is a vital lesson from 2022. Countries must expand the geography of their energy supplies, create strategic fuel reserves and, in the long term, participate in international cooperation on the exchange of electricity and hydrogen to increase mutual resilience to shortages. Diversity also means maintaining different scales of generation: from large power plants to distributed generation (*rooftop solar panels, microgrids in isolated settlements)*. This increases flexibility and public participation in the transition.

3. **A systematic, step-by-step transition**. A good strategy involves step-by-step roadmaps that break down the long-term goal into achievable intermediate stages. The phase-out or reduction of hydrocarbon use should be systematic, as replacement infrastructure becomes available. For example, coal-fired power plants are first placed in reserve as sufficient RE generation and gas peak capacity are built; only then are they finally decommissioned. Similarly, in transport, incentives for electric vehicles must be combined with the development of a charging network and fleet, before banning internal combustion engines. This approach minimizes economic shocks. It also allows social measures to be prepared in advance: if coal mines are planned to be closed by a certain year, investments should be made today to diversify the economies of coal regions, retraining workers and creating alternative jobs. Fairness of the transition is a key element: no population group should be left behind. Another aspect of gradualism means taking infrastructure depreciation into account: assets should be phased

out towards the end of their life cycle, which makes economic sense. Instead of emergency shutdowns of relatively new gas-fired power plants, it is better to let them run their course while simultaneously building RE sources, after which they can be replaced or equipped with CCUS. An adaptive schedule also builds trust: consumers and companies see that changes are not happening chaotically, but according to a clear schedule, which allows them to plan their investments and behaviour. But it also highlights the importance of long-term thinking and risk management, as an investor may be stay locked with an asset for 30–40 years.

4. **Development of grid infrastructure.** The transition to low-carbon generation reinforces the role of grid infrastructure as a key element of sustainability and integration of new technologies. As the share of distributed and variable generation grows, power grids are no longer solely responsible for transmitting power, but are becoming platforms for managing power flows, ensuring a balance between power generation, consumption, and storage. The "middle path" strategy involves the outrunning construction of infrastructure relative to the pace of new capacity commissioning, including the modernization of transmission and distribution lines, the introduction of digital monitoring and control systems, the development of two-way energy flows, and the integration of distributed generation. Insufficient grid readiness is seen as one of the main constraints to scaling up RE, so grid infrastructure planning should be considered a fundamental element of energy policy.

5. **Improving system flexibility and ensuring reserves.** The growth in the share of variable generation leads to a decrease in power system stability and increases the requirements for the flexibility of power systems. In a universal strategy, ensuring flexibility is considered an equivalent component of the energy transition alongside the generation expansion. Maintaining system balance requires a diversified set of tools, including flexible gas-fired capacity (CCGT/OCGT), pumped storage HPP, energy storage systems (BESS), demand response technologies, and functioning ancillary services markets. A universal approach involves the creation of institutional and market mechanisms that stimulate investment in flexibility, since without sufficient reserve and balancing capacity, further increases in the share of intermittent generation become technologically and economically limited.

6. **Supporting energy accessibility and social protection**. The strategy should pay particular attention to ensuring that energy remains affordable for the population and businesses. The introduction of carbon pricing must be accompanied by compensation mechanisms for vulnerable groups, otherwise social rejection will arise (*as happened with the "yellow vests" movement in France in 2018, which protested against the environmental tax on fuel)*. The revenue from environmental charges should be reinvested for the benefit of citizens, whether through reductions in other taxes, direct payments to families, or subsidies for energy-efficient housing. At the same time, it is necessary to stimulate a reduction in the costs of new technologies: as production grows, the prices of electronics, electric vehicles, and batteries fall. Governments can accelerate this process through temporary subsidies or guaranteed

demand. For example, a solar panel subsidy program in India led to a 50% drop in solar power prices over five years, making further subsidies unnecessary. The most important aspect of accessibility is achieving full coverage of the population with modern energy services. Electrification of rural areas and the introduction of autonomous RE systems where it is unprofitable to extend the grid are priorities for many countries in Asia and Africa. International cooperation should provide grants and concessional loans for such projects, as this is both a social and environmental task. Energy availability for industry is crucial: the energy transition should not lead to deindustrialization in countries that are actively reducing emissions. Energy-intensive industries may be supported through preferential financing of modernization programmes and the 'equalization' mechanisms (*CBAM, the EU's proposed tax on high-emission imports)*. Otherwise, there could be "carbon leakage" when production (*and emissions)* simply migrate to regions with cheaper electricity.

7. **Innovation and adaptation to local conditions**. Continuous investments in R&D and pilot projects is important. Many of today's "unfeasible" technologies may become more affordable in the future, so it is not advisable to discard them prematurely. Governments should monitor trends and be prepared to adjust their policies: for example, if cost-effective methods of long-term energy storage emerge in 10 years, it will be possible to accelerate the phase-out of the last gas-fired power plants; if there is a breakthrough in fusion energy, this possibility will also need to be taken into account. Local characteristics (*geography, climate, resources)* should also determine the focus: the universality of principles does not mean uniformity of solutions. For a sunny desert, the priority can be solar stations + storage; for a northern country with long winters, it may be nuclear, wind energy, and biomass. Island states can take advantage of ocean energy (*wind, wave energy)* and some types of energy storage. African developing countries in absence of grid may focus on decentralized solutions. The exchange of experience between countries, technology transfer, and open access to data on successes/failures are an integral part of international energy policy.

8. **International cooperation and exchange of technologies**. The energy system is global in nature, and challenges (*climate change, energy security, technological risks*) know no borders. The middle path requires strengthening global partnerships: from technology exchange to financial support for the poorest people. International institutions are called upon to increase transitional lending programmes, especially in the areas of energy access and clean transport. A separate area is cooperation in the field of critical raw materials (*lithium, cobalt, rare earth elements)*. The dependence of RE sources and batteries on rare materials is a new challenge for security. International partnerships can simultaneously solve development challenges and strengthen supply security (WEF, 2025). Coordination of efforts is also needed to establish uniform trade rules, ensure transparency in carbon markets, and prevent unfair competition. Interconnections play a critical role in advancing all three aspects of the trilemma, as generation costs and complexity of power systems increase.

9. **Interconnections and regional cooperation.** Power systems that operate in isolation typically require higher capacity reserves and face limited opportunities for integrating variable generation. In contrast, expanding cross-border connections and coordinating power system regimes can smooth out fluctuations in supply and demand, optimize resource utilization, and reduce aggregate investment costs. A universal "middle path" strategy views interconnections as a tool for improving reliability, economic efficiency, and accelerating the adoption of low-carbon technologies. At the same time, effective integration requires the harmonization of market rules, technical standards, mechanisms for distributing benefits and responsibilities among participants, as well as institutional forms of cooperation that ensure a balance between national interests and the reliability of power systems.

The principles listed are not exhaustive, but they provide a framework within which specific policies can be formulated. In the next section, the focus shifts to technical solutions that are consistent with the concept of the "middle path". A range of technologies and approaches are considered, from traditional to cutting-edge, with an assessment of their contribution to the energy trilemma, advantages and limitations. When combined wisely, these solutions can put a balanced strategy into practice.

4.5. An integrated "middle path" strategy for Central Asia

The energy trilemma in Central Asia poses a complex set of requirements for policy and investment. Diagnostics have shown that attempts at unilateral solutions lead to imbalances and new crises. An integrated "middle path" strategy involves simultaneous work in all areas and a constant search for balance between them.

The energy transition in Central Asia is an infrastructural and institutional transformation, not just a shift in technologies

On a practical level, this means that it is advisable for the governments of Central Asian countries to coordinate their energy development plans based on the following fundamental principles:

Balancing the goals of the energy trilemma in a regional context

For Central Asian countries, the priority is to simultaneously advance all three components of the energy trilemma. Historically, policy has often focused on one dimension: affordability through subsidized tariffs, security through reliance on a dominant resource, or environmental sustainability through rapid growth in renewable energy. Practice has shown that such imbalances lead to deficits, financial instability in the sector, and increased systemic risks.

A «middle path» strategy for the region involves a transition to a measurable and comparable system of goals for reliability, affordability, and sustainability. This means taking into account capacity reserves when decommissioning old thermal power plants, assessing the impact of RE sources on grids and tariffs, and including social indicators in energy planning. It is particularly important for Central Asia to institutionalize cross-sectoral coordination between energy, water resources, and social policy.

Diversification and technological pluralism

Central Asia has a uniquely diversified resource base, but the actual energy mix of the countries rely predominantly on a single source. The «middle path» strategy involves moving away from the logic of a dominant resource and forming a multi-component generation mix.

For countries with a predominance of coal and gas, this means the phased inclusion of RE sources, nuclear power plants, storage facilities, and flexible capacities without abruptly replacing existing plants. For hydropower-dominated countries, it means reducing dependence on seasonal runoff through alternative RE sources and reserves. For example, if the Kyrgyzstan's national energy program is successfully implemented, by 2035, solar and wind power plants will generate more electricity than the Toktogul HPP, the heart of Kyrgyzstan's power system, which currently accounts for 30% of the country's electricity generation. Diversification should also cover different scales of generation, combining large power plants with small-scale and local solutions, which enhances the reliability of supply. Distributed generation can transform the sector, optimize costs, and improve energy security, but at the same time, it places new requirements for network operation and management.

Avoiding radical measures

For Central Asia, the principle of avoiding radical measures is critical. Abruptly closing coal or gas facilities without reliable alternatives increases the risks of shortages, tariff imbalances, and reduced grid reliability. Thermal power plants currently provide not only kilowatt-hours, but also reliable heat supply and overall grid stability. The «middle path» strategy involves step-by-step roadmaps that synchronize the introduction of new capacity, grid modernization, and the phasing out of obsolete assets closer to the end of their life cycle. Particular attention is paid to the social acceptability of the transition, including employment in affected industries and the economic sustainability of regions dependent on fossil fuels.

Grid infrastructure development

For Central Asia, the grid infrastructure is the main constraint to a sustainable energy transition. High wear and tear on transmission and distribution networks, limited capacity, and low levels of digitalization create systemic risks and will exacerbate them as demand and the share of RE sources grow. In a number of countries, T&D losses remain in double digits, and fragmentation of energy systems hinders the effective management of electricity flows.

The «middle path» strategy involves upfront investment in grid infrastructure modernization. Key priorities include upgrading transmission lines, developing interconnections, digital monitoring and control systems, and introducing smart grid elements. Currently, global investment in grids accounts only for 40% of investment in power generation (IEA, 2025a). For our region, given the state of the grids, every dollar invested in generation must be backed by a dollar of investment in the grid. It is essential for the region to view grids not as a supporting element, but as the basis for reliability, integration of RE sources, and regional cooperation.

Increasing system flexibility and ensuring reserves

The growth of variable power sources in Central Asia highlights the importance of flexibility and reserve capacity. Historically, the stability of the region's power systems has been ensured by large dispatchable power plants and hydropower resources, but in the context of climate variability and growing demand, this is becoming insufficient.

Current technologies include pumped storage plants, gas-fired peaking capacity, energy storage systems, and demand management. Particular attention should be paid to maintaining grid frequency and stability as the share of conventional generation with rotating inertia declines. Thus, the formation of ancillary services markets is becoming an important institutional element that will create conditions for the implementation of technical solutions that will support grid stability.

Energy access and equity

The power sector in Central Asia has traditionally played an important social role, which is reflected in low tariffs and large subsidies. Tariff policy is a key factor in the modernization of Central Asia's power sector that enables the possibility of asset upgrades, attracting investment, and improving the reliability of supply. The continuing gap between actual tariffs and economically justified levels leads to chronic underinvestment: with residential tariffs at 2–5 cents/kWh, the sector does not generate the resources to replace worn-out infrastructure, while the long-term sustainable wholesale level is estimated at least at 7–9 cents/kWh. A gradual and predictable alignment of tariffs to economically feasible levels, accompanied by targeted social support and protection of industrial competitiveness, is a necessary condition for reducing losses, improving energy efficiency, and transitioning from crisis management to sustainable development of the region's power systems.

Adaptation of technologies and development of local expertise

It is particularly important for Central Asia to avoid technological maximalism and a focus on a single "universal" technology. The regional strategy involves a pragmatic set of solutions adapted to the climate, geography, and existing infrastructure.

It is also necessary to develop human resources, applied research, and pilot projects. Controlled experiments with new technologies make it possible to reduce risks and accumulate experience without destabilizing the system. Investments in education and institutional expertise are an integral part of a sustainable transition.

Interconnectivity and regional cooperation

After the collapse of the Central Asian Power System, electricity trade between Central Asian countries fell from 20–25% of regional consumption in the late 1980s to less than 3% by 2010. In recent years, cross-border flows have begun to recover, but even with current and announced programs, they are estimated to reach only 5–7% of regional consumption, which is significantly below historical values and international benchmarks. By comparison, in Europe, by 2024 physical cross-border exchanges accounted for about 17% of consumption, and by 2030, systemic goals for power exchanges and market integration assume an increase in this indicator to 25–30%, which highlights the scale of unrealized potential for regional connectivity in Central Asia.

External cooperation (with neighboring power systems) complements regional integration by creating demand for electricity, access to technology, and financing. Together, this creates the conditions for a sustainable energy transition in which security, affordability, and environmental sustainability reinforce each other.

In the context of the energy transition, it is advisable for Central Asian countries to functionally divide investment roles between the private sector and the state. The construction of new generating capacities, such as coal and gas power plants and renewable energy sources, can be largely financed by private investors if long-term contracts and predictable market rules are in place. However, the development of grid infrastructure, ensuring flexibility, capacity reserves (e.g. the development of peak capacity and pumped storage hydroelectric power plants), and system stability have historically been infrastructure tasks that create public benefits and do not always provide sufficient market returns. These elements require the coordinated participation of the state, system operators, and development banks, including public-private partnership mechanisms, infrastructure financing, and regulated return on investment models.

International experience confirms the effectiveness of this division of functions. In India and Brazil, the private sector actively invests in generation, while the development of transmission networks is carried out with the participation of the state and regulated network companies. In the UK and Australia, investment in energy storage and reserve capacity is supported through separate mechanisms for availability payments and system services, providing predictability of returns for investors. For Central Asia, this “middle path” is particularly relevant, as market mechanisms are at an early stage of development and are not yet able to fully ensure investment in critical infrastructure. Using a model that combines private capital in the generation sector with public and institutional participation in grid development and system flexibility will accelerate the modernization of power systems, reduce investment risks, and ensure the sustainability of the energy transition.

A high-level comparative assessment of three scenarios for the development of the Central Asian power sector indicates that it is the integrated “middle path” strategy that provides the most sustainable profile across the entire energy trilemma. Based on the plans of Central Asian countries as stated in the strategic reports, the expected total new power generation capacity amounts to at least 62.8 GW by 2035, equivalent to 230 billion kWh of new annual generation. To meet this demand, three scenarios were considered:

- “Green maximalism”: all new demand is met by variable RES plus hydropower, using oversized 4-hour energy storage systems to ensure reliability.

- “Middle path”: diversified development, generally consistent with the report: RES + hydropower + flexible gas generation + modernization of outdated thermal power plants + BESS.

- Conservative approach: construction of new facilities dominated by coal, with some support from gas-fired assets and 10% renewable energy.

The “green maximalism” scenario delivers the lowest emissions but requires the highest level of investment, accelerated development of grids, storage, digital control, and reserves. With a normalized new generation base of 230 billion kWh per year, its parameters are estimated at 239–254 billion USD CAPEX and 11–12.2 cents/kWh LCOE, while reliability remains lower than that of the hybrid model due to greater dependence on variable generation, balancing, and weather factors. The conservative scenario appears simpler from an engineering and operational standpoint, but its cost advantage virtually disappears when capital costs are updated: CAPEX amounts to 150–170 billion USD, LCOE is 9.7–11.4 cents/kWh, and the carbon intensity reaches 0.8 tonnes CO2eq/MWh, or about 184 million tons of CO2e per year, which creates high long-term carbon and operational risk.

↓ Table 8. Key indicators of energy sector development scenarios for Central Asia

Path	Total average CAPEX, bn USD	OPEX, USD/MWh	LCOE, cents/kWh	GHG emissions, million tonnes CO2eq
Green maximalism	246	15	11.0–12.2	5.0
Middle ground	161	30	8.6–10.3	35.1
Conservative approach	156	46	9.7–11.4	184.3

Against this backdrop, the "middle path" offers a balanced framework for the regional energy transition. In numerical terms, this translates to 151–179 billion USD in CAPEX, an LCOE of 8.6–10.3 cents/kWh, and greenhouse gas emissions of 0.15 tonnes CO2eq/MWh. Compared to the "green maximalism" scenario, the "middle path" reduces capital costs by 30–45%, the cost of electricity by approximately 25–35%, and, compared to the conservative scenario, reduces the carbon intensity of electricity by approximately a factor of 5 while maintaining a comparable or more favorable cost-reliability ratio.

From a practical standpoint, the "middle path" is the most compelling scenario: it retains most of the conservative scenario's advantages in terms of reliability while eliminating a significant portion of its burden in the form of emissions and long-term operational risk profiles.

Adherence to these principles may yield tangible results in the medium term. It can be expected that in 10–15 years, the energy sector in Central Asia will be transformed: dozens of gigawatts of new capacity will appear, networks will be significantly upgraded, blackouts will be reduced, the share of clean sources in the generation structure will increase significantly, and the energy efficiency of the economies will improve. At the same time, energy supply stability and social acceptability of tariffs will be maintained. The region will become more energy independent, ensuring security through internal resources and mutual assistance, while contributing to the global fight against climate change and remaining on a sustainable development path.

The main thing that the proposed set of solutions must ensure is the indivisibility of progress in all three areas. A comprehensive, balanced approach means that energy security, accessibility, and environmental sustainability will reinforce each other. For example, modernized clean power stations will be both reliable and economical; an integrated market will provide security of supply, lower prices and incentives for RE sources. This synergistic effect is the ultimate goal of energy policy. Balancing the trilemma is a complex but necessary goal, and it can only be achieved through comprehensive reforms. This report has shown that Central Asia has everything it needs to do so: rich natural resources, potential for efficiency gains, historical ties among countries, and the support of the international community.

The combination of conventional generation, renewables, storage, digitalization, and regional integration forms the foundation of the region's sustainable energy system in the 21st century

Implementing the proposed strategy will require coordinated efforts by governments, private sector, the public, and foreign partners. But the benefits will far outweigh the costs. Central Asia, having gone through a period of stagnation and disunity in the energy sector, has a chance to become an example of a successful balanced energy transition in the developing world — where reliable and clean energy is available to all. Such a future energy system will serve as the foundation for the region's prosperity and security for decades to come.

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LIST OF ABBREVIATIONS

NPP	nuclear power plant
GDP	gross domestic product
RE	renewable energy
WPP	wind power plant
WEC	World Energy Council (World Energy Council)
WEF	World Economic Forum
PSPP	pumped storage power plant
GW	gigawatt
HPP	hydroelectric power plant
EDB	Eurasian Development Bank
EU	European Union
AI	artificial intelligence
IT	information technology
KR	Kyrgyz Republic
IEA	International Energy Agency
UAE	United Arab Emirates
NDC	Nationally Determined Contribution
UN	United Nations
OECD	Organization for Economic Cooperation and Development
UES CA	Unified Energy System of Central Asia
GHG	greenhouse gases
CCGT	combined cycle gas turbine
RFC	"Financial settlement center for renewable energy sources" LLP
LNG	liquefied natural gas
USSR	Union of Soviet Socialist Republics
USA	United States of America
SPP	solar power plant
TPP	thermal power plant
CHP	combined heat and power plant
CA	Central Asia
ADB	Asian Development Bank
ADR	Automated Demand Response

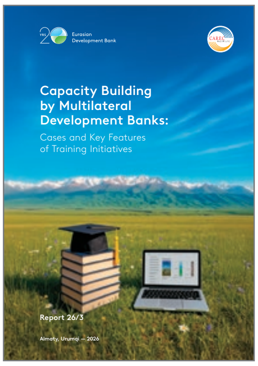
BESS	Battery Energy Storage System
CCUS	Carbon, Capture, Utilization and Storage
DER	Distributed Energy Resources
DSM	Demand Side Management
DTI	Digital Twins Instance
IEA	International Energy Agency
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JETP	Just Energy Transition Partnership
KEGOC	Kazakhstan Electric Grid Operator Company
LCOE	Levelized Cost of Electricity
SDG	UN Sustainable Development Goals
UN	United Nations
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
USD	United States dollar
VPP	Virtual Power Plants
WHO	World Health Organization
World Bank	
WEC Index	World Energy Council Energy Trilemma Index
%	percent
y.	year
kWh	kilowatt-hour
kg	kilogram
MW	megawatt
MJ	megajoule
million	million
billion	billion
m^3	cubic meter
CO_2	carbon dioxide
TWh	terawatt hour
thousand	thousand
°C	degree Celsius

Research at the EDB website

Macroeconomic Outlook
(RU/EN)

Macroeconomic Outlook 2026–2028

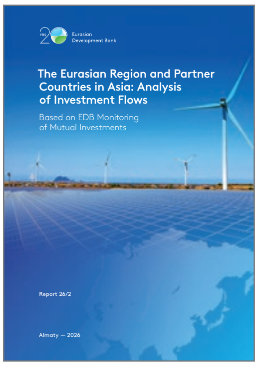
The Eurasian Development Bank (EDB) has presented its Macroeconomic Outlook for the seven member countries. The analysis reviews economic developments in 2025 and outlines key macroeconomic forecasts for 2026–2028.



Report 26/3
(RU/EN)

Capacity Building by Multilateral Development Banks: Cases and Key Features of Training Initiatives

The report provides an overview of MDBs training initiatives (academies, institutes, training programs), analyzes their goals, governance and financing models, thematic areas, and other characteristics, outlines the long-term outlook for the development of the MDB training initiatives.



Report 26/2
(RU/EN)

The Eurasian Region and Partner Countries in Asia: Analysis of Investment Flows based on EDB Monitoring of Mutual Investments

The report provides detailed information on the scale, dynamics, geographical and sectoral structure of mutual direct foreign investment stock between Asian countries and countries in the Eurasian region for the period from 2016 to the first half of 2025.

Report 26/1
(RU/EN)

Cooperation of Multilateral Development Banks in Emerging Markets and Developing Countries: Untapped Opportunities

The report examines seven promising areas for MDB cooperation: 1) mobilizing capital, 2) capital markets, 3) local currencies, 4) project expertise, 5) pooling knowledge, 6) technical assistance, 7) cross-border projects.

Report 25/15
(RU/EN)

China and the Eurasian Region: Analysis of Investment flows based on EDB Monitoring of Mutual Investments

The report provides detailed information on the scale, dynamics, geographical and sectoral structure of mutual direct foreign investment stock between China and countries in the Eurasian region for the period from 2016 to the first half of 2025.

Report 25/14
(RU/EN)

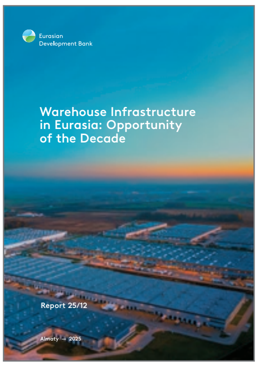
Investment Cooperation in the Eurasian Region based on EDB Monitoring of Mutual Investments

The report provides comprehensive insights into the scale, dynamics, geographical and sectoral structure of mutual direct foreign investments in the Eurasian region from 2016 to the first half of 2025, as well as key trends in investment cooperation.

Working Paper 25/13
(RU)

Arab Gulf: Macroeconomic and Financial Monitoring

The EDB's monitoring provides an analysis of the economies of six Gulf countries and assesses medium-term trends, including GDP growth, inflation, debt sustainability, and fiscal and monetary policies.



Report 25/12
(RU/EN)

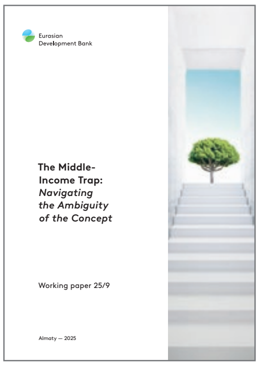
Warehouse Infrastructure in Eurasia: Opportunity of the Decade

The report presents an analysis of the current state of the warehouse logistics and storage sector in the Eurasian region, examines the main factors influencing its development, and provides a detailed forecast of demand for warehouse infrastructure in the region up to 2040.

Report 25/11
(RU/EN)

Advanced Manufacturing Potential in Eurasia: Sectoral Niches for Growth

The transition to high value-added production could become a powerful driver of economic growth in the region. The study identifies priority industries and niche markets for each country, and provides estimates of export potential and import substitution potential.



Working Paper 25/9
(RU/EN)

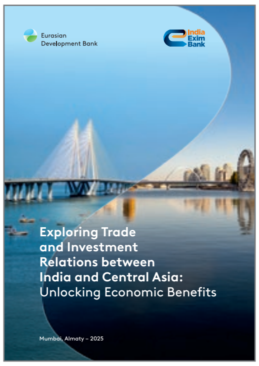
The Middle-Income Trap: Navigating the Ambiguity of the Concept

The study shows that diversity of interpretations of the "middle-income trap" makes it difficult to understand whether an economy is in it. The paper also identifies the factors of transition to a higher income: stable macroeconomics, ability to innovate, strong institutions and demographics.

Report 25/8
(RU/EN)

Investing in the future: projects of international financial organizations in Eurasia

The report analyzes 10 fundamental trends in non-sovereign financing by international financial institutions in the Eurasian region and formulates a number of proposals for more active and diversified IFI investments in development projects.



Report
(RU/EN)

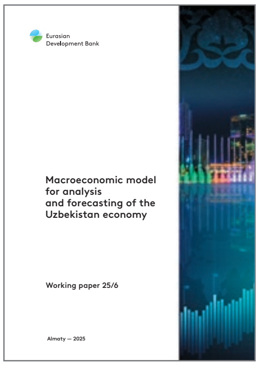
Exploring Trade and Investment Relations between India and Central Asia: Unlocking Economic Benefits

This joint report focuses on a comprehensive analysis of the current state and potential for improving bilateral trade and investment relations between India and Central Asia, and provides policy recommendations for closer cooperation.

Report
(RU/EN)

The Future of Islamic Finance in Central Asia

Joint report of the Eurasian Development Bank (EDB), the Islamic Development Bank Institute (IsDBI) and the London Stock Exchange Group (LSEG).



Working Paper 25/6
(RU/EN)

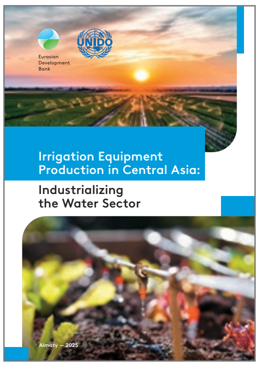
Macroeconomic model for analysis and forecasting of the Uzbekistan economy

The working paper presents the developed model of macroeconomic analysis and forecasting of the Uzbekistan economy. The integration of the new model into the EDB's model complex makes it possible to more accurately and comprehensively forecast the economic development of the Bank's region of operations, while taking into account close cross-country relationships.

Working Paper 25/5
(RU/EN)

Eurasian Transport Network: Projects Observatory and Interactive Map

This working paper aims to facilitate the monitoring and coordination of infrastructure development along the corridors and routes of the Eurasian Transport Network



Report
(RU/EN)

Irrigation Equipment Production in Central Asia: Industrializing the Water Sector

Irrigation equipment production in Central Asia is becoming a strategic area for ensuring food security and efficient water resource management. A new report by EDB and UNIDO provides a detailed analysis of the current state of the market, a forecast of its development and recommendations for creating conditions for local production.

Eurasian Development Bank

RESEARCH DEPARTMENT
EURASIAN DEVELOPMENT BANK

Your comments and suggestions concerning
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