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Optimization Modelling of the Decarbonization Scenario of the Total Energy System of Kazakhstan until 2060

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Abstract: This research article provides a comprehensive scenario analysis of key structural changes in Kazakhstan's fuel and energy complex subsectors until 2060, focusing on decarbonization efforts. The background places the issue of decarbonization in a broader context, considering the country's vast size and sparse population. The study's purpose involves analyzing the development of the climate agenda by comparing two scenarios: a "reference" scenario without decarbonization measures and a carbon neutrality scenario until 2060 (CN2060). A mathematical technical-economic model based on the TIMES paradigm (The Integrated MARKAL-EFOM System) serves as the method to optimize and simulate Kazakhstan's energy system. The main findings reveal sets of policies, standards, and legislative, economic, and political decisions that are required to achieve CN2060. Additionally, the integration of a low-carbon policy, sectoral and cross-cutting approaches, the impact of the coronavirus crisis, the Russia-Ukraine conflict, and energy security issues receive a discussion. The article concludes with projected shares of generation and investment in renewable energy sources (RES) necessary for attaining CN2060. This work offers novel insights into challenges and opportunities for Kazakhstan's transition to a low-carbon economy.

Keywords: scenario analyses; Kazakhstan; green economy; TIMES; energy systems optimization modelling; low carbon strategy; carbon neutrality; sustainable development

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1. Introduction

For most forecasts and predictive studies of the development of global energy, a scenario approach is characteristic, covering a wide cone of possible trajectories of the upcoming expansion. The specialists know that such assessments and forecasts are associated with uncertainty in all the process components. This uncertainty concerns the future demand for energy resources and the possibilities of covering them, the role of new technologies, and the potential measures that society can take to address the risks associated with climate change, including investment opportunities. Globalization, geopolitics, demographic processes, a sharp increase in social inequality, revolutions, and recent events related to the coronavirus pandemic and the Russia-Ukraine conflict, which affects the energy situation around the world, contribute to this uncertainty [1–5].

The ongoing global energy transition towards a low-carbon economy has been a topic of immense interest in recent years. The COVID-19 pandemic, also known as the coronacrisis or pandemic crisis, has significantly accelerated this transition by impacting global energy demand, greenhouse gas (GHG) emissions, and energy prices [6].

Consequently, the focus of numerous projections and scenarios has shifted towards understanding the potential impact of the pandemic on the future of global energy systems and low-carbon development.

In response to these global changes, Kazakhstan's President, K. Tokayev, announced at the virtual Climate Ambition Summit on 12 December 2020 that Kazakhstan aims to achieve climate neutrality by 2060. Subsequently, the "Strategy for achieving carbon neutrality of the Republic of Kazakhstan until 2060" was signed on 2 February 2023, outlining key milestones and objectives for the country's transition to a low-carbon economy, such as the abandonment of new coal-fired generation projects and the phasing out of coal combustion, increasing renewable energy sources, a program to plant two billion trees (2025), 100 percent sorting of municipal solid waste (2040), sustainable agriculture across 75 percent of arable land (2045), 100 percent electrification of personal passenger transport (2045), the use of green hydrogen, the complete phase-out of coal-fired production (2050), promoting energy efficiency across all sectors, investing in carbon capture and storage technologies, and fostering innovation in low-carbon technologies and sustainable practices. [7,8]. This paper explores the influence of various assumptions on the future energy system and examines the transition from a coal-based energy system to one based on nuclear and renewable energy sources.

Given the growing interest in low-carbon development and carbon neutrality scenarios from organizations such as the Intergovernmental Panel on Climate Change (IPCC), it is crucial to conduct predictive analyses using established classifications and methodologies [9]. Scenario analysis, as proposed by [10], is fundamental for energy planning, as it allows for the exploration of alternative development paths and outcomes, considering long-term planning horizons, technological lifespans, and variable implementation times. The reference scenario is typically compared with contrasting scenarios based on alternative hypotheses to evaluate the energy system's response under different conditions and to identify optimal development paths [11] (See Table 1).

Table 1. The scenarios of the future development of global energy.

Reference Scenario	**References**
Current policies scenario OPEC's reference or reference case Reference case scenario (RCS) Reference scenario (baseline scenario) Rivalry—Equinor company Planned energy scenario (PES)	IEA, 2021 [12] WOO, 2021 [13] GGO, 2021 [14] IEEJ, 2021 [15] Equinor, 2021 [16] IRENA, 2021 [17]
CN	References
World energy outlook 2021 scenarios	[18]
• Net zero scenario (net zero)	IEA, 2021
• Sustainable development scenario (SDS)	IEA, 2021
• Announced pledges scenario (APS)	IEA, 2021
• Stated policies scenario (STEPS)	IEA, 2021
Intergovernmental Panel on Climate Change, IPCC—*Special Report on Global Warming of 1.5 °C*	IPCC, 2021 [19]
1.5 °C Scenario—IRENA (world energy transitions outlook 2021)	IRENA, 2021 [20]
Scenario 1.5 °C pathway	McKinsey, 2021 [21]

Table 1. *Cont.*

Reference Scenario	References
OPEC's alternative scenarios (scenario A, scenario B)	World Oil Outlook, 2020 [22]
Carbon mitigation scenario (CMS)	GECF, 2021 [23]
Advanced technologies scenario	IEEJ, 2020 [24]
Renewal	Equinor, 2020 [25]
Rebalance	Equinor, 2020 [26]
Rapid transition scenario	BP Energy Outlook 2020 [27]
NEO climate scenarios (NCS) (green, gray, red)	BloombergNEF, 2021 [28]
New normal scenario	Global Energy and Climate Outlook, 2020 [29]

Kazakhstan's energy sector, being the country's largest source of greenhouse gas (GHG) emissions, plays a crucial role in the country's transition to a low-carbon economy. The challenges posed by the energy sector in Kazakhstan are due to its current structure, based on coal usage, and the continental climate with clearly defined seasons [23]. As the country aims to achieve carbon neutrality, it is essential to evaluate the proposed measures and their impact on various sectors, including energy, manufacturing, construction, and transportation [24].

The transition to renewable energy sources (RES) in Kazakhstan's energy sector comes with many challenges, particularly the vulnerability of RES to variable capacities [30]. The introduction of intermittent generation based on renewable energy sources can cause imbalances in the energy system, requiring changes in traditional electricity production schedules and the implementation of energy storage systems [31]. Evaluating these measures and their potential to achieve carbon neutrality is critical to the successful low-carbon development of Kazakhstan's economy.

Economic growth with low carbon output involves substantial cuts in greenhouse gas emissions relative to GDP, transitioning from fossil fuels to renewable energy sources such as solar, wind, and small-scale hydropower. It also includes lessening energy usage, thus diminishing emissions in industries and utilities. Hence, assessing the measures for achieving carbon neutrality is crucial [32–34].

In light of these considerations, this paper aims to contribute to the existing body of knowledge by critically reviewing the literature on carbon neutrality and low-carbon development strategies. This paper emphasizes the main scientific works cited in the text, highlighting their contributions to the current state of the topic, the approaches employed, the most important results obtained, and the existing unsolved issues. By doing so, this paper seeks to address the unsolved problems related to the subject and support the importance of the study within the broader context of the energy transition and carbon neutrality efforts.

Notwithstanding the increasing corpus of literature on low-carbon development and carbon neutrality scenarios, a substantial gap in knowledge persists concerning the distinctive obstacles that Kazakhstan encounters in realizing its carbon neutrality objectives. The current body of research has not adequately examined the intricate interrelationships among the energy infrastructure, regional attributes, and policy frameworks that are unique to Kazakhstan's energy system. The absence of information in the present state of knowledge poses a barrier to the formulation of all-encompassing and efficacious approaches towards attaining carbon neutrality within the nation.

The main contributions of the paper are as follows:

— A critical literature review on carbon neutrality and low-carbon development strategies is conducted, focusing specifically on Kazakhstan's energy system.

— A comprehensive analysis of the challenges and potential solutions unique to Kazakhstan's energy infrastructure is provided, considering the country's distinct climatological and geological conditions.
— The impact of different assumptions on the future energy outlook of Kazakhstan is investigated, contributing to a better understanding of the country's transition towards a low-carbon economy.
— The existing gap in the literature is identified and addressed, offering valuable insights for policymakers, industry stakeholders, and researchers working on carbon neutrality and low-carbon development.

This study's novel contributions pertain to the comprehensive analysis of Kazakhstan's energy system, encompassing the assessment of proposed measures and their effects on diverse sectors, including the energy, manufacturing, construction, and transportation sectors. Furthermore, the authors evaluate the susceptibility of sustainable energy sources to fluctuating capacities and the consequences of sporadic generation on the resilience of the energy grid.

The rest of the paper is structured as follows: Section 2 presents the methodology used for the analysis, including the scenario development and modeling approach; Section 3 discusses the results of the study, focusing on the challenges and opportunities for achieving carbon neutrality in Kazakhstan; and Section 4 offers conclusions and recommendations for future research and policy development.

2. Research Methods and Assumptions

This study employs systematic and prospective analysis techniques, providing insights into modern measures for achieving carbon neutrality at the global level and exploring potential future developments. The research methodology consists of several stages: setting the study's goal, assessing the current state of the problem, and conducting the analysis using the MARKAL-EFOM Integrated System, version 4.1.0, with the solver LP = cplex, a bottom-up model generator developed by the ETSAP (Energy Technology Systems Analysis Programme) of the IEA (International Energy Agency, Paris, France) [35–37].

The computations were executed on a computer equipped with an Intel(R) Core (TM) i7-9750H central processing unit, which operates at a frequency of 2.60 gigahertz, and with a RAM capacity of 16 gigabytes. The utilized operating system is of 64-bit architecture, and the duration of computation for the numerical outcomes was 1028.4 s.

The study encompassed a comprehensive range of sectors, including the agriculture, electricity, industry, upstream, residential, supply chains, and transportation sectors. The primary areas of interest were fuel prices, renewable energy sources, carbon taxes, and demand forecasts spanning the years 2017 to 2060.

The study is structured chronologically, starting from 2017 and spanning until 2060. The temporal intervals are demarcated by discrete annual designations, namely 2018, 2020, 2025, 2030, 2035, 2040, 2045, 2050, 2055, and 2060. The model employs a temporal resolution of 10 intervals for time segmentation, 4 intervals for seasonal differentiation, and 6 intervals for diurnal variation.

This model employs linear programming to create a lowest-cost power system optimized for various user constraints over medium and long-term time horizons. It combines two systematic approaches to energy modeling: an engineering approach and an economic approach. The model covers all stages from primary resources to the supply of energy services demanded by energy consumers, including transformation, transportation, distribution, and energy transformation.

Figure 1 shows the flowchart depicting the TIMES model structure and its usage for the scenario analysis of Reference and Carbon neutrality scenarios.

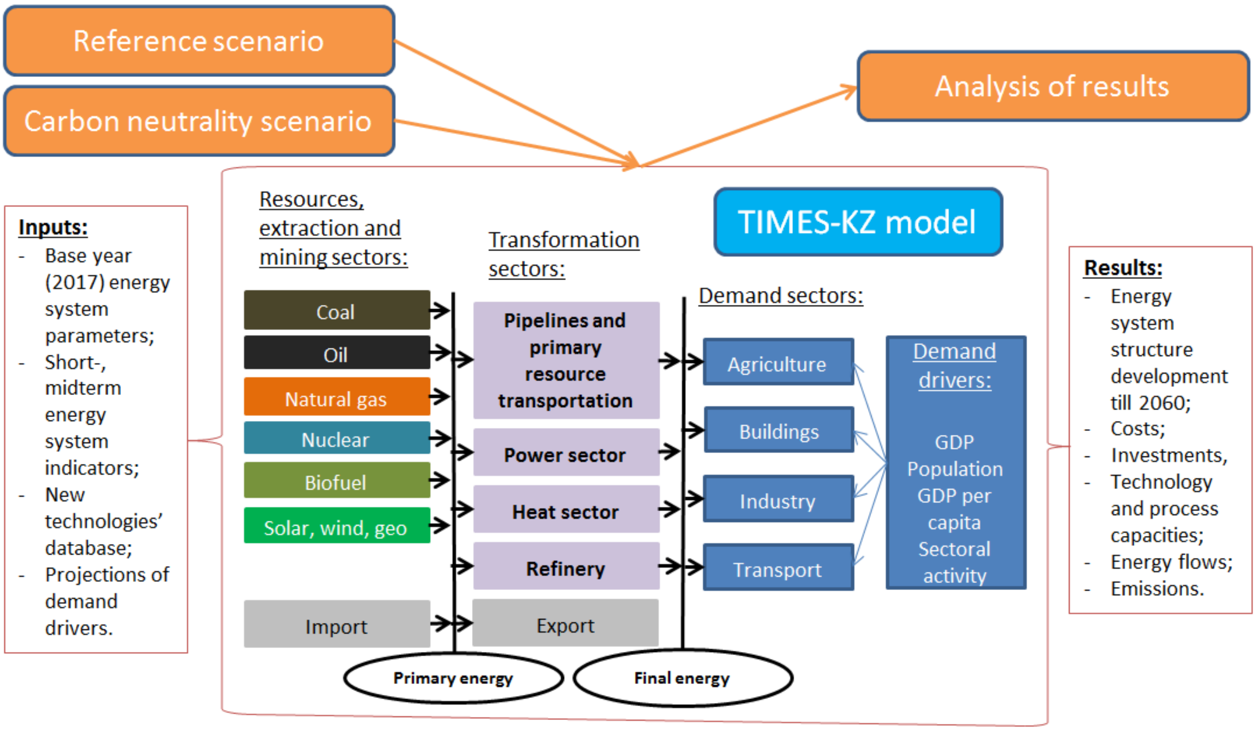


Figure 1. Flowchart of TIMES model and scenario analysis.

As can be seen in Figure 1, the assumptions of the scenario feed into the model containing a prepared structure using new technologies' database for future periods and assumed demand drivers' projections. After the results are obtained from the model, they are interpreted and analyzed for insights into the energy system's future developments.

Using the TIMES-based model, the authors analyzed the following scenarios for the development of Kazakhstan's energy system:

1. Reference scenario without long-term GHG decreasing measures until 2060 (RF);
2. The scenario of carbon neutrality until 2060 (CN).

The reference scenario reflects a possible scenario of changes in greenhouse gas emissions in a situation where no long-term measures are taken to reduce them, except gasification. In contrast, the "carbon neutrality" scenario explores the space for carbon neutrality by setting the final goal of minimizing GHG emissions by 2060 and implementing several measures planned or discussed from a mid-term perspective

Table 2 presents the assumptions for both scenarios, covering indicators such as emissions trading systems (ETS), population forecasts until 2026, oil production and gasification, and taxes. The no-measures and carbon-neutral scenarios are based on feasibility modeling for the energy sector.

Firstly, describing the general assumptions used for all scenarios is necessary. According to Table 2, GDP in the period 2022–2026 and until 2030 is forecasted to be at 4.0% per year, 3.5% per year until 2035, and around 3.0–2.0% after 2035; population growth in the period 2022–2026 and until 2035 is forecasted to in the range of 0.8–0.9% per year. Both of these forecasts are based on the Socio-Economic Development of the Republic of Kazakhstan (SED RK).

Table 2. Scenario Assumptions.

	Reference Scenario (RF)	Carbon Neutrality (CN) Scenario
General assumptions for all scenarios		
GDP in the period 2022–2026 and until 2030 is forecasted to be at 4.0% per year, 3.5% per year until 2035, and around 3.0–2.0% after 2035 (Socio-Economic Development of the Republic of Kazakhstan (SED RK)).	V *	V
Population growth in the period 2022–2026 and until 2035 is expected to be in the range of 0.8–0.9% per year (according to the forecast of the Socio-Economic Development of the Republic of Kazakhstan (SED RK)).	V	V
Oil production rises to peak (115 million tons) in 2035.	V	V
Gasification of the country is proceeding according to the forecast gas balance of the Republic of Kazakhstan as a minimum and according to scenario assumptions as a maximum.	V	V
Scenario-specific assumptions		
The share of electricity generation on natural gas is expected to be at the level of 20% and 25% in 2020 and 2030, respectively, and free from 2031.	X *	V
Share of electricity generation from RES at the level of 3%, 6%, and 15% in 2020, 2025 and 2030, respectively.	X	V
Share of coal production at 40% by 2030.	X	V
Carbon tax on non-quota sectors by the ETS, with an annual increase by 3 dollars starting from 2023 on buildings, agriculture, and transport.	X	V
Limits on GHG emissions for 2030 (minus 15% from 1990 level) and for 2060 (zero level).	X	V

* where X means “not considered”, V means “considered”.

3. Results and Discussion

3.1. The Current Policy and Measures against Climate Change in Kazakhstan

The strategy formulated the current policy in the sphere of climate change in Kazakhstan. As a major exporter of fossil raw materials, Kazakhstan recognizes the need to decarbonize the economy and create a sustainable low-carbon economic development model to create new growth drivers [7]. The main pillars of policy consist of such elements as the emission trade system (ETS), carbon budget, adaptation to the consequences of climate change, and others.

Achieving carbon neutrality by 2060 for a country as large and sparsely populated as Kazakhstan requires careful planning across the four decades. The strategy aims to achieve this through the integrated implementation of a low-carbon policy and the use of sectoral and cross-cutting approaches, including transitioning, “green” financing, research and development work, education, public consciousness, international cooperation, adaptation to climate change, and carbon regulation systems [7].

Currently, GHG emissions are regulated through the ETS, which began to work in 2013. Through the ETS, the authorized government agency has the ability to control only 43% of national GHG emissions. Only carbon dioxide emissions have quotas. Quotas are distributed free of charge [38]. However, the effect of the ETS on the GHG decrease is not observable due to the additional quota distribution to the market entities.

Some measures related to GHG mitigation were formulated via several strategic documents. *The Concept of Transition of the Republic of Kazakhstan to a Green Economy* (2013) defines the goals for energy by 2030: the share of alternative sources in electricity production—30%, the share of gas generation of electricity—25%, and the reduction of carbon dioxide (CO_2) emissions in the electric power industry by 15% [39].

The Law on Support for the Use of Renewable Energy Sources firstly regulates the measures of state support for the use of RES, not only for the commercial production of electricity and heat, but also for the use of distributed small RES installations for the own needs of households and farms, and secondly regulates the responsibility of the government, the authorized body, and the local executive bodies in this area. Distributed small-scale renewable energy in Kazakhstan has not yet developed, and official statistics on it are not being compiled.

3.2. The Results of the Scenarios

The results of the calculations are presented here. It is clear, that it is difficult to revert the inertia energy system to the new path.

The graph shows that the opportunity to reduce emissions toward carbon neutrality begins to be realized around 2025. By 2030, GHG emissions from the energy sector will reach −20% of the level of GHG emissions from the energy sector in 1990. This level declines to −40%, −54%, and −99% in 2040, 2050, and 2060, respectively (Figure 2). The level of GHG emissions from the energy sector in 2060 is 1.4 million tons of CO2-eq, which are associated with the cement industry, the use of natural gas for non-energy needs, and the production of hydrogen.

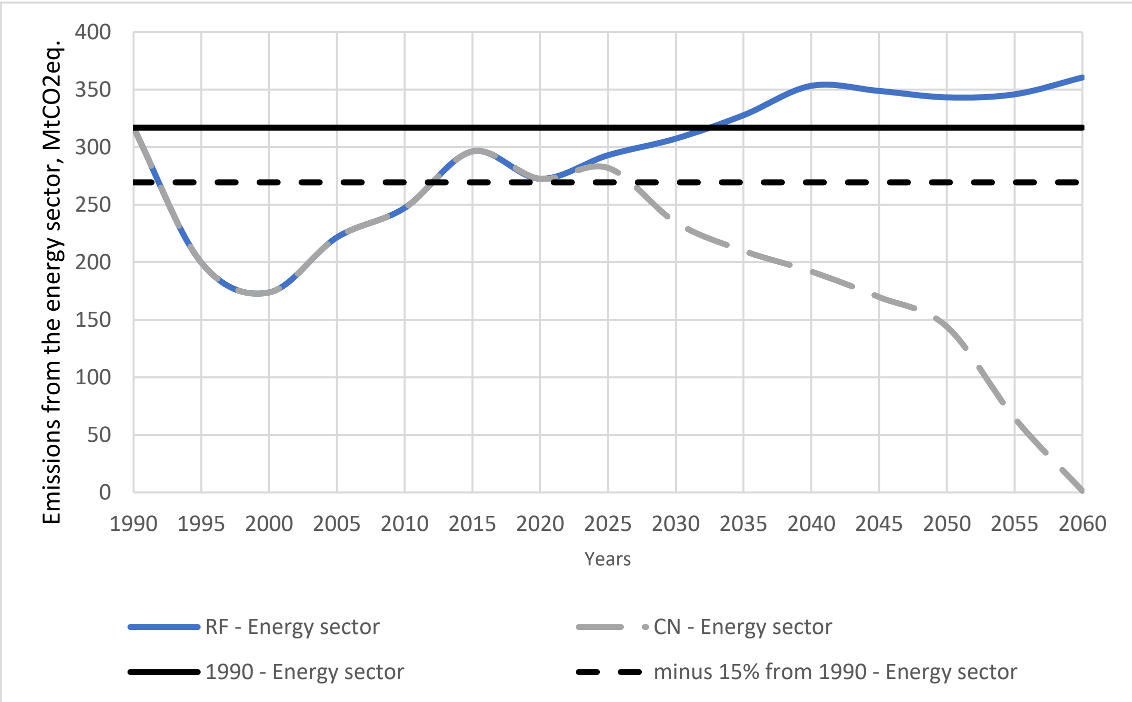


Figure 2. Scenarios for the development of greenhouse gas emissions from the energy sector, MtCO2eq.

To achieve this path, the energy system requires $544 billion in addition to the investments already happening in the reference scenario, in which the investments are around $1120 billion dollars for the total energy system. Therefore, carbon neutrality requires 48% more investments in the decarbonized energy system. However, when compared with the $610 billion required for decarbonization investments under Kazakhstan's Low-Emission Development Strategy (LEDS) [7], the pathway proposed in this paper proves to be more cost-effective as it necessitates smaller investments.

3.3. The Electricity Generation Sector

GHG emissions from the production of electricity in different scenarios are presented in Figure 3.

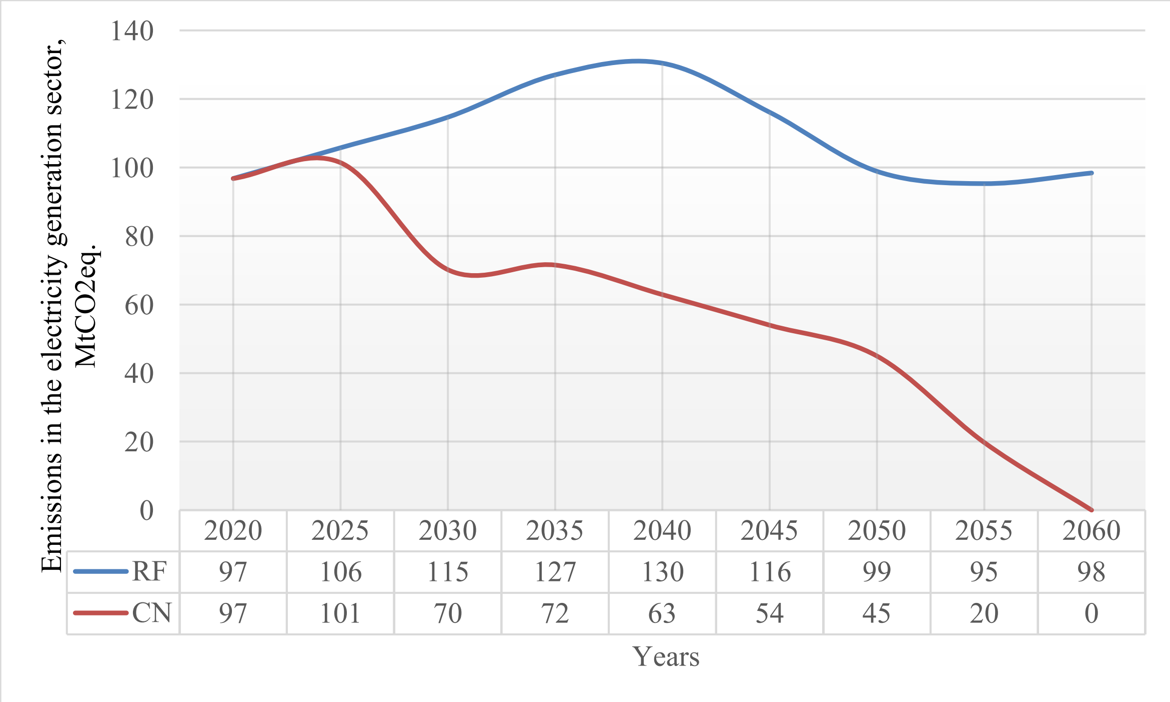


Figure 3. Scenarios for the development of greenhouse gas emissions in the electricity generation sector (MtCO2eq).

In the reference scenario, GHG emissions from the electricity sector continue to increase until 2040, subsequently dropping as a result of the increased adoption of gasification and a partial phase-out of coal (Figure 3). Conversely, in the carbon neutrality (CN) scenario, GHG emissions decrease more rapidly, thanks to a swift coal phase-out, expanded gasification, and the integration of nuclear energy and renewables into the energy mix.

Table 3 presents the electricity generation in billion kWh for various energy sources under both the RF and the CN. The data is provided for the years 2017, 2020, 2025, 2030, 2040, 2050, and 2060. The energy sources considered in the table are coal, natural gas, large hydropower plants (HPPs), small HPPs, nuclear power, solar, wind, bioenergy, and hydrogen. The table illustrates the changes in electricity generation for each energy source across different time periods under both scenarios.

Table 3. Electricity generation, billion kWh.

	Fact		Reference Scenario					CN				
	2017	**2020**	**2025**	**2030**	**2040**	**2050**	**2060**	**2025**	**2030**	**2040**	**2050**	**2060**
Coal	76.3	75.1	82.2	89.1	86.4	43.2	33.6	78.2	45.7	21.8	3.8	0.0
Natural gas	15.2	21.2	27.6	28.5	58.3	96.8	117.4	28.1	32.3	65.9	81.8	0.0
HPPs are large	11.2	9.1	11.2	11.2	13.3	13.3	7.4	11.2	13.3	13.3	13.3	7.4
HPPs are small	0.0	0.8	0.0	0.0	0.0	0.0	0.0	3.8	3.9	3.9	3.9	3.9
Nuclear power	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.9	21.5	65.5	228.6
Solar	0.0	1.3	1.0	1.0	5.4	35.1	57.7	1.9	6.9	13.8	32.8	112.8
Wind	0.3	1.1	0.8	0.8	1.8	9.5	10.0	1.8	8.7	17.3	38.5	119.3
Bioenergy	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	13.4	11.0	0.0
Total	103.0	108.6	122.8	131.3	165.1	197.7	226.2	125.0	126.8	170.9	250.4	472.0

According to the data, if generation in the reference scenario grows gradually and increases about two times by 2060, then in the carbon neutrality scenario, the growth reaches almost a little less than five times reaching 472 billion kWh, indicating the importance of electrification for carbon neutrality in energy-demanding sectors such as construction, agriculture, transport, and industry. At the same time, renewable and alternative energy sources play an essential role. The achieved level of electricity generation by 2060 is less than in LEDS, where the amount of electricity is 525 billion kWh. With this new path, the energy system requires less electricity due to the smaller share of renewables and the use of hydrogen as an intermediate energy carrier that allows for the smoothing of the intermittence of solar and wind electricity sources. The share of renewables (solar, wind, and small hydro) is 50% against 83.2% in LEDS [7].

The intermittency of renewable energy sources (RES) is tackled by natural gas capacities, batteries, and hydrogen usage as an intermittent fuel for hydrogen power plants, which source their hydrogen from RES. The hydrogen for electricity is modelled as being produced from RES and then utilized in hydrogen power plants. The modelling uses 10 slices for time differentiation, 4 for seasons, and 6 for day-night differentiation.

The model's updated capacity factor for nuclear power is 0.9 annually. Additionally, peak demand can be met by natural gas and hydrogen power plants. However, the model operates at the level of technologies, not generators, which can be challenging to capture in the TIMES model.

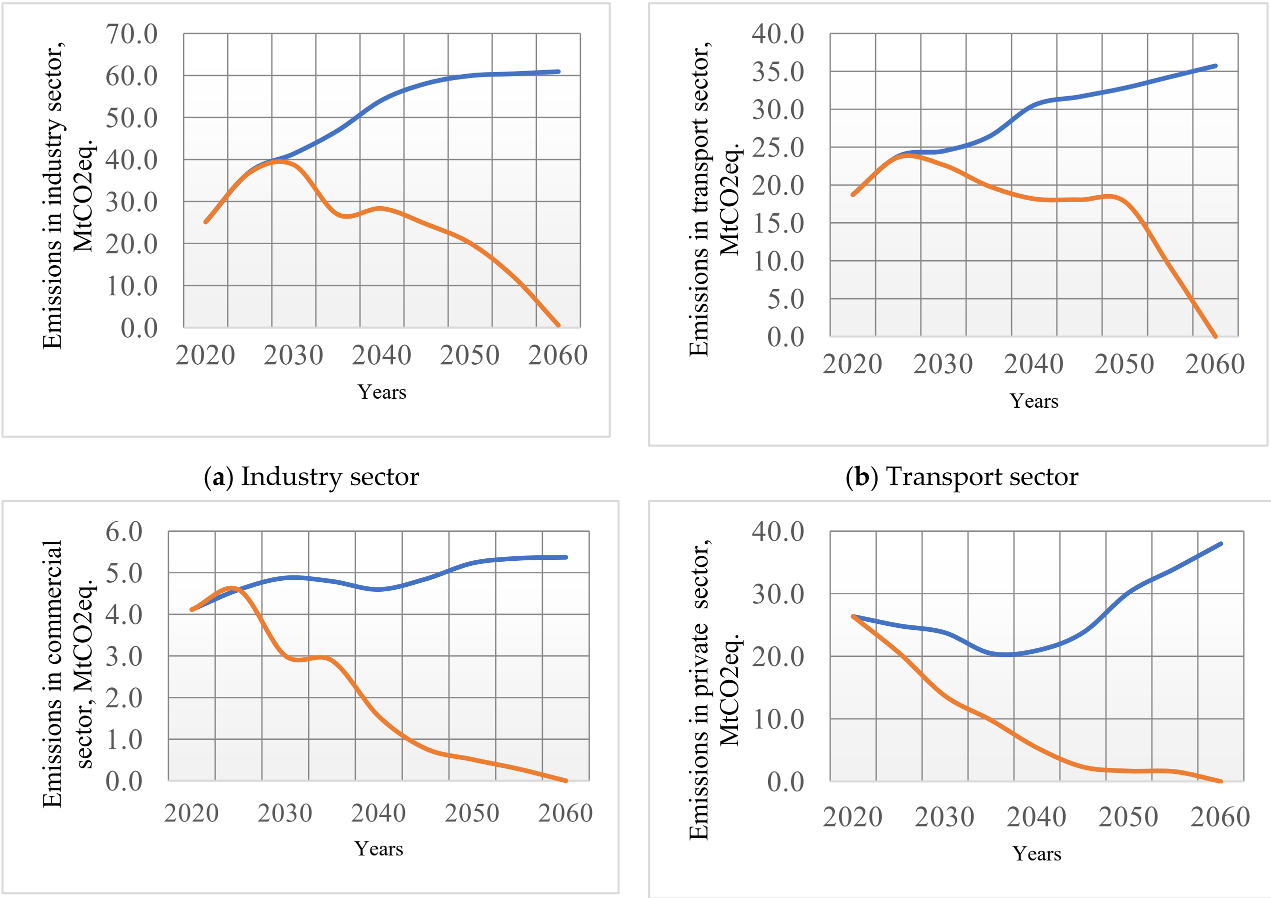
The structure of production by scenarios shows that the coal in electricity production decreases in all scenarios and reaches zero by 2060. The decrease in coal capacities should be planned due to the retirement of the existing coal capacities. There are some plans to build coal plants, mainly co-generation heat plants, but such plans are under consideration due to the evolving climate policy nationally and around the world. Even though, if they will be implemented, they can be gasified in the future when the amount of natural gas will be available in such places. Most probably, the gasification will be done with combined cycle technologies. The share of natural gas increases by 2040 and then decreases to zero, which is necessary for the interim period 2020–2050 and to achieve carbon neutrality by 2060. Implementing intensive geological explorations is necessary to find gas fields and to consider the imports from Russia and Turkmenistan. However, these measures should be weighed against energy security. This issue takes the main role in formulating plans in view of the current geopolitical challenges and situations in the world [40–44].

Hydropower does not play a significant role in either scenario due to the low possibility that the current number of hydro resources will be increased. Furthermore, there is a risk of water shortages in the future, and this is due to the shrinking of the glaciers in upstream counties and the increasing withdrawal of water from rivers by growing upstream counties' economies. The share of hydropower energy in the future decreases towards the end of the time horizon due to the retirement of the current hydropower plants and the assumption that a water shortage will occur in the meantime.

3.4. Other Sectors

Other sectors represent the key energy sectors such as industry, transport, and households (commercial and private types).

GHG emissions from the industry sector are decreasing due to the energy efficiency in the mid-term horizon, and the widespread electrification of almost all industrial processes, where possible, in the long-term horizon (Figure 4a). This aligns with the LEDS results [7]. According to obtained results, hydrogen in processes is increasingly used in addition to electrification. Hydrogen-based steel production technology exists, wherein iron ore is converted to sponge iron using hydrogen. This sponge iron is melted in an electric arc furnace (EAF) to produce steel. By 2060, the cement industry and non-ferrous metallurgy are anticipated to have virtually zero greenhouse gas emissions.



(**a**) Industry sector (**b**) Transport sector

(**c**) Commercial sector (**d**) Private sector

Figure 4. Scenarios (Blue line—RF, Orange line—CN) for the development of greenhouse gas emissions in (**a**) industry, (**b**) transport, (**c**) commercial, and (**d**) private sectors; MtCO2eq.

GHG emissions from the transport sector in the reference scenario are on the rise (Figure 4b), driven by economic growth and demand for freight and passenger transportation. In the carbon neutrality scenario, GHG emissions are reduced to zero through the electrification of transport, as well as through the use of hydrogen in aviation, rail, and water transport, where the use of electricity is not possible from the current state of knowledge.

The GHG emissions from the commercial sector are declining due to increased energy efficiency in technology and electrification (Figure 4c). This allows GHG emissions to be stabilized at the same level in the reference scenario and reduced in the carbon-neutral scenario. Moreover, in the last scenario, there is a slight increase in GHG emissions in the period 2030–2035 due to the increased use of natural gas for the hot water supply. After 2035, hot water will switch to technology using solar energy to heat water.

Regarding the private sector in the reference scenario, GHG emissions increase by 2060, but there is a period of decrease in GHG emissions from 2025–2040 before a period of further increase from 2040 to 2060 (Figure 4d). Here, the impact of switching from coal to natural gas during the period of reducing GHG emissions is evident. Further growth in emissions is associated with an increase in demand for energy from the population, which is accompanied by both an expansion of gasification until the end of the period, and an increase in the use of coal. In the case of a carbon neutrality scenario, the reduction in GHG emissions is accompanied by gasification in the medium term and an increasing role of solar and geothermal (heat pump) energy for decarbonization purposes.

The research results will play a crucial role in achieving sustainable outcomes at national and local levels by providing a comprehensive understanding of the current and projected greenhouse gas (GHG) emissions and the effectiveness of various reduction strategies. This information is valuable for policymakers and stakeholders as it can guide the development and implementation of targeted policies and regulations that promote a low-carbon, sustainable economy.

Moreover, the findings can support decision-making by helping governments set realistic and achievable targets for their sustainability and climate action plans, based on the identified key milestones and benchmarks for emissions reduction. The research also encourages innovation by highlighting promising areas for development and investment in low-carbon technologies and sustainable practices, and fosters collaboration by emphasizing the need for cross-sectoral cooperation and coordination.

By presenting a clear picture of GHG emissions and the potential for change, the research can contribute to raising public awareness and understanding of the importance of sustainable practices and climate action urgency. Furthermore, the data and projections serve as a baseline for the ongoing monitoring and evaluation of the implemented policies and strategies, allowing for adjustments and improvements as needed to ensure sustainable results.

4. Conclusions

The article considered two contrasting scenarios of actions taken in the energy sector until 2060: a reference scenario and a carbon neutrality scenario. The TIMES energy system model was employed to estimate the GHG emissions. This model was developed as a component of the project to devise the Low-Carbon Development Strategy (LEDS) of the Republic of Kazakhstan until 2060, focusing primarily on the energy sector.

According to the results, GHG emissions in the reference scenario increased over the entire forecast period. By 2030, the CN scenario achieves a 20% reduction in energy GHG emissions compared to 1990 levels, intensifying to 40%, 54%, and 99% reductions in 2040, 2050, and 2060, respectively. By 2060, the energy sector's GHG emissions level stands at 1.4 million tons of CO2-eq, primarily attributed to the cement industry, non-energy uses of natural gas, and hydrogen production.

The CN scenario necessitates a profound transformation in the energy sector, altering both the volume and structure of the primary energy supply and final energy demand over time. It demands an additional $544 billion investment in the energy sector, however, when compared to the $610 billion required for decarbonization investments in Kazakhstan's Low-carbon Economic Development Strategy (LEDS), our proposed path is more cost-efficient. The most significant reduction in emissions in the energy sector is achieved by changing the energy mix and shifting towards more sustainable sources of energy, i.e., transitioning to the use of electricity and heat instead of direct combustion of fossil fuels, as well as the increased use of natural gas, nuclear, and renewable energy.

According to the precepts of the strategy, the low-carbon policy will be accompanied by steps to ensure a favorable investment climate, including creating a supportive legislative and institutional environment, and supporting the creation and development of necessary financial and physical infrastructure for a "green" economy. Particular attention will be paid to work that continuously attracts and supports private investment, including international investment, in the decarbonization process.

The actions, implemented by the guidance of the strategy are focused on decarbonizing industries and processes related to fossil fuels, decarbonizing non-fossil fuel industries and processes, increasing natural sources of emission absorption and introducing industrial solutions for capturing, using long-term storage, and carbon sequestration. The achievement of carbon neutrality will have a significant impact on Kazakhstan's economy, including sustainable economic growth, increasing investment attractiveness, high levels of technological development and competitiveness, formation of new high-performance jobs, while maintaining a high level of employment, growth in non-commodity exports, and improving the quality of the environment and the ecological well-being of the population.

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Abbreviations

CN	carbon neutrality
GHG	greenhouse gas
LEDS	Low-Emission Development Strategy
EAF	electric arc furnace
ETS	emission trading system
ETSAP	Energy Technology Systems Analysis Programme)
HPP	Hydro Power Plant
IEA	International Energy Agency
FCCC	Framework Convention on Climate Change
IPCC	the Intergovernmental Panel on Climate Change
MEGNR	The Ministry of Ecology, Geology and Natural Resources
RES	renewable energy sources
RF	Reference scenario
SED RK	Socio-Economic Development of the Republic of Kazakhstan
UN	United Nations
CO_2	carbon dioxide
tCO2eq	tons of CO_2 equivalent

References

1. Bernath, C.; Deac, G.; Sensfuß, F. Impact of sector coupling on the market value of renewable energies–A model-based scenario analysis. *Appl. Energy* **2021**, *281*, 115985. [CrossRef]
2. Khosravi, F.; Jha-Thakur, U. Managing uncertainties through scenario analysis in strategic environmental assessment. *J. Environ. Plan. Manag.* **2019**, *62*, 979–1000. [CrossRef]
3. Frister, M. What Informal Communication about the Energy Transition Tells us: To What Extent do Professionals in the Renewable Energy Sector Act as Change Agents in this Socio-Technical Process? Bachelor's Thesis, University of Twente, Enschede, The Netherlands, 1 July 2022.
4. Pauliuk, S.; Heeren, N. Material efficiency and contribution to climate change mitigation in Germany: A deep decarbonization scenario analysis until 2060. *J. Ind. Ecol.* **2021**, *25*, 479–493. [CrossRef]
5. Żuk, P.; Żuk, P. National energy security or acceleration of transition? Energy policy after the war in Ukraine. *Joule* **2022**, *6*, 709–712. [CrossRef]
6. Padmanabhan, R.; Abed, H.S.; Meskin, N.; Khattab, T.; Shraim, M.; Al-Hitmi, M.A. A review of mathematical model-based scenario analysis and interventions for COVID-19. *Comput. Methods Programs Biomed.* **2021**, *209*, 106301. [CrossRef] [PubMed]
7. Decree of the President of the Republic of Kazakhstan Dated 2 February 2023 No. 121 "On approval of the Strategy for Achieving Carbon Neutrality of the Republic of Kazakhstan until 2060". Available online: https://legalacts.egov.kz/npa/view?id=14311815 (accessed on 10 February 2023).
8. LEDS by DIW-ECON. Supporting Green Economy in Kazakhstan and Central Asia for Low Carbon Economic Development. Available online: https://diw-econ.de/en/publications/supporting-green-economy-in-kazakhstan-and-central-asia-for-low-carbon-economic-development-times-cge-sd/ (accessed on 10 February 2023).
9. Swart, R.J.; Raskin, P.; Robinson, J. The problem of the future: Sustainability science and scenario analysis. *Glob. Environ. Chang.* **2004**, *14*, 137–146. [CrossRef]
10. Höjer, M.; Ahlroth, S.; Dreborg, K.-H.; Ekvall, T.; Finnveden, G.; Hjelm, O.; Hochschorner, E.; Nilsson, M.; Palm, V. Scenarios in selected tools for environmental systems analysis. *J. Clean. Prod.* **2008**, *16*, 1958–1970. [CrossRef]

11. Teng, F.; Xu, S.-Q. Definition of business as usual and its impacts on assessment of mitigation efforts. *Adv. Clim. Chang. Res.* **2012**, *3*, 212–219.
12. IEA. ETSAP: Energy Systems Analysis. Available online: http://www.iea-etsap.org/workshop/japan_dec2016/ESTAP%20Workshop_IEEJ.pdf (accessed on 13 July 2022).
13. BloombergNEF. New Energy Outlook 2020: BNEF. Available online: https://about.bnef.com/new-energy-outlook-2020/ (accessed on 13 July 2022).
14. IEEJ. The Institute of Energy Economics, Japan. Available online: https://eneken.ieej.or.jp/en/ (accessed on 10 February 2023).
15. World Energy Model Documentation-Microsoft. Available online: https://iea.blob.core.windows.net/assets/932ea201-0972-4231-8d81-356300e9fc43/WEM_Documentation_WEO2021.pdf (accessed on 15 July 2022).
16. Global Renewables Outlook: Energy Transformation 2050–Summary. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENA_GRO_Summary_2020.pdf?la=en&hash=1F18E445B56228AF8C4893CAEF147ED0163A0E47 (accessed on 10 February 2023).
17. IRENA. Available online: https://irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook (accessed on 10 February 2023).
18. Geco 2021. EU Science Hub. Available online: https://joint-research-centre.ec.europa.eu/geco-2021_en (accessed on 10 February 2023).
19. Energy Outlook 2030-BP. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2015.pdf (accessed on 17 July 2022).
20. About Energy Perspectives. Equinor. Available online: https://www.equinor.com/sustainability/energy-perspectives (accessed on 10 February 2023).
21. GECF. Gas Exporting Countries Forum. Available online: https://www.gecf.org/_resources/files/events/gecf-to-unveil-latest-edition-of-flagship-publication-global-gas-outlook-2050/2020-edition-of-the-gecf-global-gas-outlook-2050.pdf (accessed on 10 February 2023).
22. GECF. Global Gas Outlook 2050. Available online: https://www.gecf.org/insights/global-gas-outlook?d=2022&p=1 (accessed on 10 February 2023).
23. Keramidas, K.; Fosse, F.; Diaz-Vazquez, A.; Schade, B.; Tchung-Ming, S.; Weitzel, M.; Wojtowicz, K. *Global Energy and Climate Outlook 2020: A New Normal Beyond COVID-19*; Publications Office of the European Union: Luxembourg, 2021; Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC123203 (accessed on 10 February 2023).
24. Equinor. Energy Perspectives 2020. Available online: https://www.equinor.com/content/dam/statoil/image/how-and-why/energy-perspectives/2020/energy-perspectives-report-2020-i.pdf (accessed on 10 February 2023).
25. IEA. Net Zero by 2050–Analysis. Available online: https://www.iea.org/reports/net-zero-by-2050 (accessed on 10 February 2023).
26. IEA. World Energy Outlook 2022–Analysis. Available online: https://www.iea.org/reports/world-energy-outlook-2022 (accessed on 10 February 2023).
27. IPCC—Intergovernmental Panel on Climate Change. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf (accessed on 10 February 2023).
28. Media. McKinsey & Company. Available online: https://www.mckinsey.com/~/media/McKinsey/Industries/Oil%20and%20Gas/Our%20Insights/Global%20Energy%20Perspective%202021/Global-Energy-Perspective-2021-final.pdf (accessed on 10 February 2023).
29. OPEC. World Oil Outlook. Available online: https://www.opec.org/opec_web/en/publications/340.htm (accessed on 20 July 2022).
30. Zhakiyeva, S.; Gabbassov, M.; Akhmetbekov, Y.; Akybayeva, G.; Zhakiyev, N. The Development of a Risk Assessment Modeling for the Power System of Kazakhstan. In Proceedings of the 2021 IEEE International Conference on Smart Information Systems and Technologies (SIST), Astana, Kazakhstan, 28–30 April 2021; pp. 1–4.
31. Amanbek, Y.; Kalakova, A.; Zhakiyeva, S.; Kayisli, K.; Zhakiyev, N.; Friedrich, D. Distribution Locational Marginal Price Based Transactive Energy Management in Distribution Systems with Smart Prosumers—A Multi-Agent Approach. *Energies* **2022**, *15*, 2404. [CrossRef]
32. Kerimray, A.; Baigarin, K.; De Miglio, R.; Tosato, G. Climate change mitigation scenarios and policies and measures: The case of Kazakhstan. *Clim. Policy* **2016**, *16*, 332–352. [CrossRef]
33. Di Leo, S.; Pietrapertosa, F.; Salvia, M.; Cosmi, C. Contribution of the Basilicata region to decarbonisation of the energy system: Results of a scenario analysis. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110544. [CrossRef]
34. De Miglio, R.; Akhmetbekov, Y.; Baigarin, K.; Bakdolotov, A.; Tosato, G. Cooperation benefits of Caspian countries in their energy sector development. *Energy Strategy Rev.* **2014**, *4*, 52–60. [CrossRef]
35. Allena-Ozolina, S.; Pakere, I.; Jaunzems, D.; Blumberga, A.; Bazbauers, G. Integrated MARKAL-EFOM System (TIMES) model for energy sector modelling. In Proceedings of the 2020 IEEE 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 5–7 November 2020. Available online: http://www.conference.rtu.lv/qazcdeTGBmjU/RTUCON2020_paper_99Ln97dW10Bi87.pdf (accessed on 25 May 2022).
36. Perissi, I.; Martelloni, G.; Bardi, U.; Natalini, D.; Jones, A.; Nikolaev, A.; Eggler, L.; Baumann, M.; Samsó, R.; Solé, J. Cross-Validation of the MEDEAS Energy-Economy-Environment Model with the Integrated MARKAL-EFOM System (TIMES) and the Long-Range Energy Alternatives Planning System (LEAP). *Sustainability* **2021**, *13*, 1967. [CrossRef]

37. Di Leo, S.; Caramuta, P.; Curci, P.; Cosmi, C. Regression analysis for energy demand projection: An application to TIMES-Basilicata and TIMES-Italy energy models. *Energy* **2020**, *196*, 117058. [CrossRef]
38. Otarov, R.; Akhmetbekov, Y.; Zhakiyev, N. Determination of optimal CO_2 allowance prices for stimulation of investments in CCS, RES and other carbon-clean technologies in Kazakhstan. In *Sustainable Energy in Kazakhstan: Moving to Cleaner Energy in a Resource-Rich Country*; Taylor and Francis: Milton Park, UK, 2017; pp. 123–133.
39. Bakdolotov, A.; De Miglio, R.; Akhmetbekov, Y.; Baigarin, K. Techno-economic modelling to strategize energy exports in the Central Asian Caspian region. *Heliyon* **2017**, *3*, e00283. [CrossRef] [PubMed]
40. Wyrwa, A.; Suwała, W.; Pluta, M.; Raczyński, M.; Zyśk, J.; Tokarski, S. A new approach for coupling the short-and long-term planning models to design a pathway to carbon neutrality in a coal-based power system. *Energy* **2022**, *239*, 122438. [CrossRef]
41. Aliakbari Sani, S.; Maroufmashat, A.; Babonneau, F.; Bahn, O.; Delage, E.; Haurie, A.; Mousseau, N.; Vaillancourt, K. Energy Transition Pathways for Deep Decarbonization of the Greater Montreal Region: An Energy Optimization Framework. *Energies* **2022**, *15*, 3760. [CrossRef] [PubMed]
42. Abdi, G.; Zhakiyev, N.; Toilybayeva, S. Decarbonisation Opportunities and Emerging Carbon Pricing Instruments in Central Asia. In *Climate Change in Central Asia: Decarbonization, Energy Transition and Climate Policy*; Springer Nature: Cham, Switzerland, 2023; pp. 51–65.
43. Kerimray, A.; Suleimenov, B.; De Miglio, R.; Rojas-Solórzano, L.; Gallachóir, B.Ó. Long-term climate change mitigation in Kazakhstan in a post-Paris agreement context. In *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development*; Springer International Publishing: Cham, Switzerland, 2018; pp. 297–314.
44. Gaeta, M.; Businge, C.N.; Gelmini, A. Achieving Net Zero Emissions in Italy by 2050: Challenges and Opportunities. *Energies* **2022**, *15*, 46. [CrossRef]