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The Impact of Energy System Integration on Climate Change Mitigation Strategies to Achieve Sustainable Development Principles

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ABSTRACT

Climate change mitigation requires systemic transformations in the energy sector, particularly through the integration of energy systems across technological and spatial levels. This study aims to assess the potential of energy system integration as a tool for sustainable development planning and climate change mitigation, with a focus on Kazakhstan. The research employs a mixed qualitative–quantitative approach combining a structured literature review with an expert survey involving 48 specialists in the fields of energy, climate policy, and sustainable development. The collected data were analyzed using ranking procedures, Pearson's chi-squared test, and Kendall's concordance coefficient to ensure the consistency and reliability of expert evaluations. The results identify three key models of energy system integration: intelligent system operation and aggregation, cross-vector integration, and Power-to-X technologies. The main advantages include improved resource efficiency, decarbonization, and enhanced system reliability. In addition, three core components of integrated energy systems are highlighted: closed-loop production, electrification of end-use sectors, and the use of low-emission renewable fuels, including hydrogen. The findings demonstrate that energy system integration can serve as an effective instrument for sustainable development planning by increasing the flexibility, resilience, and environmental performance of energy systems. The study contributes to the existing literature by providing a structured assessment of integration models and their implications for climate policy and regional energy planning. Practical implications include the development of decentralized energy systems, cross-border energy cooperation, and the expansion of renewable energy markets in regions with high resource potential.

Keywords: *Climate change, Energy system, Energy system integration, Power supply system, Renewable energy sources*

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INTRODUCTION

In this context, sustainable development increasingly depends on the ability to design and manage energy systems as integrated, multi-level infrastructures. Energy planning is no longer limited to balancing supply and demand but involves the coordination of diverse energy carriers, spatial distribution of resources, and cross-sectoral interactions between energy, transport, and industrial systems. Integrated energy systems are therefore considered a key instrument for achieving long-term sustainability goals, as they enable more efficient resource allocation, reduce environmental impact, and enhance the adaptability of energy supply systems under conditions of climate uncertainty.

From a policy and planning perspective, the transition toward integrated energy systems requires the development of new governance mechanisms, regulatory frameworks, and decisionmaking tools capable of addressing both local and transboundary energy challenges. In countries with high dependence on fossil fuels and significant renewable energy potential, such as Kazakhstan, the integration of energy systems becomes particularly relevant for aligning national development strategies with global climate commitments. This highlights the need for applied research that identifies effective models, components, and benefits of energy system integration to support sustainable energy planning and climate policy implementation.

According to experts, global warming, as part of the global process of climate change, can create many difficulties for the organisms inhabiting the Earth.

A legal definition of climate change was introduced in Article 1, Section 2 of the UN Framework Convention on Climate Change. Per this definition, climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (United Nations, 1992; Svensson & Lindberg, 2026).

Climate change can be natural, caused by impacts related to astronomical (e.g., changes in solar activity) or volcanic factors, and resulting from human activities (e.g., fossil fuel combustion) (Yelnazarkyzy & Stybaev, 2026). The research interests of numerous interdisciplinary climate change groups center around the negative impacts of global warming caused by unrestricted and climate-destructive human activities.

Thus, the article's relevance and problem statement are connected with opportunities for climate protection offered by integrating a country's energy system.

The study's novelty lies in describing the possibility of integrating a country's energy system as a mechanism aimed at mitigating climate change.

The study aims to analyze the possibilities of climate protection by integrating a country's energy system.

The research questions addressed in this article are as follows:

1. What models of energy system integration can prevent negative climate change?
2. What are the benefits of integrating the energy system for climate protection?
3. What are the key components of energy system integration?

The remainder of the article is organized as follows. The next section presents a literature review on the impact of the need for climate protection, the associated reduction of greenhouse gas emissions, on changes in the energy system, and climate neutrality for energy transformation and energy system integration. Following this, we describe and discuss the research methods and results. The conclusions disclose the potential of energy system integration in protection against climate change.

Background

Climate protection and net-zero economy

The thesis of climate change and its impact on the future of life on Earth requires clear articulation due to the existing controversy in the scientific community (Potapov *et al*., 2026) since there are many different hypotheses about climate change and its consequences (Schiermeier, 2010). The 6th edition of the UN Intergovernmental Panel on Climate Change (IPCC) report, published in 2021 (Intergovernmental Panel on Climate Change [IPCC], 2021), contains 78,000 comments from scientists around the world proving the existence of climate change adverse to life on Earth and indicating the magnitude of the impact, the methods of adaptation, and recommendations for mitigating its effects. The authors argue that to prevent an increase in average annual temperatures, global anthropogenic emissions of CO2 and other substances need to be reduced by about 45% by 2030 compared to 2010 levels and reach net zero by about 2050. The report stresses the need for prompt and far-reaching socioeconomic changes in energy, transportation, industry, economy, technology, healthcare, water resource management, and environmental protection with a coherent political vision and broad public participation.

This suggests that stopping climate change requires transforming the economic system. Depending on a country's political system, these changes will affect the state. The effectiveness of efforts to transform the economy to operate within the net-zero model (climate change transformation) will require both coordination and cooperation on the part of public authorities and local self-government bodies, and the participation of the public (Poberezhskaya & Bychkova, 2022; Yessenali *et al*., 2024). It should be noted that "the main driving force for development should be represented by market mechanisms, which the state can and should influence to mitigate social impacts, but which cannot be replaced by the state's solutions" (Poberezhskaya & Danilova, 2022; Jaouhari *et al*., 2023; Kuts *et al*., 2024; Nagesh *et al*., 2025). However, reducing greenhouse gas emissions, which concerns the energy sector to the greatest extent as the most emitting economic sector (Zhang *et al*., 2019; Damaševičius *et al*., 2025) (climate and energy transformation), demands that the state perform its climate-related duties urgently. For this reason, the state's active participation in transforming climate change and the energy sector to achieve net-zero emissions cannot be limited to the role of the so-called night watchman (Sinyakova *et al*., 2013). The state needs to take on responsibility for the state of the economy (Mudretsov *et al*., 2019; Kowalski *et al*., 2024).

The reason for the high level of emissions among industrialized nations (International Energy Agency [IEA], 2022) is coal-based energy production. World coal resources are estimated at 1,139,471 tons, which, if current consumption levels are maintained, will cover the demand for this raw material for a maximum period of 133 years (Worldometers, 2024). Coal stored in the Earth's deposits is limited (while its mining directly causes the increase in global temperatures, the accumulation of which can cause extreme weather phenomena, such as repeated glaciations) (Feulner, 2017). Coal burning is not the only factor causing negative climate change, because natural gas is also an emissions-intensive fuel. However, natural gas can compensate for the energy deficit during the transition period that will begin with the shutdown of coal power plants (Aliev & Zakharchaeva, 2021). Natural gas contains much less methane; in the future, the gas network may be supplied with decarbonized gases (Malykh, 2019), such as hydrogen (Gielen *et al*., 2019).

Climate neutrality for transforming energy and integrating the energy system

The growing recognition of the consequences of global warming

(Kobysheva *et al*., 2015) resulted in legal and political consequences. There is a large-scale discussion of climate and energy transition, aiming to achieve zero greenhouse gas emissions in all economic sectors (climate neutrality).

The first legal response to climate change was the issuance of the Kyoto Protocol (United Nations, 1998), in which the signatory countries pledged to reduce their CO2 emissions by at least 5% by 2012 compared to 1990 levels. However, the absence of a mechanism to verify the declarations submitted by the parties to the Protocol necessitated the adoption of the Paris Agreement (United Nations, 2015). Although the Agreement does not specify a timeframe for implementing its provisions, Art. 4 Par. 10 announced a date for the verification of states' actions (so-called national contributions).

A prominent role in the struggle against the consequences of climate change is played by the UN Climate Conferences: the only forum in the world that includes representatives from almost all countries. The most recent summit was concluded by adopting the Glasgow Climate Pact (United Nations Climate Change Conference, 2021). The provisions of this Pact should be viewed not as a change in the conclusions drawn as a result of previous summits, but rather as a clarification and reinforcement of the commitments made so far (Kirton & Warren, 2022). One of the most important items in the Pact is the provision contained in Section 22, Part IV, which mandates a 45% reduction in CO2 and other greenhouse gas emissions from 2010 levels by 2030 (Brodjonegoro *et al*., 2022). This means that decarbonization, understood as the economy's abandonment of coal-based fuel and energy production, will become an increasingly progressive process whose rate will be largely determined by reducing greenhouse gas emissions.

In analyzing the work of the UN in the sphere of climate change and building a net-zero economy, we should make note of the 2030 Agenda for Sustainable Development (United Nations General Assembly, 2015). This Agenda outlines 17 sustainable development goals. From the standpoint of our research goal, the most important of these is Goal 7, which specifies priorities in the energy sector (World Bank, 2021) (as noted previously, it is the most emission-intensive sector), i.e., "to ensure access to affordable, reliable, sustainable, and modern energy for all". Thus, the goal of the energy sector is to ensure universal access to modern energy services and to increase the effectiveness and introduction of renewable energy sources (RES) (Gaspari *et al*., 2021; Zagaria *et al*., 2024).

Today, the energy system is being transformed into an electric power system (electricity supply system). The goal of this transformation is to generate electricity from various emission-free energy carriers through a wide range of organizations that become both energy producers and consumers (Niekurzak & Mikulik, 2023).

The factors shaping the transformation of the energy sector include political consensus, cooperation between public authorities and local self-government bodies, participation of the public, stable and amicable legal regulation, and utilization of the innovative potential of entrepreneurs (Ahmad *et al*., 2016). The operation of the newly emerging energy system will not be solely the result of state intervention at the legal and political level but will require broad societal participation, and perhaps this will define the energy transformation (Buchanan *et al*., 2014).

Among other things, the energy sector needs to achieve climate-related goals, introduce RES while preserving the operational safety of the energy system, include users in the supply chain, and store excess energy or ensure cross-border energy exchange (García-Olivares *et al*., 2018). The electric power transformation coupled with climate commitments introduces the notion of an integrated energy system, i.e., one that will produce clean energy in a sustainable, competitive, and affordable way while reducing the carbon intensity of energy production.

This process is grounded on the rejection of vertical, centralized energy monopolies (i.e., moving away from the model of energy production by state-owned companies) in favor of a decentralized energy supply system in which energy is produced from many, including renewable, energy sources by many energy market participants (Lovell *et al*., 2017). The coordination of an energy system based on less stable production of RES will require close coordination of energy policies of neighboring states in connection with cross-border energy flows (York & Bell, 2019). Here we should once again underscore that the climate has no administrative borders. Therefore, greenhouse gas emissions are not an exclusive problem of a single territory.

Researchers define energy system integration as coordinated planning and operation of the energy system with consideration of energy carriers, infrastructures, and energy consumption sectors (Ruth & Kroposki, 2014; Metelenko *et al*., 2025).

An integrated energy system is a multi-vector system. This should be interpreted as the process of coordinating the operation and planning of energy systems across multiple directions and/or geographic scales to provide reliable and economically efficient energy services with minimal environmental impact (Galus *et al*., 2012). For an example of an efficient system, see (Bianco *et al*., 2024). The value of energy systems integration lies in transforming the energy sector to operate within the net-zero model and coordinate the production and delivery of energy in all forms to reliably achieve economic and environmental objectives (Jenkins, 2018).

Energy integration in Kazakhstan

Being a member of the UN, Kazakhstan is obliged to fulfill international energy and climate commitments as a party to the Kyoto Protocol (Parliament of the Republic of Kazakhstan, 2009) and the Paris Agreement (Parliament of the Republic of Kazakhstan, 2016). International law is complemented by Kazakhstan's national laws on environment, energy, and climate protection, which come in the form of scattered rules.

After ratifying the Kyoto Protocol, Kazakhstan has been regularly submitting reports on annual national greenhouse gas emission inventories to the UNFCCC Secretariat in the form of national inventory reports (NIRs) and spreadsheets (CRFs). Preparing the national greenhouse gas inventory is one of the main international commitments undertaken by Kazakhstan under the UNFCCC.

As part of the Paris Agreement, Kazakhstan pledged its contribution in the form of unconditional reduction of greenhouse gas emissions by 15% and conditional (in case of international support) reduction by 25% by 2030 compared to the 1990 level. In 1990, Kazakhstan's total greenhouse gas emissions reached 386 million tons of CO2 equivalent, which means that by 2030, the country must not exceed 328 million tons of CO_2 equivalent. To achieve this, Kazakhstan is developing a set of market mechanisms, including an emissions trading system, projects to reduce emissions and absorb greenhouse gases, and the development of the green investments market (Bureau of National Statistics, 2022).

The emissions trading system is a market mechanism that stimulates nature users to reduce greenhouse gas emissions through investing in new clean technology, upgrading their technological capacities, and creating new, efficient production (Mazina *et al*., 2022). Furthermore, Kazakhstan's commitments to energy and climate change will require changes in energy legislation to adapt the energy system to predominantly RES-based energy production (Abdullayev *et al*., 2023; Kurmanov *et al*., 2024). The approach and position of Kazakhstan with respect to reducing greenhouse gas emissions presupposes the mechanisms covered by the Paris agreement.

In this context, our study focuses on the applicability of the concept of an integrated energy system in the framework of solving global warming problems in Kazakhstan, as a country that has already taken its first steps in this direction.

MATERIALS AND METHODS

To achieve the goal and answer the research questions, we employed a qualitative and quantitative approach based on a literature review and expert survey, followed by ranking their summarized results.

Data collection

Scientific sources for the literature review were selected using the Russian scientific citation database RSCI and the international databases Web of Science and Scopus, using the keywords "sustainable development", "climate protection", and "energy system integration" in Russian and English, and a restriction on the date of publication to no more than 15 years ago.

Data collection was carried out from November 10, 2022, to February 10, 2023, and involved the analysis of scientific literature on the research problem, choosing the pool of experts, conducting an expert survey via email, and processing and analyzing its results.

Emails with an invitation to participate in the survey were sent to 55 experts from Kazakhstan, Uzbekistan, and Russia. The sampling criterion for the expert pool was having at least three articles on the research problem published in peer-reviewed journals. A total of 48 experts agreed to take part in the study, after which they were forwarded emails with questions that remained unanswered after the completion of the literature review:

1. In your opinion, what energy system integration models can combat negative climate change?
2. In your opinion, what are the advantages of energy system integration for climate protection?
3. What are the main components of energy system integration?

The letters additionally asked experts to justify their answers in free form. All survey participants were informed of the survey goals and our intent to publish the obtained results in a summarized form.

Pearson's chi-squared, calculated as:

$$\chi 2=((Oi-Ei)2/Ei) \quad (1)$$

was used to assess the statistical significance of differences between the observed (Oi) and expected (Ei) frequencies. With a large enough sample size, as in our case with 48 respondents, the power of this statistical test increases, allowing us to conclude differences or relationships with a high degree of confidence. For the chi-squared test, it is important for the expected frequencies in each category not to be too small (in our case, it is 5). A sample of 48 people spread over several categories will usually satisfy this criterion. Thus, our sample size can be deemed sufficient for justified statistical conclusions if the conditions for applying the test are met.

After the responses to the first survey were obtained, the experts were sent a second email asking them to rank the importance of specific parameters (energy system integration models, the advantages of energy system integration, the components of energy system integration) identified during the study by assigning points. Following this, the rank of each parameter was determined based on the points given by experts.

Data analysis

For a more objective analysis of the data obtained in the expert survey, the consistency of the experts' opinions was measured using Kendall's concordance coefficient:

$$(W): W = 12S/n2(m3\text{-}m) \quad (2)$$

where: S – the sum of squared deviations of all rank estimates of each parameter from the mean; n – the number of experts; m – the number of assessed parameters (energy system integration models, the advantages of energy system integration, and the components of energy system integration in order of assessment).

Next, the information obtained in the expert survey was processed to determine the weights of the obtained parameters by constructing a rank transformation matrix and then calculating the arithmetic mean of individual weights for each parameter. The final weights indicate the significance of each parameter according to the experts.

In the process of data analysis, triangulation was used to ensure the validity and reliability of empirical findings. Triangulation was accomplished through researcher triangulation, which involves multiple researchers participating in information processing. The analysis was concluded by a discussion, as a result of which the information agreed upon by all participants was entered into the report. The triangulation process improved the reliability of expert survey data and increased the quality of the obtained information. All results were recorded in the research report.

RESULTS AND DISCUSSION

The expert survey provided information about various models of energy system integration **(Table 1)**.

Table 1. Models of energy system integration

No.	Model	Technologies	Rank	Weight
1	Intelligent operation and aggregation of energy systems	Automation, communication, and storage technologies focused on optimizing the use of energy resources	1	0.48
2	Cross-vector integration	Technologies combining two or more energy vectors to produce and deliver energy services	2	0.31
3	Power-to-X technology	Using energy sources, such as hydrogen, as an interface between different energy vectors Note: compiled based on the expert survey; the concordance coefficient W = 0.77 ($p < 0.01$), indicating a strong consistency of expert opinions	3	0.21

The advantages of energy system integration highlighted by the experts are found in three areas **(Table 2)**.

Table 2. Advantages of energy system integration

No.	Advantages of energy system integration	Rank	Weight
1	Efficient resource use	1	0.47
2	Decarbonization	2	0.30
3	Improved safety and operation of the system	3	0.23

Note: compiled based on the expert survey; the concordance coefficient W = 0.71 ($p < 0.01$), indicating a strong consistency of expert opinions.

The expert survey further suggests that energy system integration should rely on three mutually complementary components **(Table 3)**.

Table 3. Components of energy system integration

No.	Components of energy system integration	Rank	Weight
1	Closed-loop production	1	0.42
2	Electrification of end-use sectors	2	0.31
3	Utilization of low-emission renewable fuels (including hydrogen) for end use	3	0.27

Note: compiled based on the expert survey; the concordance coefficient W = 0.73 ($p < 0.01$), indicating a strong consistency of expert opinions.

The expert survey results demonstrate that the advantages of energy system integration can be found in three areas: efficient resource use, decarbonization, and the system's improved safety and operation **(Table 2)**.

The first sphere refers to the optimization of resources and the striving to increase the system's efficiency and rationalize production processes. This result is consistent with the findings of Gaspari *et al*. (2021), which indicate that the efficiency of the energy system depends on the system's coordination and the repeated use of energy carriers (energy system synergy) (Trusina *et al*., 2024).

The second advantage of an integrated energy system is decarbonization (Probohudono *et al*., 2024). High-emission fuel combustion is set to give way to electrification, i.e., using electricity in other processes, such as conversion to heat. Although electrification will lead to fluctuations in energy demand, it will reduce emissions because, according to York and Bell (York & Bell, 2019), multi-directional energy transmission will compensate for increased demand (for Kazakhstan, see (Samambet, 2024)).

The third element in the benefits offered by energy system integration is the system's improved safety and operation, which includes greater flexibility. In this process, the input and output streams are diversified, meaning that energy demand is transferred between different subsystems as part of the cross-vector mutual transformation (or transmission) (Akintayo *et al*., 2024). Technologies that can be used for energy services will be crucial. The third pillar of benefits also includes improved system reliability and resilience. Reliability will be verified based on system quality and safety metrics. Resilience will focus on preventing failures and extreme weather phenomena that accompany energy production (Teoh *et al*., 2023).

Furthermore, the expert survey results suggest that energy system integration needs to rely on three mutually complementary components **(Table 3)**: closed-loop production, the electrification of end-use sectors, and the utilization of low-emission renewable fuels (including hydrogen) for end use.

Regarding the first element, the key element of the closed loop is to improve energy efficiency, i.e., to create synergies between individual sectors, such as waste utilization in thermal power plants (Dzhusupova *et al*., 2024).

The electrification of end-use sectors involves rapidly developing RES-based energy production and its cost competitiveness to satisfy growing energy demand, for example, using heat pumps for space heating (Jenkins, 2018).

The ultimate goal of transforming energy toward integration is the deployment of large-scale renewable energy production while maintaining the reliability and competitiveness of energy trade, which can only be achieved by keeping the system flexible (Hernanda *et al*., 2023). This concept stems from the global acceptance of the imperative to reduce CO2 emissions (Ruth & Kroposki, 2014).

The flexibility of an energy system can be ensured through the integration of its subsystems (i.e., electric power, gas, heating, and cooling) by physically connecting different energy vectors (electricity, heat, and fuel) and coordinating them with other infrastructures (water supply or transportation). This coordination can already be observed in some office buildings (Ator *et al*., 2024). The changes will encompass the objective sphere in terms of energy production sources (a shift from coal and natural gas to RES) and the subjective sphere by changing the concept of an energy producer (no longer a power plant (thermal power station) but a polyenergy concern, energy cluster, energy cooperative, or consumer).

As part of using green fuels for end-use, it is essential to introduce technologies for their production, especially when electrification is impossible, inefficient, or unprofitable (Ilyushin & Afanaseva, 2020). An integrated domestic energy market should be based on the development of decarbonized gases (including hydrogen), which will make it possible to store the energy produced from RES with unpredictable production characteristics, exploiting synergies between the electricity, gas, and end-use sectors (Gielen *et al*., 2019).

The strategy of energy system integration needs to be closely tied to the strategies developed in flexible markets, digitalization, intelligent neural networks, and smart metering (Niekurzak & Mikulik, 2023; Ydyrys *et al*., 2023). This owes to the fact that the new energy system will be multidirectional, so it will entail the creation of new markets, for example, the hydrogen market or the market of steppe wind energy, which is relevant in Kazakhstan (Maheshwari *et al*., 2023). Moreover, these markets should be cross-border, so cooperation in this area will be carried out at the level of interstate organizations. Energy system integration leads to the creation of many new networks in energy cooperation.

An example of this is the Baltic Sea Declaration for Offshore Wind Energy, signed on September 30, 2020, by the European Commission and representatives of the state administrations of Poland, Denmark, Estonia, Finland, Lithuania, Latvia, Germany, and Sweden. The Declaration opens a close cooperation between the countries of the Baltic Sea region. This cooperation aims to accelerate wind energy development in the Baltic Sea and to coordinate and optimize activities leading to the full use of this energy and the economic potential of the sea.

As demonstrated in previous studies, climate and energy transformation should transform the functioning of all sectors of the net-zero economy. As a result, the global economy will become climate-neutral. The new energy system will be multidirectional, consisting of a multitude of multifunctional energy carriers (Tolkachev *et al*., 2023).

CONCLUSION

The study demonstrates that the energy system needs to be based on accessible energy distribution. Therefore, energy system integration should not be considered an exclusively macroeconomic task. It is an opportunity to improve the quality of socioeconomic life locally and strengthen the focus on utilizing the potential of RES-based energy production in the zones most favorable for this technology. Responsibility for the safety and stability of supply will be shared jointly by the energy producers present in the territory. Autonomous energy territories will be covered by a network of cooperation crossing administrative boundaries, which will stimulate scientific and socioeconomic development. An integrated energy system should be safe, environmentally sound, and stable by having RES complement each other, ensuring the system's resilience to changing weather conditions.

Our research has both theoretical and practical significance. The theoretical significance lies in our ranking of the most promising directions of energy system integration. Relying on the opinions of verified experts in the field, the survey highlights automation technologies in energy management, efficient use of available reserves, and closed-loop energy utilization. The practical solutions proposed by the experts include creating a hydrogen market and a steppe wind energy market.

Despite its theoretical and practical contribution, this study is partially limited by the small sample size and allows only partial generalizations. Similar research on this problem involving experts from countries other than Kazakhstan will build a more generalized picture of climate protection requirements as a crucial factor for energy system integration.

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CONFLICT OF INTEREST: The study combined a structured literature review with an expert survey conducted among specialists in the fields of energy, climate policy, and sustainable development. Participation in the survey was voluntary. All experts were informed about the purpose of the study and agreed that their responses would be analyzed and reported in aggregated and anonymized form. The study did not involve experiments on humans or animals and was conducted in accordance with the applicable ethical principles for social science research.

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