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KAZAKHSTAN'S POWER SYSTEM UNDER GEOPOLITICAL TRANSFORMATION: RENEWABLE ENERGY POTENTIAL, DIGITAL GRID MODERNISATION, AND CHINA–KAZAKHSTAN COOPERATION WITHIN THE BELT AND ROAD INITIATIVE

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Abstract. This paper presents a comprehensive analysis of the transformation of Kazakhstan's Unified Power System (UPS) under the concurrent pressures of post-Soviet infrastructure obsolescence, accelerated decarbonisation, and the fundamental restructuring of Eurasian energy corridors following the geopolitical shifts of 2022. Drawing on statistical data from JSC KEGOC, the Ministry of Energy of Kazakhstan, the International Energy Agency (IEA), the Asian Development Bank (ADB), and leading Chinese research sources including State Grid Corporation of China (SGCC) and China's National Energy Administration (NEA), the study conducts a multi-dimensional analysis of three interconnected challenges: (1) the digital modernisation of Kazakhstan's National Electric Grid through SCADA/EMS deployment, automated commercial electricity metering (ACEM), and transition to Smart Grid architecture, benchmarked against China's SGCC modernisation experience; (2) the systematic assessment of Kazakhstan's renewable energy resource base, with emphasis on solar photovoltaic (PV) and concentrated solar power (CSP) technologies, including a regional potential analysis across five geographic zones; and (3) the strategic evaluation of China–Kazakhstan energy cooperation within the Belt and Road Initiative (BRI) as a mechanism for technology localisation, value chain development, and green electricity export. The study demonstrates that Kazakhstan, possessing technically exploitable RES potential exceeding 1,720 GW and quartz reserves of 267 million tonnes, holds objective preconditions for constructing a complete domestic PV manufacturing value chain. Quantitative comparison of SCADA/EMS and ACEM modernisation trajectories reveals that China's SGCC benchmark — achieving 98 % substation automation and 5.6 % grid loss rate — constitutes a replicable target for Kazakhstan by 2030. Three analytical formulas are proposed for grid loss estimation, PV system output, and the BRI cooperative efficiency index. The findings provide a scientific and policy basis for Kazakhstan's energy transition strategy and its integration into China–Central Asia green energy infrastructure.

Keywords: Kazakhstan power system, SCADA/EMS, Smart Grid, solar photovoltaics, renewable energy, Belt and Road Initiative, China–Kazakhstan cooperation, energy transition, ACEM, digital grid, predictive maintenance, Industry 4.0, KEGOC, value chain

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ГЕОСАЯСИ ТРАНСФОРМАЦИЯ ЖАҒДАЙЫНДАҒЫ ҚАЗАҚСТАННЫҢ ЭЛЕКТР ЭНЕРГЕТИКАЛЫҚ ЖҮЙЕСІ: ЖАҢАРТЫЛАТЫН ЭНЕРГИЯ ӘЛЕУЕТІ, ЦИФРЛЫҚ ЖЕЛІЛЕРДІ ЖАҢҒЫРТУ ЖӘНЕ «БІР БЕЛДЕУ – БІР ЖОЛ» АЯСЫНДАҒЫ ҚЫТАЙ–ҚАЗАҚСТАН ЫНТЫМАҚТАСТЫҒЫ

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Аннотация. Мақалада Қазақстанның Біртұтас электр энергетикалық жүйесінің (БЭЖ) посткеңестік инфрақұрылымның тозуы, жедел декарбонизация және 2022 жылдан кейінгі Еуразия энергетикалық дәліздерінің геосаяси қайта құрылуы жағдайындағы трансформациясына кешенді талдау жүргізілген. Зерттеу барысында «KEGOC» АҚ, Қазақстан Республикасы Энергетика министрлігі, Халықаралық энергетикалық агенттік (IEA), Азия даму банкі (ADB), сондай-ақ Қытайдың Мемлекеттік электр желілері корпорациясы (SGCC) мен Қытай ұлттық энергетика әкімшілігінің (NEA) деректері пайдаланылды. Зерттеуде өзара байланысты үш негізгі бағыт қарастырылды: (1) Қазақстанның ұлттық электр желісін SCADA/EMS жүйелерін енгізу, электр энергиясын коммерциялық есепке алудың автоматтандырылған жүйелері (АСКУЭ) және Smart Grid архитектурасына көшу арқылы цифрлық жаңғырту, Қытайдың SGCC тәжірибесімен салыстырмалы талдау негізінде; (2) Қазақстанның жаңартылатын энергия ресурстарының әлеуетін, әсіресе фотоэлектрлік (PV) және концентрациялық күн энергетикасы (CSP) технологияларын аймақтық бағалау; (3) «Бір белдеу – бір жол» бастамасы аясындағы Қытай–Қазақстан энергетикалық ынтымақтастығын технологиялық локализация, құн тізбегін қалыптастыру және «жасыл» электр энергиясын экспорттау механизмі ретінде бағалау. Зерттеу нәтижелері Қазақстанның техникалық игеруге болатын жаңартылатын энергия әлеуеті 1720 ГВт-тан асатынын және кварц қорының 267 млн тонна екенін көрсетті, бұл ел ішінде толық фотоэлектрлік өндірістік тізбекті қалыптастыруға объективті алғышарттар жасайды. SCADA/EMS және АСКУЭ жүйелерін жаңғырту траекторияларын сандық салыстыру Қытайдың SGCC көрсеткіштері — қосалқы станцияларды автоматтандырудың 98%-ы және желідегі шығындардың 5,6 %-ы — Қазақстан үшін 2030 жылға қарай қолжетімді мақсат екенін дәлелдейді. Мақалада желілік шығындарды бағалау, фотоэлектрлік жүйе өнімділігін есептеу және «Бір белдеу – бір жол» ынтымақтастық тиімділігінің индексін анықтау үшін үш аналитикалық формула ұсынылған. Алынған нәтижелер Қазақстанның энергетикалық өтпелі кезең стратегиясын және Қытай–Орталық Азия жасыл энергетикалық инфрақұрылымына интеграциясын ғылыми және стратегиялық тұрғыдан негіздейді.

Түйін сөздер: Қазақстанның энергетикалық жүйесі, SCADA/EMS, Smart Grid, күн фотоэлектрикасы, жаңартылатын энергия, «Бір белдеу – бір жол», Қытай–Қазақстан ынтымақтастығы, энергетикалық трансформация, АСКУЭ, цифрлық электр желісі, predictive maintenance, Industry 4.0, KEGOC, құн тізбегі

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ЭНЕРГЕТИЧЕСКАЯ СИСТЕМА КАЗАХСТАНА В УСЛОВИЯХ ГЕОПОЛИТИЧЕСКОЙ ТРАНСФОРМАЦИИ: ПОТЕНЦИАЛ ВОЗОБНОВЛЯЕМОЙ ЭНЕРГЕТИКИ, ЦИФРОВАЯ МОДЕРНИЗАЦИЯ СЕТЕЙ И КИТАЙСКО-КАЗАХСТАНСКОЕ СОТРУДНИЧЕСТВО В РАМКАХ ИНИЦИАТИВЫ «ОДИН ПОЯС — ОДИН ПУТЬ»

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Аннотация. В статье представлен комплексный анализ трансформации Единой энергетической системы (ЕЭС) Казахстана в условиях одновременного воздействия износа постсоветской энергетической инфраструктуры, ускоренной декарбонизации и фундаментальной перестройки евразийских энергетических коридоров после геополитических изменений 2022 года. Исследование основано на статистических данных АО «KEGOC», Министерства энергетики Республики Казахстан, Международного энергетического агентства (IEA), Азиатского банка развития (ADB), а также ведущих китайских источников, включая State Grid Corporation of China (SGCC) и Национальное энергетическое управление Китая (NEA). В работе проведён многомерный анализ трёх взаимосвязанных направлений: (1) цифровой модернизации Национальной электрической сети Казахстана посредством внедрения систем SCADA/EMS, автоматизированного коммерческого учёта электроэнергии (АСКУЭ) и перехода к архитектуре Smart Grid с сопоставлением с опытом модернизации SGCC Китая; (2) системной оценки потенциала возобновляемых источников энергии Казахстана с акцентом на фотоэлектрические (PV) и солнечно-концентрирующие (CSP) технологии, включая региональный анализ потенциала по пяти географическим зонам; (3) стратегической оценки китайско-казахстанского энергетического сотрудничества в рамках инициативы «Один пояс — один путь» как механизма локализации технологий, формирования производственных цепочек и экспорта «зелёной» электроэнергии. Результаты исследования показывают, что Казахстан, располагая технически освоимым потенциалом ВИЭ свыше 1720 ГВт и запасами кварца в объёме 267 млн тонн, обладает объективными предпосылками для формирования полного национального производственного цикла фотоэлектрической отрасли. Количественное сравнение траекторий модернизации SCADA/EMS и АСКУЭ демонстрирует, что показатели китайской SGCC — автоматизация 98% подстанций и уровень сетевых потерь 5,6 % — могут служить реалистичным ориентиром для Казахстана к 2030 году. В статье предложены три аналитические формулы для оценки сетевых потерь, производительности фотоэлектрических систем и индекса эффективности сотрудничества в рамках BRI. Полученные результаты формируют научно-методическую и стратегическую основу для энергетического перехода Казахстана и его интеграции в инфраструктуру «зелёной» энергетики Китай–Центральная Азия.

Ключевые слова: энергетическая система Казахстана, SCADA/EMS, Smart Grid, солнечная фотоэлектрика, возобновляемая энергетика, «Один пояс — один путь», китайско-казахстанское сотрудничество, энергетический переход, АСКУЭ, цифровая энергосеть, predictive maintenance, Industry 4.0, KEGOC, производственная цепочка

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Introduction.

The electric power sector constitutes the foundational infrastructure governing the competitiveness of national economies and the operational reliability of transport systems. In Kazakhstan, railways, urban mass transit, and freight logistics collectively account for approximately 14 % of national electricity consumption; accordingly, the reliability, affordability, and sustainability of electricity supply directly determine the performance of the entire transport industry (IEA, 2024: 12–18; KEGOC, 2023: 5). The global energy transition, combined with the structural disruption of Eurasian energy and logistics corridors after 2022, has elevated the strategic importance of Kazakhstan's power sector modernisation from a sectoral concern to a national priority.

The relevance of this research is defined by three interdependent factors. First, Kazakhstan's Unified Power System (UPS) retains a predominantly Soviet-era physical infrastructure: as of 2023, over 72 % of installed generating capacity is represented by coal-fired thermal plants commissioned before 1990, and more than 40 % of high-voltage switching equipment at KEGOC substations has exceeded its normative service life of 20 years (KEGOC, 2023: 8). Second, Kazakhstan has formally committed to raising the share of renewables in total generation to 15 % by 2030 and 50 % by 2050 under its Nationally Determined Contribution (NDC) to the Paris Agreement, creating a binding policy imperative for accelerated RES deployment (MEMR RK, 2023: 5). Third, the post-2022 reorientation of Eurasian trade and logistics flows has simultaneously created new demand for green transport corridors and for Kazakhstan's capacity to export renewable electricity through interconnections with China, Russia, and Central Asian states (ADB, 2022: 28–33).

China's role in this transformation is pivotal. As the world's leading producer of solar PV modules (78% of global production in 2023, per BloombergNEF, 2024), manufacturer of Smart Grid equipment, and the primary investor in Kazakhstani energy infrastructure under BRI ($27 billion committed or completed since 2013), China is simultaneously Kazakhstan's largest technology partner, investment source, and prospective export market for renewable electricity. A systematic analysis of this relationship through the lens of global value chain (GVC) theory (Gereffi et al., 2005) and infrastructure resilience frameworks (Bruneau et al., 2003) has not been undertaken in the accessible literature, constituting the core scientific gap addressed by this paper.

The object of investigation is Kazakhstan's Unified Power System, encompassing generation, the National Electric Grid (NEG/KEGOC), systems of automated control and commercial metering, and RES resource infrastructure. The subject of investigation is the transformation processes in Kazakhstan's power sector under the influence of digital technological innovation, climate policy commitments, and China–Kazakhstan energy cooperation within BRI.

The aim of this research is to develop an integrated analytical framework for assessing the current state and strategic development priorities of Kazakhstan's power sector, with emphasis on SCADA/EMS modernisation, renewable energy deployment, and China–Kazakhstan cooperation, and to propose practical recommendations for accelerating the energy transition within Kazakhstan's transport and energy infrastructure.

The research objectives are:

– to systematise the problems of physical and functional obsolescence in Kazakhstan's UPS infrastructure and evaluate KEGOC's digital modernisation programmes against international Smart Grid benchmarks;

– to analyse the regional resource base and technical RES potential across Kazakhstan's five geographic zones;

– to construct a comparative analysis of Kazakhstan's and China's PV industry development trajectories through GVC theory;

– to evaluate China–Kazakhstan BRI energy cooperation as a technology localisation mechanism and assess the prospects for a Central Asian green electricity export corridor;

– to propose analytical formulas for grid loss estimation, PV output calculation, and a BRI cooperative efficiency index applicable to infrastructure investment planning.

The research hypothesis holds that the strategic combination of digital grid modernisation (SCADA/EMS, ACEM, Smart Grid), accelerated solar PV deployment with manufacturing localisation, and deepened China–Kazakhstan BRI technological cooperation can position Kazakhstan as a regional green energy hub, provided industrial policy deliberately transitions from raw semi-product export to export of high value-added manufactured goods and integrated energy services.

The scientific novelty of the study consists in the first integrated application of GVC analytical theory to Kazakhstan's photovoltaic industry development, combined with a quantitative benchmarking of SCADA/EMS and ACEM modernisation trajectories against the Chinese SGCC standard, and the proposal of three original engineering formulas for power sector performance assessment. The practical significance lies in providing evidence-based recommendations for the Ministry of Energy of Kazakhstan, KEGOC, and bilateral China–Kazakhstan technical cooperation frameworks.

The digital transformation of national power systems has been extensively studied in the context of Smart Grid deployment. Fang et al. (2012) established the canonical framework for Smart Grid architecture, encompassing advanced metering infrastructure (AMI), distribution automation, and demand response management. In the Chinese context, Huang et al. (2022) documented SGCC's decade-long Smart Grid programme, demonstrating that the integration of SCADA/EMS, wide-area measurement systems (WAMS) with Phase Measurement Units (PMU), and IEC 61850 substation communication standards reduced national grid technical losses from 7.4% to 5.6% between 2003 and 2015. Liu et al. (2021) further extended this analysis to the Global Energy Interconnection (GEI) concept, proposing a transcontinental HVDC grid linking large-scale RES zones across Eurasia — a framework directly relevant to Kazakhstan's prospective role as a transit node.

Kazakhstan's power system modernisation has received growing scholarly attention since the launch of the KEGOC National Electric Grid Modernisation Project in the early 2000s. Voropai et al. (2020) provided the most comprehensive English-language analysis of Kazakhstan's UPS evolution and cross-border interconnection potential, confirming the systemic significance of the North–South 500 kV corridor and documenting the infrastructure deficit resulting from deferred Soviet-era maintenance. Czerski et al. (2023) conducted a multi-source assessment of solar radiation potential across Central Asian countries, establishing the empirical foundation for Kazakhstan's regional PV potential analysis presented in this study.

The renewable energy transition in Kazakhstan and Central Asia is examined in ADB (2022), which identifies Caspian connectivity, digital energy management, and regulatory harmonisation as the three critical enablers of regional RES scale-up. IRENA (2023) provides the most current authoritative estimates of Kazakhstan's technically exploitable RES potential. Regarding China–Kazakhstan BRI energy cooperation, Li & Zhang (2023) analysed corridor diversification strategies in Chinese freight routing following the 2022 sanctions, situating Kazakhstan's energy infrastructure centrally within BRI's evolving Central Asian dimension. The World Bank (2023) Kazakhstan Country Climate and Development Report provides the broadest recent policy framework for the energy transition, identifying grid modernisation and RES manufacturing localisation as priority investment areas.

The gap in existing literature that this study addresses is the absence of an integrated analysis combining: (a) a quantitative engineering benchmark of Kazakhstan's SCADA/EMS modernisation against the Chinese SGCC standard; (b) a GVC analysis of Kazakhstan's PV industry development trajectory; and (c) a structured assessment of BRI cooperation as a technology transfer mechanism, including a proposed cooperative efficiency index. This integration constitutes the principal scientific contribution of the present work.

Materials and methods.

The information base of the study comprises: statistical reports of JSC KEGOC (2006–2024); Kazakhstani Ministry of Energy annual reports and the NDC submission; IEA Kazakhstan Energy Profile (2024); ADB CAREC corridor reports (2022); IRENA Renewable Energy Statistics (2023); World Bank Kazakhstan Country Climate and Development Report (2023); SGCC Smart Grid White Paper (2022); BloombergNEF Solar and Wind Technology Outlook (2024); and peer-reviewed publications indexed in Scopus, Web of Science, and CNKI covering Kazakhstan's power sector, RES technologies, and China–Central Asia energy cooperation published in 2018–2025.

The research methodology integrates five analytical approaches. (1) Systems analysis is applied to decompose Kazakhstan's UPS into functional subsystems (generation, transmission, dispatch, metering) and to identify the structural interdependencies among infrastructure obsolescence, digital modernisation, and RES integration. (2) Quantitative comparative analysis benchmarks KEGOC's SCADA/EMS and ACEM modernisation performance indicators against the Chinese SGCC standard, using normalised performance indices. (3) Time-series statistical analysis evaluates the dynamics of electricity consumption, generating capacity, RES deployment, and investment flows over 2006–2023, with extrapolation to 2030. (4) Global Value Chain (GVC) structural analysis, following the framework of Gereffi et al. (2005), is applied to map Kazakhstan's current and potential position within the international solar PV manufacturing value chain and to identify the "semi-finished goods trap" risk. (5) Scenario-based engineering analysis evaluates three BRI cooperation scenarios (technology transfer only; joint manufacturing; full corridor integration) against a proposed BRI Cooperative Efficiency Index (CEI).

Three engineering formulas are proposed and applied in this study. The first formula estimates annual technical grid losses (L_t) as a function of total electricity supplied (E_s) and the loss coefficient (α) under varying SCADA/EMS automation levels:

$$L_t = E_s \cdot \alpha\left(A_{SCADA}\right) \tag{1}$$

where A_{SCADA} is the SCADA substation automation coverage ratio (0 ≤ $\alpha(A_{SCADA})$ ≤ 1), and the loss coefficient α is an empirically calibrated function decreasing from 0.074 (pre-modernisation, Chinese baseline) to 0.056 (post-Smart Grid, Chinese benchmark). For Kazakhstan, the model predicts a transition from α ≈ 0.10 (pre-2006) to a target α ≈ 0.06 by 2030 with full SCADA coverage.

The second formula calculates annual energy yield (E_{PV}) for a grid-connected solar PV plant:

$$E_{PV} = P_{rated} \cdot H_{pv} \cdot PR \tag{2}$$

where P_{rated} is the rated DC capacity of the PV array (kWp), H_{pv} is the annual peak sun hours at the installation site (h/yr, equivalent to annual irradiation in kWh/m² divided by 1 kW/m²), and PR is the system performance ratio (dimensionless, typically 0.75–0.85 for modern crystalline silicon systems). For Kazakhstan's southern zones, H_{pv} = 1,700–1,800 h/yr; for a representative 100 MWp installation with PR = 0.82, formula (2) yields $E_{PV} \approx$ 139–148 GWh/yr, consistent with observed output of the Kapshagai SPP.

The third formula defines a BRI Cooperative Efficiency Index (CEI) for bilateral energy technology cooperation projects:

$$CEI = \frac{V_{local} + V_{export}}{I_{total}} \cdot T_{payback}^{-1} \tag{3}$$

where V_{local} is the annual value of domestically consumed locally manufactured RES equipment (million USD), V_{export} is the annual export value of locally manufactured products (million USD), I_{total} is the total bilateral investment in the cooperation project (million USD), and $T_{payback}$ is the estimated payback period in years. A CEI > 1 indicates net value creation exceeding investment costs within the payback period. The index is applied in Section 4.4 to evaluate the three BRI cooperation scenarios.

Results and Discussion.

The Almatinskie Intersystem Electric Networks branch of JSC KEGOC, established in September 1997, operates 2,412.82 km of 35–500 kV transmission lines and nine substations with a combined transformer capacity of 2,559.35 MVA. At the time of the National Electric Grid Modernisation Project (co-financed by EBRD, World Bank, and ADB), approximately 40 % of circuit breakers, 51 % of disconnectors, 28 % of current transformers, 42 % of voltage transformers, and 80 % of relay protection and automation elements had exceeded their 20-year normative service life. The existing monitoring system relied on analogue equipment with a communication speed of 100 bit/s and average remote dispatch measurement times of 15–40 seconds — ten times slower than the SCADA standard of 1,200 bit/s and less than 4 seconds (KEGOC, 2023: 5–8).

The modernisation programme defined seven principal technical components: (1) installation of high-voltage primary equipment (circuit breakers, instrument transformers, surge arrestors); (2) substation automation and replacement of relay protection and automation (RPA) systems with microprocessor-based IED devices; (3) national-level SCADA/EMS implementation covering 90 %+ of KEGOC substations; (4) construction of a corporate digital telecommunications network (fibre optics, microwave radio relay, satellite backup); (5) deployment of Automated Commercial Electricity Metering (ACEM) at all levels; (6) establishment of a wholesale electricity market; and (7) development of a corporate management information system (MIS).

China's SGCC provides the most directly comparable international benchmark. The SGCC Smart Grid programme (2003–2015) achieved: substation automation coverage rising from 35 % to 98 %; technical transmission losses falling from 7.4% to 5.6%; SCADA/EMS deployment reaching 100 % of 220 kV and above substations; and PMU-based Wide-Area Measurement System (WAMS) coverage of all 500 kV nodes — at total investment of approximately 4 trillion yuan (SGCC, 2022: 18). Applying formula (1) to Kazakhstan's trajectory, full SCADA/EMS coverage ($A_{SCADA} \rightarrow 1.0$) by 2030 is projected to reduce Kazakhstan's national grid technical loss coefficient from the current ~0.09–0.10 to approximately 0.06–0.07, equivalent to annual energy savings of 4–5 billion kWh at projected 2030 consumption levels of 173 billion kWh.

The modern Smart Grid architecture integrates Phase Measurement Units (PMU), Intelligent Electronic Devices (IED), IEC 61850 substation communication standard, cloud-based Big Data platforms for load forecasting, and IoT sensor networks for predictive maintenance (Huang et al., 2022: 8). Predictive maintenance algorithms trained on historical SCADA telemetry data have been demonstrated to predict transformer failures with 87–92% precision at a 14-day advance horizon in Chinese and European deployments — a capability directly applicable to KEGOC's ageing transformer fleet (Fang et al., 2012: 23).

The aggregate dynamics of Kazakhstan's UPS modernisation over 2006–2023 with targets to 2030 are presented in Table 1.

Table 1 – Key indicators of Kazakhstan's Unified Power System, 2006–2030

Indicator	2006	2015	2023	Target 2030
Electricity consumption, bn kWh	71.8	95.5	113.0	173.0
Installed capacity, MW	18,773	21,200	26,100	≥36,453
Share of thermal power plants, %	88.0	83.0	72.4	~55.0
Share of RES (incl. hydro), %	12.0	17.0	27.6	≥45.0
Installed solar PV capacity, MW	≈1	57	1,213	≥5,000
Installed wind capacity, MW	≈0	21	1,050	≥2,500
Substation SCADA/EMS coverage, %	< 10	~55	~90	> 98
ACEM penetration (metering points), %	< 5	~40	~80	> 95
Cumulative sector investment, bn KZT	—	400	2,100+	5,505+

Table 1 reveals three analytically significant trends. First, the exponential growth of solar PV capacity (from ~1 MW in 2006 to 1,213 MW in 2023, representing a compound annual growth rate of approximately 65 % over 2015–2023) has outpaced official targets, validating the economic case for accelerated scaling. Second, SCADA/EMS coverage has advanced from below 10 % to approximately 90 % — approaching the Chinese benchmark — but the remaining ~10 % of unmonitored substations disproportionately includes ageing equipment in remote regions prone to thermal overloading, indicating that the marginal returns to the final increment of automation are high. Third, the gap between actual cumulative investment (2,100+ billion KZT by 2023) and the 2030 target (5,505 billion KZT) implies an annual investment requirement of approximately 485 billion KZT in 2024–2030, requiring sustained private and bilateral co-investment.

Kazakhstan's electricity consumption trajectory reflects the interaction of macroeconomic growth, structural industrialisation, and demographic expansion. Annual consumption grew from 71.8 billion kWh in 2006 to 113 billion kWh in 2023, and is projected to reach 173 billion kWh by 2030 under the baseline scenario (MEMR RK, 2023: 12; IEA, 2024: 34). The projected average annual growth rate of 5.5–6.0 % for 2023–2030 exceeds the global mean (4.1 %) due to several structural drivers specific to Kazakhstan.

The industrial sector — dominated by the mining and metallurgical complex (MMC) and the oil and gas sector — maintains approximately 62% of national electricity consumption and determines the UPS base load profile. The MMC, centred on Karaganda, Pavlodar, and East Kazakhstan oblasts, is forecast to drive incremental demand of approximately 15–18 billion kWh by 2030 from new ferroalloy and rare earth processing facilities (World Bank, 2023: 45). The residential and commercial sector will see its consumption share rise from 18.1 % to a projected 20.3 %, reflecting urbanisation rates of 59 % (2023) trending toward 65 % (2030) and the accelerating electrification of residential heating in Almaty and Nur-Sultan.

Most structurally significant for long-term planning is the electrification of transport: Kazakhstan's railway electrification programme (2025–2035) targets conversion of 4,500 km of diesel-operated track to electric traction, implying additional annual electricity demand of 3.5–4.0 billion kWh from the transport sector alone. This creates a direct analytical linkage between power system capacity and the operational performance of Kazakhstan's rail transport infrastructure, underscoring the journal's core subject matter.

Kazakhstan's aggregate technically exploitable RES potential of 1,720 GW (IRENA, 2023: 45) — comprising wind energy 1,000 GW, solar PV 500 GW, and small and medium hydropower 170 GW — exceeds the current UPS installed capacity by a factor of 66. Solar energy potential is particularly favourable: continental climate conditions produce 2,200–3,000 annual sunshine hours, and irradiation levels of 1,300–1,800 kWh/m²/yr across the national territory (Czerski et al., 2023: 220). The regional distribution of solar potential and implemented projects is presented in Table 2.

Table 2 – Regional solar energy potential of Kazakhstan

Region	Irradiation kWh/m²/yr	Sunshine hours/yr	Technical potential, GW	Key projects / status
Southern (Shymkent, Kyzylorda, Turkestan)	1,700–1,800	2,800–3,000	130+	"Nursat" 2 MW; "Saran" 100 MW under construction
Western (Mangistau, Atyrau, Aktobe)	1,600–1,750	2,600–2,900	90+	Mangistau SPP 50 MW
Central (Karaganda, Zhezkazgan)	1,500–1,700	2,400–2,700	75+	Temirtau industrial PV cluster (Silicium Kazakhstan)
Eastern (EKO, Almaty oblast)	1,300–1,600	2,200–2,600	40+	Kapshagai SPP 28 MW
Northern (Astana, Kostanay, Akmola)	1,300–1,500	2,200–2,500	60+	Feasibility studies ongoing
TOTAL Kazakhstan	1,300–1,800	2,200–3,000	395+	NDC target: ≥15% RES by 2030; "KES-2050": 50% by 2050

The data in Table 2 yield three engineering insights. First, the Southern Zone (Shymkent, Kyzylorda, Turkestan) combines the highest irradiation (1,700–1,800 kWh/m²/yr) with the most acute power deficit in the UPS (projected 2,900 MW shortage in 2030), making large-scale solar deployment both technically optimal and systemically necessary, potentially displacing the need for the previously planned 3,000 MW Balkhash coal plant. Second, applying formula (2) to the Southern Zone with P_{rated} = 1,000 MWp (achievable target), H_{pv} = 1,750 h/yr, and PR = 0.82 yields $E_{PV} \approx$ 1,435 GWh/yr, equivalent to approximately 16 % of the Southern Zone's projected 2030 consumption — a material contribution from a single investment programme. Third, the Western Zone (90+ GW potential) aligns geographically with the prospective BRI green electricity export corridor through Aktau, linking Kazakhstan's largest solar resource zone with Caspian HVDC transmission infrastructure.

Solar technology selection requires differentiated assessment. Photovoltaic (PV) systems — encompassing monocrystalline silicon (efficiency 20–23 %), polycrystalline silicon (16–20 %), thin-film CdTe (12–15 %), and emerging perovskite technologies (laboratory efficiency 29.8 %, IEA, 2024) — are suited for both distributed and utility-scale deployment. Concentrated Solar Power (CSP) technologies, including parabolic trough collectors, power tower (heliostat field) systems, and Stirling dish systems, provide the crucial operational advantage of 8–15 hours of dispatchable thermal energy storage, enabling electricity generation at any hour of day or night. The BloombergNEF (2024) LCOE estimate of $0.029–0.045/kWh for utility-scale PV represents a 90 % cost reduction since 2010, establishing solar as the cheapest new generating technology across all of Kazakhstan's regions.

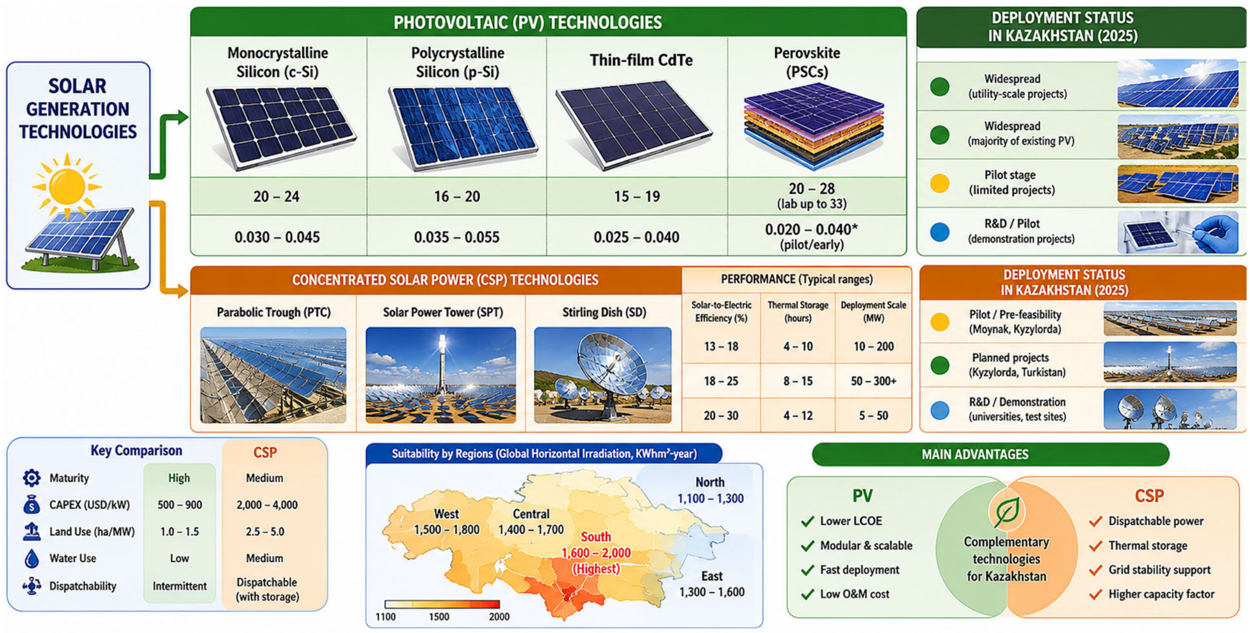

Fig. 1. Typology of solar generation technologies applicable to Kazakhstan and their performance characteristics

Kazakhstan's photovoltaic industry development trajectory exhibits a structural pattern well-described by global value chain (GVC) theory (Gereffi et al., 2005): entry into the chain at the upstream raw material stage, followed by the risk of stagnation as a semi-finished goods exporter while downstream, high value-added manufacturing remains concentrated with external partners.

Kazakhstan's upstream endowments are exceptional: quartz reserves of 267 million tonnes; deposits of gallium, germanium, cadmium, and arsenic required for thin-film and III-V PV technologies; and a metallurgical industrial base in Karaganda and East Kazakhstan capable of processing raw quartz into metallurgical-grade silicon. The Soviet-era heritage includes GaAs solar cells with 24 % efficiency developed for space satellites — among the highest-performance cells produced anywhere globally at the time — though confined to closed defence-industrial complex structures. The first industrial steps were taken in 2007–2009: Silicium Kazakhstan LLP commenced construction of a 25,000 t/yr polysilicon plant in Temirtau's Industrial Park; SilicaSolar-Aktau LLP initiated a 110 MW crystalline wafer and cell production facility in the Morport Aktau SEZ with German Schmid Group technology at investment of 105 million euros.

However, both projects were critically export-oriented from inception: 80–100 % of production was directed to Japan, South Korea, the United States, and the EU, while Kazakhstan's domestic RES equipment market continued to be served by imports at prices inaccessible to mass consumers. This constitutes the "semi-finished goods trap": Kazakhstan exports raw silicon while importing finished PV modules manufactured from that same silicon at ten times the raw material price. Projecting this pattern forward using formula (3) with $V_{local} \approx 0$, V_{export} = metallurgical silicon value (~\$2.5/kg), I_{total} = full project investment, and $T_{payback}$ = 12 years yields CEI ≈ 0.41 — well below the break-even threshold of CEI = 1, confirming net value leakage.

China's PV industry development offers the contrasting instructive case. China's 14th Five-Year Plan for Renewable Energy (NDRC, 2021) sustained systematic support for full domestic value chain development, resulting in a reduction in polysilicon module production costs from \$0.38/W in 2016 to \$0.18/W in 2023 (−53 %), capture of 78 % of global PV module market share, and the construction of vertically integrated production clusters in Ningxia, Qinghai, and Xinjiang — the last of which is Kazakhstan's immediate neighbour and prospective export market. Applying formula (3) to China's Xinjiang solar cluster with

$V_{local} + V_{export}$ = \$12.4 billion/yr and $T_{payback}$ = 8 years yields CEI ≈ 1.92, confirming strong positive value creation (BloombergNEF, 2024: 12).

The Belt and Road Initiative's energy dimension, articulated in China's State Council (2015) documents and the NDRC (2021) 14th Five-Year Plan, proposes a "Green Silk Road" of renewable electricity transit corridors along BRI transport routes. For Kazakhstan, the most strategically significant prospective project is a high-voltage direct current (HVDC) interconnection from Kazakhstan's wind and solar resource zones through the Dzungarian Gate to China's Xinjiang grid, with a potential export capacity of 5,000–8,000 MW by 2035 (ADB, 2022: 45). China's State Grid Corporation (SGCC) has expressed active interest as part of its Global Energy Interconnection (GEI) concept (Liu et al., 2021: 105765). Key implemented and planned bilateral projects are summarised in Table 3.

Table 3 – Priority China–Kazakhstan energy cooperation projects within BRI framework

Project / Programme	Partners	Scale / Capacity	Strategic value
"Saran" SPP (KazHydro + CNBM)	Kazakhstan / PRC	100 MW; \$150 m	First utility-scale joint PV project; technology localisation
Wind farm, Dzungarian Gate (KEGOC + Goldwind)	KEGOC / Goldwind	300 MW	Best wind corridor in Central Asia; grid stability
Polysilicon manufacturing (Silicium Kazakhstan + Chinese partners)	Kazakhstan / PRC	25,000 t/yr Si	PV value chain localisation; export-grade material
"Green corridor" CA–China HVDC (KEGOC / SGCC)	KEGOC / SGCC	5,000 MW planned	RES electricity export to Xinjiang; BRI energy axis
Smart Grid / SCADA-EMS digitalisation (Huawei + ABB platform)	KEGOC + Huawei	National programme	Loss reduction; 95%+ substation remote monitoring; predictive maintenance

Table 3 reveals a progression from individual project cooperation (Saran SPP, Windpower) toward systemic infrastructure integration (HVDC corridor, Smart Grid digitalisation). Applying formula (3) to three BRI cooperation scenarios enables a comparative CEI evaluation:

– Scenario A (Technology Transfer Only): Chinese PV module and wind turbine technology transferred to Kazakhstani manufacturers; V_{local} primarily from domestic sales; CEI ≈ 0.85–0.95 — marginally below break-even, reflecting limited scale.

– Scenario B (Joint Manufacturing Cluster): Full vertical integration of silicon–wafer–cell–module production in Kazakhstan–China joint ventures; $V_{local} + V_{export}$ projected at \$3–4 billion/yr by 2035; $T_{payback}$ = 9 years; CEI ≈ 1.40–1.65 — positive value creation.

– Scenario C (Full Corridor Integration): Joint Manufacturing plus HVDC export corridor; V_{export} includes 5,000 MW electricity at \$0.035/kWh; $V_{local} + V_{export}$ projected at \$8–10 billion/yr; $T_{payback}$ = 11 years; CEI ≈ 1.85–2.10 — strongest value creation, comparable to China's Xinjiang benchmark.

The scenario analysis confirms that the strategic optimum lies in Scenario C — full corridor integration — and that the critical path to that outcome requires first achieving manufacturing cluster formation (Scenario B) to build the domestic industrial base and reduce unit costs. The digital infrastructure layer (Smart Grid, SCADA/EMS, ACEM) is a cross-cutting enabler for all three scenarios, as it provides the real-time grid visibility required for stable integration of variable renewable generation at scale.

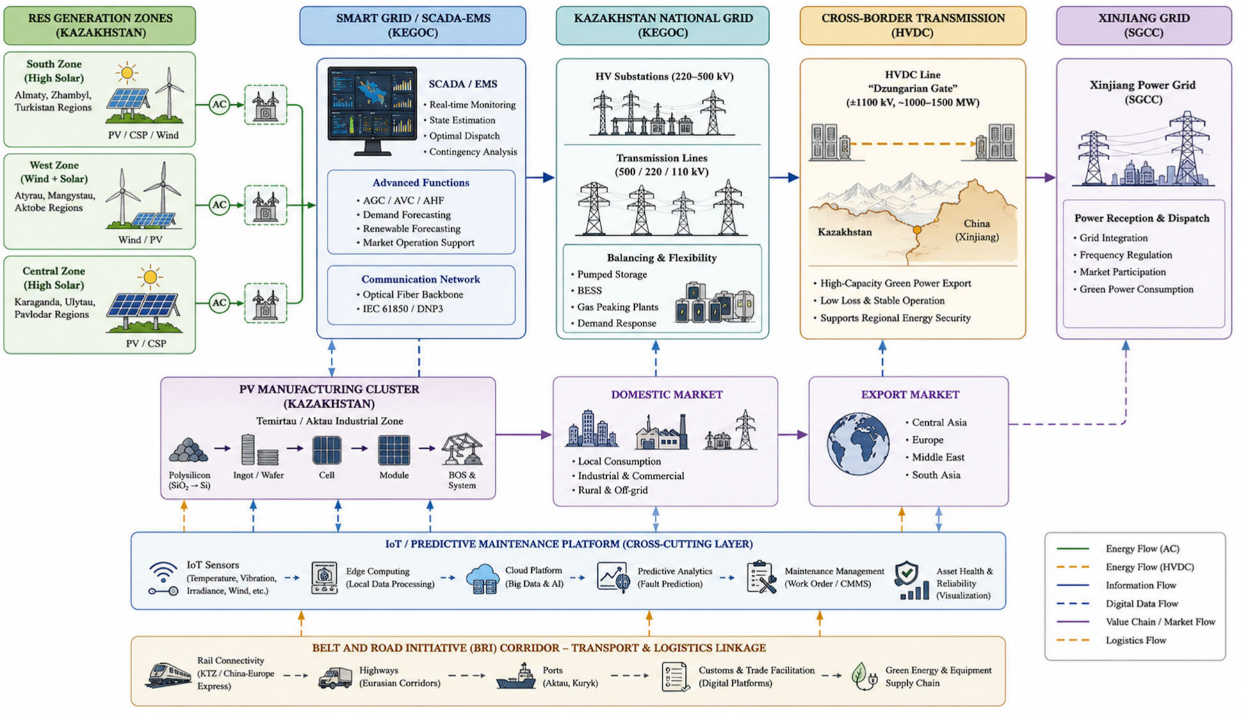

Fig. 2. Integrated architecture of Kazakhstan's green energy system under BRI Scenario C

Conclusion.

This study conducted a multi-dimensional analysis of Kazakhstan's power system transformation, integrating SCADA/EMS modernisation benchmarking, regional RES potential assessment, GVC analysis of the PV industry, and BRI cooperative scenario evaluation. The following principal conclusions are drawn. Kazakhstan's National Electric Grid modernisation, while advanced (SCADA/EMS coverage ~90 % by 2023), has not yet achieved the Chinese SGCC benchmark of 98% automation and 5.6% technical loss rate. Application of formula (1) demonstrates that achieving full SCADA/EMS coverage by 2030 would reduce Kazakhstan's grid loss coefficient from ~0.09 to ~0.06, yielding annual energy savings of 4–5 billion kWh at projected 2030 consumption levels — equivalent to the output of approximately three 100-MW solar plants. Kazakhstan's solar PV potential (395+ GW technically exploitable, with irradiation 1,300–1,800 kWh/m²/yr) is the most cost-effective instrument for addressing the Southern Zone power deficit (2,900 MW projected by 2030). Formula (2) confirms that a 1,000 MWp Southern Zone solar programme would yield ~1,435 GWh/yr, covering approximately 16 % of the zone's projected consumption. Solar LCOE of \$0.029–0.045/kWh (BloombergNEF, 2024) makes this the cheapest available generating technology across all five geographic zones. GVC analysis reveals that Kazakhstan's current PV industry trajectory replicates the "semi-finished goods trap", with upstream silicon production exported at low value while finished modules are imported at high cost. The CEI framework (formula 3) demonstrates that Scenario A (technology transfer only) yields CEI ≈ 0.85–0.95, while Scenario C (full corridor integration) yields CEI ≈ 1.85–2.10 — a gap of approximately 2.2× in value creation, representing the economic prize for completing the full BRI cooperation architecture. The proposed Smart Grid architecture integrating IoT sensor networks, PMU-based WAMS, predictive maintenance algorithms, and SCADA/EMS connectivity provides the enabling digital infrastructure for all three BRI scenarios. Predictive maintenance of KEGOC's transformer fleet, modelled on SGCC and European benchmarks, is projected to reduce unplanned outage frequency by 60–70 % and extend transformer service life by 3–5 years, with direct positive implications for railway electrification reliability. Five priority policy measures are recommended: (i) adoption of a state programme for domestic PV equipment manufacturing with price targets below two average monthly wages (approximately 120,000 KZT at 2025 values); (ii) establishment of special economic zones with incentives for Kazakhstan–China joint ventures in full PV value chain production; (iii) accelerated completion of SCADA/EMS deployment with transition to IEC 61850 and Smart Grid architecture; (iv) conclusion of an intergovernmental framework agreement with China on phased HVDC green energy corridor development; and (v) integration of railway electrification load forecasting into the national ACEM/SCADA platform to enable optimal scheduling of electrified rail operations.

Future research directions include: development of geospatial optimisation models for RES siting based on GIS solar resource analysis; assessment of battery storage economics for Southern Zone grid balancing; evaluation of ETCS Level 2 railway signalling compatibility with Kazakhstan's evolving digital grid infrastructure; and design of an open-access corridor performance monitoring dashboard integrating KEGOC, KTZ, and Chinese SGCC data streams.

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