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G.S. Nygymetov[1]*, G.S. Smagulova[1], R.K. Satova[2], L.Zh. Ashirbekova[1]

[1]Al-Farabi Kazakh National University, Almaty, Kazakhstan
[2]Almaty University of Power Engineering and Telecommunications named after G. Daukeev, Almaty, Kazakhstan
*e-mail: gansak1983@mail.ru

ECONOMIC POTENTIAL OF GREEN TECHNOLOGIES DIGITALIZATION FOR ACHIEVING CARBON NEUTRALITY IN KAZAKHSTAN

The research problem lies at the intersection of the climate and digital agendas of the Republic of Kazakhstan – a country that simultaneously ranks among the world's twenty largest greenhouse gas emitters and has committed to carbon neutrality by 2060. The purpose of the work is to quantify the synergetic economic effect of the joint deployment of digital and green technologies in Kazakhstan's energy sector. The scientific significance consists in extending the twin-transition concept to the class of resource-dependent economies with coal-dominated generation; the practical significance – in designing an operational framework for national decarbonization programmes. The methodology combines a five-vector effect decomposition through the explicit formula $E = \Sigma B_i \cdot R_i \cdot k_i \cdot P_i$, three-scenario modelling (business-as-usual, target, breakthrough), and comparative analysis of experience from Germany, China, Denmark, and the United States. Main results: under the target scenario, the direct annual economic effect by 2030 is estimated at USD 615–835 million, rising to USD 3.2–4.1 billion (1.0–1.3% of GDP) when multiplier effects are included; the potential CBAM burden on EU-bound exports is reduced by 32–38% through MRV digitalization. The research value consists in developing a methodology with justified realizability coefficients for Kazakhstan's institutional environment, as well as in constructing a matrix of twelve policy measures with measurable indicators. The practical significance of the results lies in their direct applicability in programmes of the Ministry of Energy and the AIFC, as well as in the transferability of the approach to comparable resource-dependent economies of the CIS and SCO.

Keywords: digitalization, green technologies, carbon neutrality, twin transition, Kazakhstan.

Г.С. Нығыметов[1]*, Г.С. Смағұлова[1], Р.К. Сатова[2], Л.Ж. Аширбекова[1]

[1]Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан
[2]Ғ. Дәукеев атындағы Алматы энергетика және байланыс университеті, Алматы, Қазақстан
*e-mail: gansak1983@mail.ru

Қазақстандағы көміртек бейтараптылығына жету үшін жасыл технологияларды цифрландырудың экономикалық әлеуеті

Зерттеу мәселесі Қазақстан Республикасының климаттық және цифрлық күн тәртібінің тоғысында жатыр. Қазақстан бір мезгілде әлемдегі парниктік газдардың ең ірі жиырма эмитентінің қатарына кіретін және 2060 жылға қарай көміртектік бейтараптыққа қол жеткізуді мақсат етіп отырған ел болып табылады. Жұмыстың мақсаты – Қазақстанның энергетика секторындағы цифрлық және «жасыл» технологияларды үйлесімді дамыту нәтижесінде туындайтын синергиялық экономикалық әсерді сандық тұрғыдан бағалау. Ғылыми маңыздылығы «қос өтпелі кезең» (twin transition) тұжырымдамасын көмір үстемдігі бар ресурсқа тәуелді экономикалар класына таратуда; практикалық маңыздылығы – декарбонизация бойынша ұлттық бағдарламалар үшін операциялық базаны қалыптастыруда. Әдіснама $E = \Sigma B^i \cdot R^i \cdot k^i \cdot P^i$ нақты формуласымен бес әсер ету бағыты бойынша декомпозицияны, үш сценарлы модельдеуді (инерциялық, мақсатты, серпінді сценарийлер) және Германия, Қытай, Дания, АҚШ тәжірибесіне салыстырмалы талдауды біріктіреді. Негізгі нәтижелер: мақсатты сценарий шеңберінде 2030 жылға қарай жылдық тікелей әсер 615–835 млн АҚШ долларын, мультипликаторларды ескергендегі жиынтық әсер – 3,2–4,1 млрд долл. (ЖІӨ-нің 1,0–1,3%) құрайды; ЕО-ға экспортқа CBAM-ның ықтимал жүктемесі MRV-ні цифрландыру есебінен 32–38%-ға азаяды. Зерттеудің құндылығы – Қазақстанның институционалдық ортасы үшін негізделген жүзеге асыру коэффициенттерімен әдіснаманы әзірлеуде, сондай-ақ өлшенетін индикаторлары бар он екі саяси шарадан тұратын матрицаны құруда. Нәтижелердің практикалық маңызы – Энергетика министрлігі мен AIFC келей қолдану және тәсілді ТМД мен ШЫҰ-ның ұқсас ресурсқа тәуелді экономикаларына тарату мүмкіндігі.

Түйін сөздер: цифрландыру, жасыл технологиялар, көміртек бейтараптылығы, қос өтпелі кезең, Қазақстан.

Г.С. Нығыметов[1]*, Г.С. Смагулова[1],
Р.К. Сатова[2], Л.Ж. Аширбекова[1]

[1]Казахский национальный университет имени аль-Фараби, Алматы, Казахстан
[2]Алматинский университет энергетики и связи имени Г. Даукеева, Алматы, Казахстан
*e-mail: gansak1983@mail.ru

Экономический потенциал цифровизации зелёных технологий для достижения углеродной нейтральности в Казахстане

Проблематика исследования лежит на стыке климатической и цифровой повесток Республики Казахстан – страны, одновременно входящей в двадцатку крупнейших эмитентов парниковых газов мира и декларирующей углеродную нейтральность к 2060 году. Цель работы – количественно оценить синергетический экономический эффект от сопряжённого развития цифровых и «зелёных» технологий в энергетическом секторе Казахстана. Научная значимость состоит в распространении концепции «двойного перехода» (twin transition) на класс ресурсозависимых экономик с угольной доминантой; практическая значимость – в формировании операциональной рамки для национальных программ декарбонизации. Методология сочетает декомпозицию эффекта по пяти направлениям воздействия с явной формулой $E = \Sigma B^i \cdot R^i \cdot k^i \cdot P^i$, трёхсценарное моделирование (инерционный, целевой, прорывной сценарии) и сравнительный анализ практики Германии, Китая, Дании и США. Основные результаты: в целевом сценарии прямой годовой экономический эффект к 2030 году оценивается в 615–835 млн долл. США, совокупный с учётом мультипликаторов – в 3,2–4,1 млрд долл. (1,0–1,3 % ВВП); потенциальная нагрузка CBAM на экспорт в ЕС сокращается на 32–38 % за счёт цифровизации MRV. Ценность исследования состоит в разработке методики с обоснованными коэффициентами реализуемости для институциональной среды Казахстана, а также в построении матрицы из двенадцати политических мер с измеримыми индикаторами. Практическое значение результатов – прямое использование в программах Министерства энергетики и AIFC, а также возможность переноса подхода на сопоставимые ресурсозависимые экономики СНГ и ШОС.

Ключевые слова: цифровизация, зелёные технологии, углеродная нейтральность, двойной переход, Казахстан.

Introduction

Climate change has reshaped the architecture of twenty-first century economic policy, dissolving the traditional separation between energy and environmental agendas. Within this reshaped landscape, Kazakhstan occupies a distinctive position: the country simultaneously ranks among the twenty largest global emitters of greenhouse gases and has adopted one of the most ambitious regional commitments – reaching carbon neutrality by 2060 (Decree of the President of RK, 2023). The Carbon Neutrality Strategy envisages a comprehensive restructuring of the national economy, with aggregate investment requirements estimated at approximately USD 610 billion (Resolution of the Government of RK, 2023).

A key, yet often underappreciated, channel for realising this transformation is digitalization. A distinguishing feature of the current phase of the global energy transition is its inseparable link to digital technologies: the most advanced economies pursue decarbonization and digital modernisation simultaneously – a pattern established in academic literature under the term twin transition (Ajunwa & Nguyen, 2023). Empirical studies consistently show that digital intensification of energy systems reduces the unit operating costs of renewable assets, enhances generation predictability, and lowers non-technical losses. According to the International Energy Agency, intelligent grids and consumer-facing applications alone could save approximately USD 1.8 trillion in global energy investment by 2050 (IEA, 2022).

The object of the research is the process of jointly developing digital and green technologies in Kazakhstan's power sector. The subject – the economic effects arising at the intersection of these two transformational processes.

The Kazakhstani academic debate on decarbonization has developed primarily within engineering and regulatory frames. Existing studies examine either renewable energy and its barriers, or the digitalization of energy assets, as separate phenomena, without quantitatively comparing their effects or assessing their synergy. This separation leaves unanswered a practically important question: what is the economic contribution of the joint – rather than sequential – application of digital and green solutions in a resource-dependent economy with dominant coal generation? The present article addresses this question through quantitative assessment.

The objective of the research is to quantify the synergetic economic effect of green technologies digitalization in Kazakhstan and to formulate policy priorities enabling its realisation. Achieving this objective requires solving five tasks: refining the country's carbon profile and the baseline of energy digitalization; systematising relevant international experience; developing a transparent analytical framework for economic assessment; building a three-scenario model of effects through 2030; identifying systemic barriers and proposing a matrix of policy measures with measurable indicators. The research hypothesis states that under Kazakhstani conditions, the synergy of digital and green technologies generates an economic effect sufficient to justify accelerated state investment (at least 1% of GDP annually), if price distortions in the carbon market are addressed in parallel.

This study primarily focuses on the energy sector because it represents one of the most significant sources of greenhouse gas emissions in Kazakhstan and remains central to national decarbonization policy. The energy sector also has a direct impact on the technological modernization of other industries, as the transition to low-carbon energy infrastructure creates systemic conditions for broader green economic transformation.

Other carbon-intensive sectors, including transport, mining, and agriculture, are also important for achieving carbon neutrality. However, they are not included in the main analytical framework of this article to maintain a clear research scope and avoid methodological dispersion. These sectors require separate sector-specific indicators, data structures, and regulatory assumptions, and therefore should be examined in future research.

The scientific novelty of the study comprises three elements. First, a calculation framework is proposed for assessing the economic performance of green technologies digitalization, distinguished by an explicit specification of the realizability coefficient that accounts for Kazakhstan's institutional constraints. Second, for the first time in the Kazakhstani context, a three-scenario comparison of direct, indirect, and multiplier effects is conducted across five impact vectors. Third, the barriers to the twin transition are linked, in matrix form, to a concrete set of policy instruments, implementing authorities, and key performance indicators.

Literature review

The theoretical foundation of this research rests at the intersection of three scholarly directions. The twin transition concept has been actively developed in the work of European researchers and international organisations. Ajunwa & Nguyen (2023), using a cross-country sample, show that exceeding the average level of digital readiness by one standard deviation is associated with a 15–20% reduction in GDP carbon intensity, controlling for structural factors. In a related study, the same authors (Ajunwa & Nguyen, 2022) establish a positive relationship between the depth of digitalization and the pace of renewable penetration in the electricity mix. Chien *et al.* (2021), analysing 68 OECD and emerging-market economies, empirically confirm a robust causal link between ICT diffusion and the intensity of the shift towards low-carbon sources.

The applied strand of the literature focuses on specific technological solutions – from intelligent dispatch to AI forecasting of renewable generation. Synthesis reports by the IEA (2022; 2023), IRENA (2023), and the World Bank (2022) converge on the following effect ranges: a 10–25% reduction in the operating costs of renewable assets, a 5–15% reduction in technical grid losses, and a 20–30% improvement in supply reliability. For resource-dependent economies, these ranges require downward adjustment to reflect additional friction arising from infrastructure deterioration and market structure.

The Kazakhstani segment of the literature is represented by studies systematising policy and regulatory barriers to renewable deployment (Karatayev *et al.,* 2016); constructing a spatial model of the national power system (Assembayeva *et al.,* 2020); evaluating energy efficiency potential in thermal generation (Sarbassov *et al.,* 2020). Guliyev (2024) provides a comprehensive assessment of Kazakhstan's energy transition progress and bottlenecks. An adjacent line of work – applied econometrics of decarbonization – is developed in Suiundikov *et al.* (2024), which models the impact of digitalization on the economic efficiency of Kazakhstan's energy industry. Comparable Central Asian studies highlight the same structural constraints: high coal dependence, deteriorating infrastructure, and underdeveloped market institutions.

The three streams above have developed in parallel, without meeting in a common analytical frame. Within the twin-transition concept, no quantitative decomposition and verification of effects has been attempted for Kazakhstan. Applied work on power-sector digitalization rarely moves beyond technological description and does not connect these solutions to the 2060 carbon agenda. Strictly decarbonization-focused models do not include an explicit digital component. The present study addresses this gap by integrating the three streams within a single analytical framework and proposing a formalised procedure for linking digital solutions to carbon-policy objectives.

Methodology

Research question. What is the quantitative economic effect that the digitalization of green technologies in Kazakhstan's energy sector could yield by 2030, given existing institutional constraints?

Hypothesis. Under Kazakhstani conditions, the synergy of digital and green technologies generates an economic effect sufficient to justify accelerated state investment (at least 1% of GDP annually), provided that price distortions in the carbon market are addressed in parallel.

Research stages. The work proceeds through six stages: (1) verification of the country's carbon profile using primary sources; (2) systematisation of international practice in green-technology digitalization; (3) formalisation of the effect-decomposition framework; (4) end-to-end calculation of economic effects across five impact vectors; (5) three-scenario uncertainty assessment; (6) construction of the policy-measures matrix linked to barriers, horizons, and indicators.

Research methods. The work combines four approaches: structural-functional analysis (to describe the chain 'digital solution → physical effect → cost saving → contribution to carbon intensity'); comparative study (to identify practices applicable to Kazakhstani conditions); decomposition calculation (for assessment of effects by vector); scenario modelling (for quantification of uncertainty). Triangulation of sources ensures verification of numerical parameters across three independent databases for every key indicator.

The aggregate annual effect was estimated using the following decomposition model:

$$E = \Sigma B_i \cdot R_i \cdot k_i \cdot P_i \tag{1}$$

Where:

B_i – baseline resource volume;

R_i – technological reduction coefficient;

k_i – realizability coefficient;

P_i – unit price of the resource;

i – digitalization vector (AMI, AI forecasting, BMS, MRV, optimization of TPPs and grids).

The realizability coefficient k_i is adopted in a lower range relative to European practice (which uses 0.8–0.9) based on four factors that sequentially reduce the theoretical potential. The infrastructural factor relates to grid obsolescence, which constrains the integration of new digital solutions without accompanying capital investment. The regulatory factor reflects suppressed tariffs that limit the profitability of modernisation. The human-capital factor relates to the shortage of qualified digital energy engineers. The organisational factor captures inertia in large incumbent energy companies. The upper bound $k_i = 0.8$ applies to vectors with mature regulatory foundations (AMI, MRV); the lower bound $k_i = 0.6$ is reserved for vectors facing the highest regulatory friction (thermal power plant optimization).

End-to-end example (Vector 1 – AMI). The rollout of four million smart meters by 2027 covers approximately 85% of residential and small-commercial consumers. Aggregate non-technical losses in Kazakhstan's distribution grids are estimated at 5.8 TWh per year; the loss-reduction coefficient for automated metering, per World Bank data (World Bank, 2022), is R = 0.15–0.20. With realizability coefficient k = 0.75 and a weighted average price of lost energy P = 19 KZT/kWh (approximately USD 0.042 at the rate of 453 KZT/USD), the calculation yields $E_i = 5.8 \cdot 10_i \cdot 0.175 \cdot 0.75 \cdot 0.042 \approx$ USD 32 million. Additional effects include reduced commercial losses at the retail level, lower costs of meter-reading and billing, and improved payment discipline – together contributing USD 60–75 million. The resulting range of the effect for this vector is USD 95–110 million per year.

The assessment is carried out in three scenarios through 2030 differing in deployment pace and regulatory intensity (parameters in Table 6). Indirect and multiplier effects are tracked separately through three channels: creation of new jobs in the green and IT sectors (following the IRENA & ILO (2024) methodology); induced demand for related services – engineering, information security, consulting; and additional tax revenues. The overall multiplier m is set at 4.0–5.5 based on comparable country studies.

Data sources. The analysis uses primary data from the International Energy Agency (IEA, 2022; IEA, 2023), IRENA (2023), the World Bank (2022), ICAP (2024), EBRD (2024), UNFCCC (2025), IMF (2023), the Ministry of Energy of the Republic of Kazakhstan, the Bureau of National Statistics of the Republic of Kazakhstan, JSC KEGOC, and the AIFC (2023) for the period 2018–2025. Monetary indicators are converted to USD at the corresponding year's average exchange rate.

The selection of model parameters was based on a combination of theoretical assumptions, available national statistical data, strategic policy documents, and expert interpretation of Kazakhstan's decarbonization priorities. Although the proposed model does not claim to provide a fully econometrically validated forecast, it offers an indicative analytical framework for assessing the economic potential of green technologies digitalization under the conditions of Kazakhstan's transition toward carbon neutrality.

Econometric validation was not the primary objective of this study, as the article is focused on developing a conceptual and scenario-based assessment framework rather than testing causal relationships through time-series or panel data models. Future studies may expand the proposed approach by applying econometric techniques to validate the relationships between digitalization indicators, green technology adoption, investment intensity, and emission reduction outcomes.

The study does not include Monte Carlo simulation, which may be considered a limitation of the proposed model. Probabilistic simulation could further strengthen the robustness of the findings by estimating the range of possible outcomes under different combinations of uncertain parameters. This approach is recommended for future research.

Results and discussion

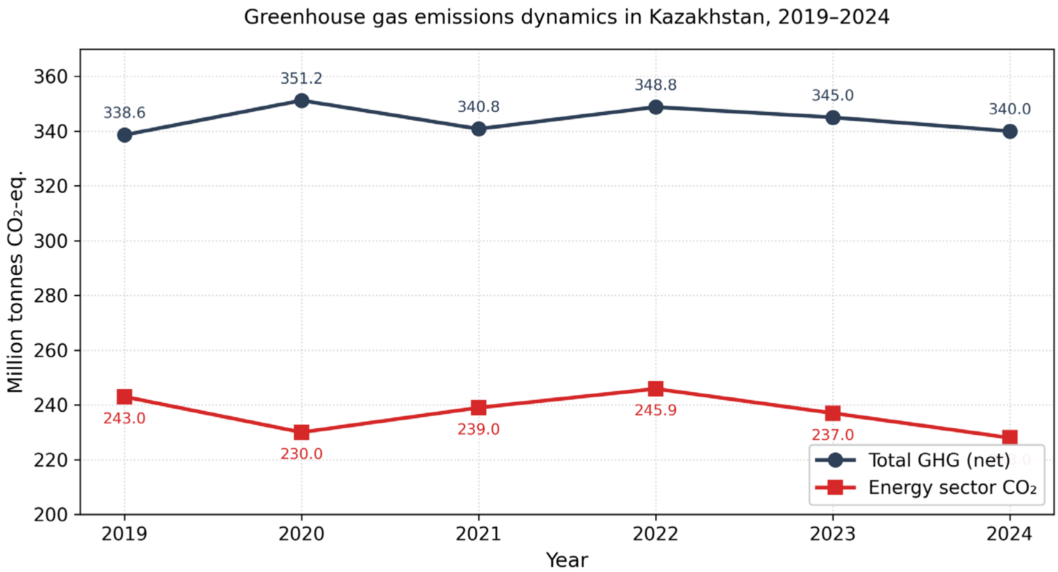
Carbon profile: initial conditions

According to the First Biennial Transparency Report (UNFCCC, 2025), Kazakhstan's aggregate net greenhouse gas emissions in 2022 amounted to 348.8 million tonnes CO_2-eq., which is 8.5% below the 1990 baseline (385.4 Mt). Preliminary data for 2024, according to Enerdata's early estimates, indicate a moderate downward trend of 1.5–2% year-on-year; however, this trend is not yet sustainable and is sensitive to winter heat-consumption variability (Figure 1).

Aggregated emissions dynamics over the past six years are presented in Table 1. The UNFCCC BTR1 dataset serves as the primary series, cross-checked against IEA and Enerdata.

Figure 1

Greenhouse gas emissions dynamics in Kazakhstan, 2019–2024



Note: compiled by the authors based on sources (UNFCCC, 2025; IEA, 2022)

Table 1
Greenhouse gas emissions dynamics in Kazakhstan, 2019–2024

Year	Total GHG (net), Mt CO_2-eq.	Energy sector, Mt CO_2	Cross-check with alternative source
2019	338.6	243.0	IEA: 340.1 (+0.4%)
2020	351.2	230.0	IEA: 347.8 (−1.0%)
2021	340.8	239.0	UNCTAD: 342.5 (+0.5%)
2022	348.8	245.9	EDGAR: 350.1 (+0.4%)
2023	≈345.0	237.0	IEA: 343.7 (−0.4%)
2024*	≈340.0	≈228.0	Enerdata: 339.0 (−0.3%)

Note: Preliminary estimate. Compiled by the authors based on sources (UNFCCC, 2025; IEA, 2022)

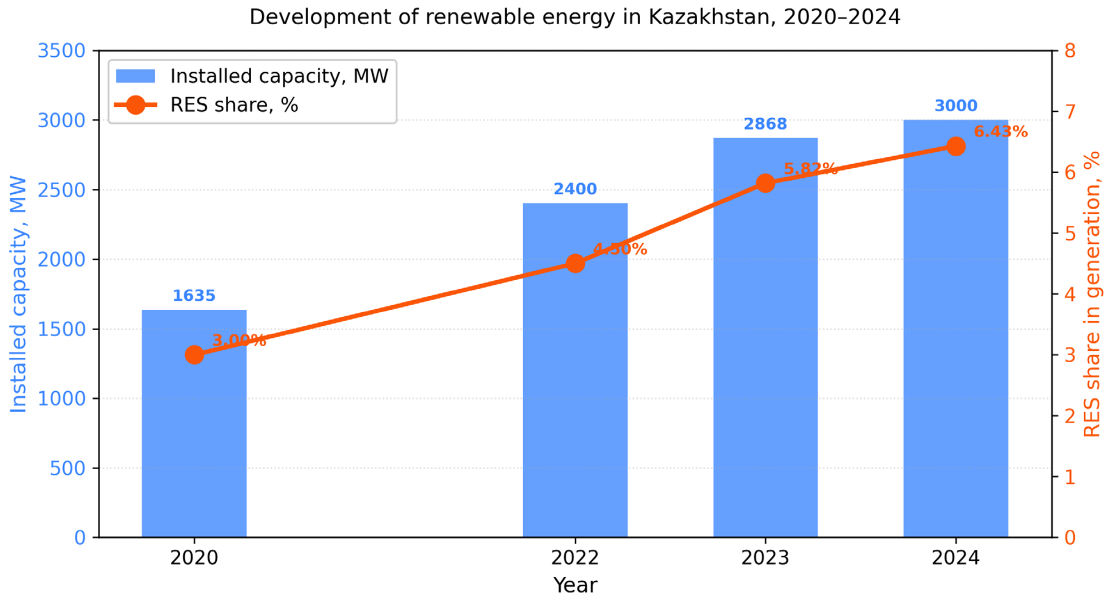
The structure of emissions remains highly unbalanced: the energy sector accounts for 77–82% of total emissions, with coal providing approximately 70% of electricity generation and 99% of district heating, and producing more than 67% of all CO_2 emissions (IEA, 2022). Per capita emissions – 12.3–12.4 t CO_2 per person in 2023 – were roughly twice the global average (Climate Action Tracker, 2024).

The technological context reinforces the case for digitalization: about 65% of generating capacity has been in operation for more than two decades; the average efficiency of thermal power plants is approximately 32%, some 10 percentage points below the European level; and aggregate grid losses reach 15%. These parameters define the upper bound of efficiency gains achievable through digital solutions (Sarbassov et al., 2020).

Renewables and digital infrastructure: the baseline

Despite the dominance of coal, Kazakhstan has shown accelerated growth in installed renewable capacity. According to QazaqGreen (2025) and the Ministry of Energy, the renewable share in electricity generation reached 6.43% in 2024 at an installed capacity of approximately 3 GW (Figure 2, Table 2). The Concept for the Development of the Electricity Industry targets a share of 15% by 2030 and 50% by 2050 (Resolution of the Government of RK, 2023).

Figure 2
Development of renewable energy in Kazakhstan, 2020–2024



Note: compiled by the authors based on sources (QazaqGreen, 2025; IEA, 2022)

Table 2

Development of renewable energy in Kazakhstan, 2020–2024

Year	RES share, %	Installed capacity, MW	Generation, GWh	Comment
2020	3.00	1 635	4 600	Launch of incentive auctions
2022	4.50	2 400	5 400	Commissioning of several PV and wind projects
2023	5.82	2 868	6 600	Mega-deals signed with Masdar, TotalEnergies
2024	6.43	3 000	7 600	ACWA Power – 1 GW agreement

Note: compiled by the authors based on sources (QazaqGreen, 2025; IEA, 2022)

The digital layer of energy infrastructure comprises two complementary levels – system (under JSC KEGOC) and distribution. At the system level, an automation project for managing the Unified Electric System has been delivered, incorporating modules for wide-area measurement (WAMS), centralised emergency system control (CESC), and automatic frequency and power regulation (AFPR). Supported by the European Bank for Reconstruction and Development, the 500 kV Karabatan–Ulke line modernisation began in 2024 with total financing of EUR 267 million (EBRD, 2024).

An important institutional development in 2025 was the official launch by the Ministry of Energy of the national digital platform EnergyTech, built on the QazTech infrastructure. The platform integrates a heating-season readiness module (projected to reduce the accident rate by up to 25%), digital tariff regulation (a 56% reduction in administrative burden), and a renewable-assets registry (Times of Central Asia, 2025). In parallel, a programme is being rolled out to install four million smart meters by 2027.

International experience in green-technology digitalization

To verify calculation parameters and assess the applicability of international practices, four cases with different digitalization foci are reviewed (Table 3).

Table 3

International experience in energy-sector digitalization: key effects

Country / region	Leading technology	Quantitative effect	Applicability to Kazakhstan
Germany (Energiewende)	Digital asset passports + balancing markets	12–15% reduction in RES integration system costs	High – for asset passports and MRV
China (SGCC, UHV + AI)	AI dispatch for RES and HVDC	28% curtailment reduction; 8% increase in transfer capacity	Medium – requires grid upgrades
Denmark (Energinet)	AI forecasting of wind generation	Forecast error < 4%; up to EUR 150 M/year saved	High – for Masdar, TotalEnergies projects
USA (CAISO, WEIM)	Regional digital balancing market	Cumulative effect of USD 4.6 bn over 2014–2025	High – for a Central Asian regional market

Note: systematised by the authors based on sources (IEA, 2022; IEA, 2023; IRENA, 2023)

The cases reveal a pattern: the economic effect of digitalization grows monotonically with the share of renewables up to a threshold of approximately 30%, beyond which gains decelerate due to saturation of system opportunities. Kazakhstan is at an early phase of this curve, implying a high marginal return on every additional dollar invested in digitalization – an estimated 1.5–2 times higher than in countries with already high renewable shares.

Digital maturity indices and human capital

Kazakhstan's position in international digital-maturity rankings presents a mixed picture (Table 4). The country holds relatively strong positions in formal e-government and infrastructure-connectivity indices but lags substantially in the deep digitalization of industry and energy.

Human-capital availability remains a critical constraint. According to a recent estimate (Times of Central Asia, 2025), Kazakhstan has about 19,500 IT specialists against a declared demand of 100,000. The gap is concentrated in industrial automation, cybersecurity for critical infrastructure, and data science for the energy sector. Implementing the proposed volume of energy-sector digitalization will require either accelerated training of 6,000–8,000 specialists per year or the contracted engagement of international teams.

Table 4
Digital maturity indices of Kazakhstan (most recent available data)

Index	Value / rank	Year	Comment
UN E-Government Development Index (EGDI)	28th of 193	2024	Strong segment – e-services
IMD World Digital Competitiveness	35th of 64	2024	Weakest component – knowledge (49th)
Network Readiness Index (NRI)	57th of 134	2024	Regulatory-environment gap

Note: compiled by the authors based on sources (United Nations, 2024; IMD, 2024; Portulans Institute, 2024).

Economic effect: five vectors and their aggregation

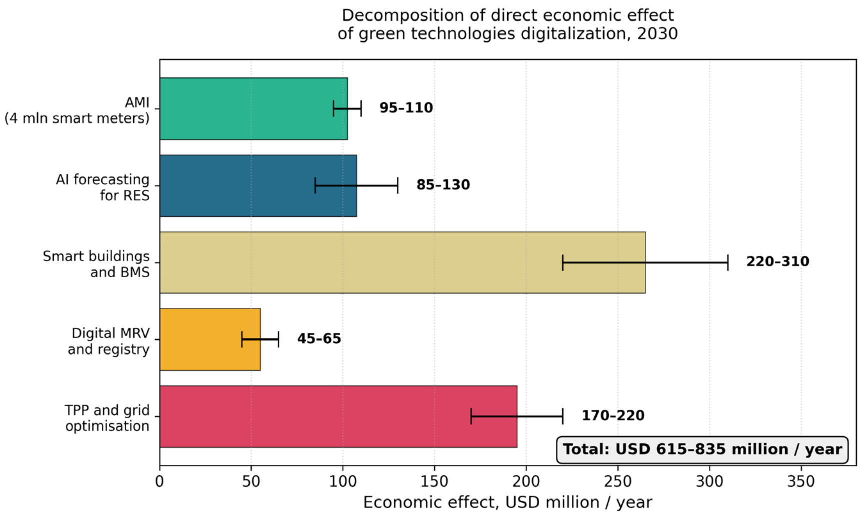
Applying formula (1) to the five priority digitalization vectors yields a detailed decomposition of the annual economic effect by 2030 (Table 5, Figure 3). Each row presents the baseline volume B_i, the coefficients R_i and k_i, the weighted average price P_i, and the resulting effect range.

Table 5
Decomposition of direct economic effect of green technologies digitalization, 2030

№	Vector	B_i (baseline)	R_i	k_i	P_i	Effect, USD mn/year
1	AMI (4 mln smart meters)	5.8 TWh losses	0.15–0.20	0.75	0.042 USD/kWh	95–110
2	AI forecasting of RES (3→6 GW)	9.2 TWh	0.08–0.12	0.70	0.055 USD/kWh	85–130
3	Smart buildings and BMS	24 TWh heat consumption	0.10–0.15	0.65	0.063 USD/kWh	220–310
4	Digital MRV (CBAM readiness)	33 Mt exports to EU	–	0.70	CBAM penalties	45–65
5	TPP and grid optimization	OPEX USD 4.5 bn	0.03–0.05	0.60	–	170–220
	Total (direct effect)	–	–	–	–	615–835

Note: authors' calculations based on sources (IEA, 2022; IRENA, 2023; World Bank, 2022) and methodology of formula (1)

Figure 3
Decomposition of direct economic effect of green technologies digitalization, 2030



Note: constructed by the authors based on Table 5

The aggregate direct effect is concentrated primarily in heating and generation optimization – together accounting for about two-thirds of the total. This reflects structural features of the Kazakhstani economy: abnormally high specific heat consumption in buildings (~270 kWh/m² compared with 120–140 kWh/m² in EU countries of similar climate) and a large legacy fleet of thermal power plants, where even incremental optimization yields a substantial monetary effect.

Adding multiplier effects broadens the aggregate estimate to USD 3.2–4.1 billion per year, equivalent to 1.0–1.3% of GDP. New green-economy jobs are estimated at 10,000–12,000 by 2030, of which approximately 40% are in the IT segment, 35% in engineering-installation occupations, and 25% in ancillary services (IRENA & ILO, 2024).

Scenario analysis

To strengthen the robustness of the proposed analytical framework, a simplified scenario-based stress-testing approach was applied. The scenarios reflect different combinations of renewable-energy deployment, digitalization intensity, regulatory support, and institutional readiness in Kazakhstan's energy sector. Such an approach allows assessment of the sensitivity of the projected economic effect to changes in key policy and technological parameters.

The range USD 615–835 million corresponds to the central target scenario. To quantify uncertainty, two additional scenarios are constructed, differing in the pace of technology deployment and regulatory intensity (Table 6).

The shift from business-as-usual to the target scenario roughly doubles the direct effect at a proportional increase in investment, whereas the move to the breakthrough scenario yields an additional 60% gain at 2.2 times the aggregate investment – indicating diminishing returns. This finding has important practical implications: the optimal strategy concentrates resources on the transition from business-as-usual to the target trajectory, while the breakthrough scenario is justified primarily in flagship projects – in export-oriented industries exposed to CBAM.

Table 6
Scenario range of direct economic effect by 2030

Parameter	Business-as-usual	Target (base)	Breakthrough
Installed RES capacity, GW	4.5	6.0	8.0
AMI coverage, % of consumers	55	85	95
Floor area with BMS, % of stock	3	10	18
KazETS allowance price, USD/t CO_2	3–5	15–20	35–50
Realizability coefficient k_i	0.5	0.7	0.8
Direct effect, USD mn/year	310–420	615–835	1 050–1 400
Aggregate effect with multiplier, USD bn/year	1.4–1.9	3.2–4.1	5.1–6.8

Note: authors' calculations using formula (1) under the respective scenario parameters

A sensitivity perspective indicates that the results of the model are particularly dependent on three groups of parameters: the rate of green technology adoption, the level of digital infrastructure development, and the volume of investment support. Changes in these parameters may significantly affect the estimated economic potential. Therefore, the results should be interpreted as indicative estimates rather than deterministic forecasts.

The scenario comparison demonstrates that the economic potential of green technologies digitalization depends strongly on the intensity of investment, the pace of digital transformation, and the consistency of state policy. Under the optimistic (breakthrough) scenario, digital tools may significantly accelerate the transition toward carbon neutrality, while under the business-as-usual scenario their impact remains substantially constrained by institutional and infrastructural barriers. The scenario-based approach therefore serves as a simplified robustness assessment of the proposed model under different transition conditions.

Carbon market, CBAM, and fiscal instruments

The Kazakhstan Emissions Trading System (KazETS) – the first full-fledged ETS in Asia, launched in 2013 – currently covers 212 large installations

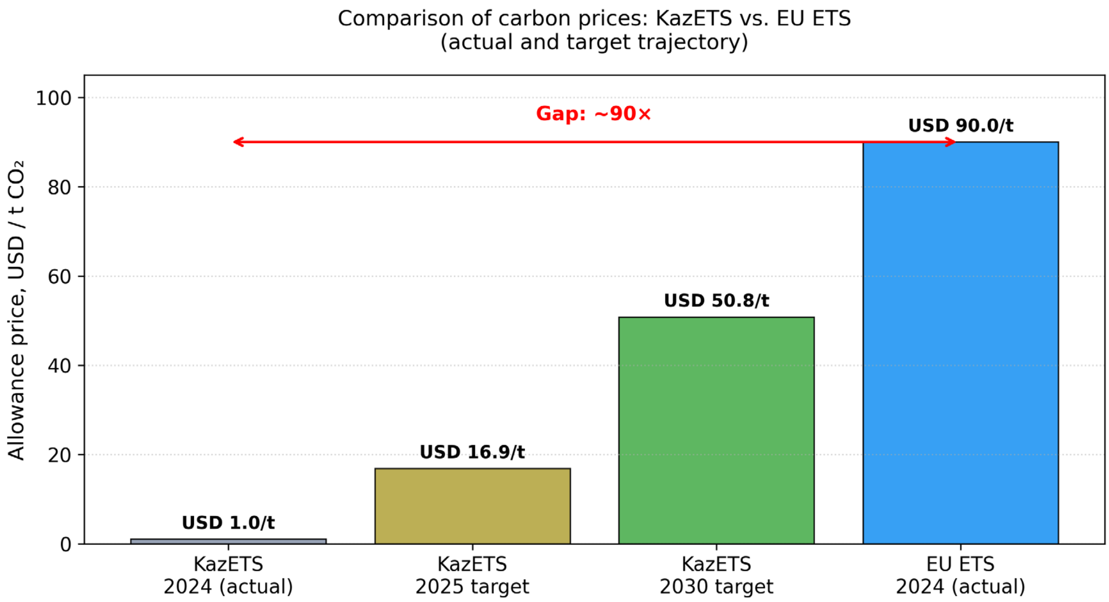
(135 companies) with an aggregate cap of 162.1 Mt CO_2 for 2024, providing roughly half of the economy's carbon coverage (ICAP, 2024). However, the price signal remains critically weak: the average allowance price in 2024 was approximately USD 1/t CO_2, about 90 times below the EU ETS level (Figure 4). The NDC roadmap envisages a gradual price increase to USD 16.9/t by 2025 and USD 50.8/t by 2030 (ICAP, 2024).

A key external driver of carbon policy is the EU Carbon Border Adjustment Mechanism (CBAM), entering its full charging phase on 1 January 2026. The European Union is the largest destination for Kazakhstani exports (about 39% of deliveries); however, CBAM exposure is distributed unevenly across product groups (Table 7).

Digitalization reduces the actual CBAM burden through two channels: documentary verification of the real carbon footprint (instead of default values that are typically higher), and the justified deduction of the price already paid under KazETS. Both channels require a digital MRV platform integrated with the EU CBAM registry – precisely the instrument announced within the EnergyTech platform (Times of Central Asia, 2025). MRV digitalization thus ceases to be a 'soft' environmental policy measure and acquires the character of a defensive investment in export competitiveness.

Figure 4

Comparison of carbon prices: KazETS vs. EU ETS (actual and target trajectory)



Note: compiled by the authors based on source (ICAP, 2024)

Table 7

CBAM exposure by product groups of Kazakhstani exports to the EU

Product group	Exports to EU, USD mn (2023)	Carbon footprint, t CO_2/t	CBAM burden at P = USD 90/t, USD mn/year	MRV effect, %
Ferroalloys and ferrous metals	1 450	4.5–5.0	210–240	30–40
Aluminium	380	16–18	95–115	25–35
Mineral fertilisers	290	2.0–3.5	45–65	35–45
Cement and clinker	95	0.8–1.0	15–25	40–50
Total	≈2 215	–	365–445	32–38

Note: authors' calculations based on sources (OECD, 2024; UNFCCC, 2025)

The fiscal imbalance warrants attention: Kazakhstan's fossil fuel subsidies are estimated at around 6% of GDP (IEA, 2022; IMF, 2023). Combined with low allowance prices, this creates a negative price signal that substantially weakens decarbonization incentives for part of producers. A parallel policy of gradual subsidy reduction and upward adjustment of the minimum allowance price is a necessary condition for the economic rationality of digital investment in the green segment.

Risks and limitations of digital transformation

Despite the positive aggregate effect, energy-sector digitalization involves three major categories of risks. Energy consumption of digital infrastructure: data centres and communications networks currently consume approximately 1.5–2.0% of global electricity; Kazakhstan's share remains below 0.5%, but with the implementation of announced programmes it could rise to 3–4% by 2030. In a coal-dominated generation mix, this means that part of the digitalization savings may be neutralised by additional emissions. Mitigation requires mandatory linkage of new data centres to renewable capacity or dedicated green contracts.

Cybersecurity of critical infrastructure. The deployment of WAMS, CESC, and integrated dispatch systems increases connectivity and, simultaneously, the attack surface. European experience shows that the typical economic damage from a successful attack on critical infrastructure substantially exceeds the annual savings from digitalization. For Kazakhstan, it is advisable to combine the deployment of digital solutions with mandatory categorisation of assets under the critical-information-infrastructure legislation and certification against international standards (ISA, 2023).

Rebound effect (Jevons paradox). Increased efficiency in individual segments, combined with persistently low energy prices, can trigger a rise in aggregate consumption, partially offsetting the environmental benefit. International estimates of the rebound effect in the residential sector range from 10% to 30%. For Kazakhstan, this reinforces the case for parallel strengthening of price signals.

Twin transition barriers and policy matrix

Systemic barriers to the twin transition are classified into four groups: technological, financial/price, institutional, and human-capital. To translate this diagnosis into an operational policy tool, barriers are linked to specific instruments, horizons, and indicators (Table 8).

Table 8
Twin-transition policy matrix

№	Barrier	Policy instrument	Horizon	Key indicator	Responsible authority
1	Generation obsolescence (57% TPPs > 36 years)	TPP modernisation with mandatory IPS/SCADA	2025–2030	TPP efficiency, %; digital-twin share	Ministry of Energy
2	Grid obsolescence (15% losses)	Trunk grid refurbishment + WAMS	2025–2030	Losses, %; SAIDI/SAIFI	JSC KEGOC
3	Fossil-fuel subsidies (~6% of GDP)	Gradual phase-out with compensation	2026–2030	Subsidy share of GDP, %	MoF, MoE
4	Low KazETS allowance price	Floor price USD 5–7/t; USD 50.8/t by 2030	2026–2030	Avg allowance price, USD/t	MoE, Zhasyl Damu
5	Absence of AMI mandate	Legislative mandate with milestones	2025–2027	Smart meter coverage, %	Ministry of Energy
6	Absence of MRV platform	Launch with EU CBAM integration	2025–2027	Exporters with digital passports, %	Ministry of Ecology
7	Institutional fragmentation	Interagency council	2026	Agreed strategic decisions/year	Government of RK
8	Weak regional market	Central Asian balancing platform	2028–2030	Cross-border exchange share, %	JSC KEGOC, MFA
9	Human-capital gap (~80 thousand)	Targeted training programme	2025–2030	Annual profile graduates	MoSHE, MDDAI
10	Cyber risks of critical infrastructure	Mandatory security certification	2026–2028	Certified assets share	NSC, MDDAI

Continuation of the table

№	Barrier	Policy instrument	Horizon	Key indicator	Responsible authority
11	Low building quality	Codes + BMS for new construction	2026–2030	Specific consumption, kWh/m²	MIID, local authorities
12	Access to green finance	Taxonomy + sovereign green bond	2025–2027	Green bonds volume	MoF, NBK, AIFC

Note: compiled by the authors based on sources (The Concept of Development of the Electric Power Industry of the Republic of Kazakhstan for 2023–2029; IEA, 2022; IRENA, 2023; World Bank, 2022; ICAP, 2024; AIFC, 2023)

The matrix structures the set of measures so that every policy initiative can be traced to a specific barrier and a measurable indicator. Implementation horizons are sequenced: short-term measures (Nos. 4–6, 9) build the regulatory and human-capital foundation; medium-term measures (Nos. 1–3, 7, 10–12) form the investment framework; the long-term measure (No. 8) shapes the institutional architecture at the regional level.

Conclusion

What are the research objectives and methods? The work was devoted to a quantitative assessment of the synergetic economic effect from the joint development of digital and green technologies in Kazakhstan using a transparent calculation framework (formula 1), three-scenario modelling, and comparative analysis of international experience. For the first time, the study formalises the procedure for linking digital solutions to the objectives of the 2060 carbon strategy in Kazakhstani conditions.

What are the results? The economic potential of the twin transition for Kazakhstan is assessed under the target scenario at USD 615–835 million in direct annual effect by 2030 and USD 3.2–4.1 billion including multipliers, equivalent to 1.0–1.3% of GDP. MRV digitalization is shown to reduce the potential CBAM burden on Kazakhstani exports by 32–38%, reclassifying digital investment from environmental to defensive export-oriented.

What conclusions? First, in resource-dependent economies with coal-dominated generation, digitalization and decarbonization should increasingly be treated as mutually reinforcing processes. Second, the greatest economically justified gain is realised in the transition from business-as-usual to the target trajectory; the breakthrough scenario exhibits diminishing returns and is justified mainly in export-oriented flagship projects. Third, the matrix of twelve policy measures transforms the twin-transition concept from rhetoric into an operational instrument of public management.

What are the prospects and possibilities for application? The resulting parameters can serve as a methodological foundation for the design of green-economy digitalization programmes in comparable CIS and SCO countries. Directions for further research include extending the calculation framework to the transport, mining, and agriculture sectors; regional decomposition of effects across the 17 oblasts of Kazakhstan; application of Monte Carlo simulation and sensitivity testing; and verification of realizability coefficients through panel econometrics as data from 2025–2030 accumulate.

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Author Contributions

GSN: contributed to data analysis and preparation of the manuscript.

GSS: contributed to the development of the study and revision of the manuscript.

RKS: contributed to the interpretation of the results and review of the manuscript.

LZh.A: contributed to the methodological support of the research and revision of the manuscript.

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Information about the authors:
Nygymetov Gani Saktaganovich (corresponding author) – PhD candidate, Higher School of Economics and Business, Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: gansak1983@mail.ru).
Smagulova Gulzhikhan Sovetbekovna – Candidate of Economic Sciences, Associate Professor, Higher School of Economics and Business, Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: gsmagulova_72@mail.ru).
Satova Raushan Kulmagambetovna – Doctor of Economic Sciences, Professor, Almaty University of Power Engineering and Telecommunications named after G. Daukeev (Almaty, Kazakhstan, e-mail: 1idn@mail.ru).
Ashirbekova Laura Zhalgasovna – Candidate of Economic Sciences, Associate Professor, Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: turar200480@mail.ru).

Авторлар туралы мәлімет:
Нығыметов Ғани Сақтағанұлы (корреспонденттік автор) – әл-Фараби атындағы Қазақ ұлттық университеті Экономика және бизнес жоғары мектебінің PhD докторанты (Алматы, Қазақстан, e-mail: gansak1983@mail.ru).
Смағұлова Гүлжихан Советбекқызы – экономика ғылымдарының кандидаты, әл-Фараби атындағы Қазақ ұлттық университеті Экономика және бизнес жоғары мектебінің доценті (Алматы, Қазақстан, e-mail: gsmagulova_72@mail.ru).
Сатова Раушан Құлмағамбетқызы – экономика ғылымдарының докторы, Ғ. Дәукеев атындағы Алматы энергетика және байланыс университетінің профессоры (Алматы, Қазақстан, e-mail: 1idn@mail.ru).
Аширбекова Лаура Жалгасовна – экономика ғылымдарының кандидаты, әл-Фараби атындағы Қазақ ұлттық университетінің доценті (Алматы, Қазақстан, e-mail: turar200480@mail.ru).

Сведения об авторах:
Ныгыметов Гани Сактаганович (корреспондирующий автор) – PhD докторант Высшей школы экономики и бизнеса Казахского национального университета имени аль-Фараби (Алматы, Казахстан, e-mail: gansak1983@mail.ru).
Смагулова Гульжихан Советбековна – кандидат экономических наук, доцент Высшей школы экономики и бизнеса Казахского национального университета имени аль-Фараби (Алматы, Казахстан, e-mail: gsmagulova_72@mail.ru).
Сатова Раушан Кулмагамбетовна – доктор экономических наук, профессор Алматинского университета энергетики и связи имени Г. Даукеева (Алматы, Казахстан, e-mail: 1idn@mail.ru).
Аширбекова Лаура Жалгасовна – кандидат экономических наук, доцент Казахского национального университета имени аль-Фараби (Алматы, Казахстан, e-mail: turar200480@mail.ru).

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