Forecasting of GHG Emissions from Energy and Industrial Sectors of Kazakhstan and Assessment of Mitigation Scenarios with High Share of Renewables

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Abstract- This study leverages the TIMES-KAZ model and linear regression techniques to explore strategies for reducing emissions from energy and industrial sectors by integration more renewables. The scenario analysis of Kazakhstan's energy sector reveals a progressive shift towards cleaner energy sources, with increased investments in renewables, particularly in the Current Measures (CM) and Current and Additional Measures (CAM) scenarios. Despite this, complexities arise in emission patterns, particularly within the heat production sector, highlighting the need for a balanced energy transition approach. The analysis of Kazakhstan's industrial sector indicates a rising trend in GHG emissions, driven primarily by growth in metallurgy and mineral industries with consideration green hydrogen. The CAM scenario integrate advanced low-carbon technologies like hydrogen-based steel production, integration of renewables and electric arc furnaces, demonstrates the potential to cut emissions by half by 2035.

Keywords Greenhouse gas emissions; industrial sector; renewable integration; mitigation; scenario analysis; Kazakhstan.

1. Introduction

The industrial and energy sectors are significant contributors to global carbon dioxide emissions. In 2022, the industrial sector alone was responsible for about a quarter of the global energy system's CO2 output, totalling 9.0 gigatonnes (Gt) [1]. The most notable sectoral increase in emissions in 2022 was observed in electricity and heat generation, which saw an increase of 1.8%, or 261 Mt. Specifically, global emissions from coal-fired electricity and heat generation rose by 224 Mt, representing a 2.1% increase [2].

Enhancing energy efficiency is crucial, particularly in the residential and industrial sectors, which are the most energy-intensive and carbon-intensive in Kazakhstan, collectively contributing approximately 80% of the nation's total CO2 emissions [2].

The steel and iron manufacturing industries currently account for over one-third of the total energy consumption in the industrial sector, predominantly fueled by coal. There is significant potential to decarbonize this challenging sector through the application of carbon capture, utilization, and storage (CCUS) technologies and the adoption of hydrogen [3].

Electricity and heat generation are responsible for over half of Kazakhstan's CO2 emissions. The country's energy mix remains heavily reliant on fossil fuels, with coal accounting for nearly 50% of the total energy supply, while renewable energy sources contribute a mere 1.6% [4]. To address this, Kazakhstan must implement extensive low-

carbon deep electrification across all sectors. With an anticipated 57% increase in electricity demand over the next decade, Kazakhstan faces the dual challenge of balancing domestic energy needs with export objectives, all while transitioning to a lower carbon footprint.

Achieving carbon neutrality by 2060 requires Kazakhstan to expand its renewable energy generation by a factor of approximately 140, equating to around 500 TWh [4,5]. However, subsidized energy tariffs, which do not reflect the true cost of energy, pose a significant barrier to scaling renewable energy and energy storage solutions. In response, Kazakhstan has initiated auction mechanisms to attract investment in renewable energy and flexible generation capacities, including large-scale gas-fired, nuclear, and hydropower projects.

Despite growing global attention on climate change, the methods used to forecast GHG emissions and assess mitigation scenarios specific to Kazakhstan remain underdeveloped. Common approaches, such as econometric models, trend analysis based on historical data, and scenario analysis, provide estimates based on assumptions about economic growth, technological advancement, and policy interventions [6-9]. However, these methods often fail to account for the regional characteristics and unique conditions of Kazakhstan's industrial sector. As a result, there is an increasing need for more accurate, localized models that reflect the specific dynamics of Kazakhstan's economy and industrial landscape. The TIMES model (an acronym for The Integrated MARKAL-EFOM System) appears particularly attractive in this regard because it is adaptive to local energy systems and suited to the analysis of energy-environmental policies, thanks to the detailed technological-level representation of all combustion sectors of interest in terms of reducing greenhouse gas emissions [10]. However, the model does not consider the interaction of combustion sectors with other sectors of the economy and, accordingly, cannot account for intersectoral interactions with them.

National TIMES models have been utilized in similar works by experts to forecast greenhouse gas emissions and evaluate mitigation strategies (TIMES-DK, TIMES-Spain, China-TIMES) [11-13]. Several studies, including notably the Wang [6] and Allena-Ozolina [14] groups, have reported pioneering advances in utilizung TIMES-model for industry sector.

In the study conducted by Wang and others, using the Global TIMES model, the pathways for the industrial sector to transition to the 2-degree target are explored [6]. A comparative analysis of regions at different stages of industrialization, such as China, India, and Western Europe, reveals various challenges and potential solutions. The modeling results indicate that significant reductions in CO2 emissions and changes in the energy structure, including rapid electrification and improvements in energy efficiency, are necessary to achieve climate targets.

Using the TIMES model, the study in Latvia analyzed industrial sub-sectors and assessed the impact of measures in the National Energy and Climate Plan up to 2030. The findings suggest that while current measures enhance renewable energy use and energy efficiency, additional actions are required to achieve climate neutrality by 2050 [14].

To assess the impact of various strategies on Kazakhstan's energy system, the techno-economic model TIMES-KZ was developed. The application of this model for Kazakhstan's energy sector until 2060 was described previously in the article [15].

Linear regression models are a popular tool for predicting CO2 emissions. Studies have revealed that Linear Regression is effective in forecasting CO2 trapping efficiency using factors like CO2 emissions, population density, fossil fuel share, energy consumption, and GDP [16]. Multiple Linear Regression (MLR) models are also used to examine the links between CO_2 emissions and economic indicators, showing that the most influential predictors depend on a country's level of development and specific regional factors. For instance, in the UK, agriculture plays a significant role in predicting CO2 emissions, while in Malaysia, transport is a key predictor [17].

2. Mitigation and Control Policy

Recognizing the critical need for joint global action to address climate change, Kazakhstan signed the Paris Agreement on August 2, 2016, and ratified it on December 6, 2016 [18]. The country has set nationally determined contributions (NDCs) in line with the Paris Agreement, committing to an absolute reduction of greenhouse gas emissions by 15% from 1990 levels by 2030. This target is aimed at promoting sustainable economic development, enabling Kazakhstan to transition to a low-carbon, environmentally friendly trajectory, and contributing to the global goal of limiting the increase in global temperature to below 2°C.

The Republic of Kazakhstan's transition to a "green economy" concept includes reducing the carbon intensity of the Gross Domestic Product (GDP) as a key principle. Since the majority of greenhouse gas emissions in the country are associated with fuel combustion, reducing energy intensity and carbon intensity of GDP is directly dependent on policies in this sector.

Low-carbon economic development requires significant reductions in greenhouse gas emissions relative to GDP, a shift to renewable energy sources (solar, wind, and small hydroelectric plants), and a decrease in energy resource consumption [19, 20]. These measures aim to reduce greenhouse gas emissions in the industrial and housing sectors.

To implement this strategy, Kazakhstan has enacted the "Law on Supporting the Use of Renewable Energy Sources," set target indicators for the renewable energy sector, and introduced auction mechanisms for electricity procurement. Additionally, the "Rules for Providing Targeted Assistance to Individual Consumers" and the "Rules for Formulating Plans for the Placement of Renewable Energy Facilities" have been approved.

The Government of Kazakhstan has undertaken numerous initiatives to promote industrial sector mitigation, including the adoption and enhancement of the Environmental

Code No. 212, which, through its latest amendment, introduced the "polluter pays and rectifies" principle and established a framework for a 1.5% annual reduction in the carbon budget until 2030.

Another potential solution is the expansion of the existing emissions trading system. In Kazakhstan, greenhouse gas emissions are regulated by an emissions trading system, which operates on the principle of quota allocation. According to the plan, by 2030, greenhouse gas emissions should be reduced by 15% from the 1990 level. However, this level is already being exceeded. For example, in 2018, GHG emissions in Kazakhstan amounted to 401.9 million tons, which is 4% higher than the 1990 level.

Meanwhile, the price of a greenhouse gas quota in the EU is 50 euros per ton, whereas in Kazakhstan it is 1.1 euros. Therefore, it is advisable to expand the system. If an exporting country already has its own emissions trading system, the cost of emissions will be deducted from the established EU cost, eliminating the tax entirely when the emissions prices are equal.

Operators in the oil and gas, metallurgical, agricultural, energy, chemical, mining, and transport sectors, whose greenhouse gas emissions exceed 20 ktons of CO2-equivalent per year, are not allowed to operate unless they obtain greenhouse gas emission quotas.

The Government of Kazakhstan has adopted several measures to encourage the reduction of environmental impact and ensure the sustainable development of the national economy in the industrial sector. The State Program for Industrial and Innovative Development and Reconstruction for 2020-2025 (SPIID) is one of the main initiatives in this direction. The core principle of this program is that climate change mitigation should not harm economic growth but should simultaneously contribute to achieving other policy goals, such as the development of innovative clusters, the promotion of technological entrepreneurship, and the renewal of major equipment. Among various approaches to mitigation, energy efficiency has become a top priority, as seen in the state programs "Digital Kazakhstan." The mining and manufacturing industries are in the process of transitioning to a new technological level in line with the concept of Industry 4.0. This concept involves the integration of renewables, physical objects, processes, and digital technologies.

3. Methods

3.1 TIMES-KAZ model

To forecast greenhouse gas (GHG) emissions and assess the impact of measures in the energy, the Republic of Kazakhstan's energy system model, based on the TIMES (The Integrated MARKAL-EFOM System) tool, was utilized. Developed for the Low-Carbon Development Concept of Kazakhstan, the TIMES-KAZ model addresses combustion sectors according to the UNFCCC classification and includes CO_2, CH_4, and N_2O emissions. Using 2017 as the base year due to complete data availability, the model's time horizon extends to 2035.

The TIMES-KAZ model is a comprehensive, bottom-up, technological model employing linear programming to create a least-cost energy system optimized over medium- and long-term horizons. It details Kazakhstan's energy system, incorporating existing technologies and their costs. The model explores potential energy futures through various scenarios. For this analysis, an updated 2021 version of the TIMES-KAZ model was used, including advanced technologies such as hydrogen production and geothermal energy utilization. This model can be used for both quantitative assessments of specific aspects and overall analyses, where interactions between policies and measures can influence GHG emission reductions.

The equations (1), (2) allow for the calculation of efficiency improvements resulting from the difference between existing technology and new technologies (referred to as energy efficiency improvement), on the production side (EFF(t)EXIST(i0) <= EFF(t)NEWPROD(J)) and on the demand side (EFF(t)EXIST(i0) <= EFF(t)NEWDEM(J)).

$$\sum_{j=1}^{m}(EFF(t)_{NPT(j)} - EFF(t)_{EPT(i0)}) \quad (1)$$

$$\sum_{k=1}^{q}(EFF(t)_{NDT(k)} - EFF(t)_{EDT(z0)}) \quad (2)$$

Within the framework of the study, the following scenarios for the development of the energy system of Kazakhstan were considered:

1. No Measures Scenario (NM);
2. Current Measures Scenario (CM);
3. Current and Additional Measures Scenario (CAM).

3.2 Linear regression model

To forecast greenhouse gas emissions in the industrial processes and product use sector (hereinafter referred as IPPU), not related to fuel combustion, under the scenarios with measures, without measures, and with additional measures, a linear regression model was used. This model considers the design capacities of industrial installations in the Republic of Kazakhstan based on the forecasting tools of the Excel program, which utilizes a series of historical data, expert forecasts of economic development, and product demand.

The multiple regression model is employed when there are several predictors influencing a single response variable. This approach, as a form of extrapolation, operates on the premise that historical data can serve as a basis for forecasting future trends. In this paper, it is assumed that future CO2 emissions will likely continue the trends observed in historical data.

The linear regression equation is represented as:

$$a\,x = w0 + w1x1 + w2x2 + \cdots + wdxd, \quad (3)$$

where $a\,x$ - is the model's prediction;

$x1$, $x2$, … - are the features (predictors);

$w0$, $w1$, $w2$, … - are the model's weights.

Table 1. General assumptions for all scenarios

General assumptions for all scenarios	**No Measures Scenario (NM)**	**Current Measures Scenario (CM)**	**Current and Additional Measures Scenario (CAM)**
General assumptions for all scenarios			
GDP from 2022–2026 according to the Forecast of Socio-Economic Development of the Republic of Kazakhstan (Ministry of National Economy of the Republic of Kazakhstan) and further up to 2030 at 4.0% per year, up to 2035 at 3.5% per year	V	V	V
Population Growth from 2022–2026 according to the Forecast of Socio-Economic Development of the Republic of Kazakhstan (Ministry of National Economy of the Republic of Kazakhstan) and further up to 2035 with annual growth rates ranging from 0.8-0.9% per year	V	V	V
Oil Production increases to a peak (115 million tons) by 2035	V	V	V
Gasification of the Country proceeds according to the forecast balance of gas of the Republic of Kazakhstan at a minimum and according to scenario assumptions at a maximum	V	V	V
2020 – 24,587 million m³ (minimum)	V	V	V
2025 – 22,243 million m³ (minimum)	V	V	V
2030 – 21,016 million m³ (minimum)	V	V	V
Scenario assumptions			
The share of electricity generation from natural gas at the level of 20% and 25% in 2020 and 2030 respectively	X	V	V
The share of electricity generation from renewable energy sources (RES) at the level of 3%, 6%, and 15% in 2020, 2025, and 2030 respectively	X	V	V
The share of coal-based electricity generation at the level of 40% by 2030	X	X	V
The commissioning of a nuclear power plant (NPP) with a capacity of 1.5 GW in 2030 and 2.0 GW in 2050	X	X	V
Carbon tax on non-quota sectors within the emissions trading system	X	X	V

The forecast "with measures" encompasses currently implemented and adopted policies and measures. The forecast "without measures" excludes all policies and measures implemented, adopted, or planned after the base year selected for this forecast. Emission projections are strictly presented in relation to actual cadastral data from previous years.

For the "with measures" and "with additional measures" forecasts, the latest cadastral year serves as the baseline. The forecast is presented on a sectoral basis—GHG Inventory Program (GHG-IP). Sectoral categories are structured according to the GHG inventory. Projections are provided for each gas individually for the following GHGs: CO2, CH4, N2O, HFCs, PFCs, SF6, and NF3 (HFCs and PFCs are considered jointly). The forecasts are also compiled in both detailed and aggregated forms, as well as for the overall national total.

Within the framework of the study, the following scenarios for the development of the energy system of Kazakhstan were considered:

1. No Measures Scenario (NM);
2. Current Measures Scenario (CM);
3. Current and Additional Measures Scenario (CAM).

The scenario with additional measures describes and incorporates eco-friendly technologies and new energy technologies, such as carbon capture in cement production, green steel manufacturing, and the use of green hydrogen. Energy storage systems (CAES, batteries) could be integrated into the system for further model development. As the current project is of a strategic (as opposed to operational) nature, it is assumed that these technologies provide a full set of alternatives across all scenarios.

4. Results

4.1 TIMES Model Results

4.1.1 Production of heat and electricity

In the production of heat and electricity, GHG emissions under different scenarios are presented in the Figure 1.

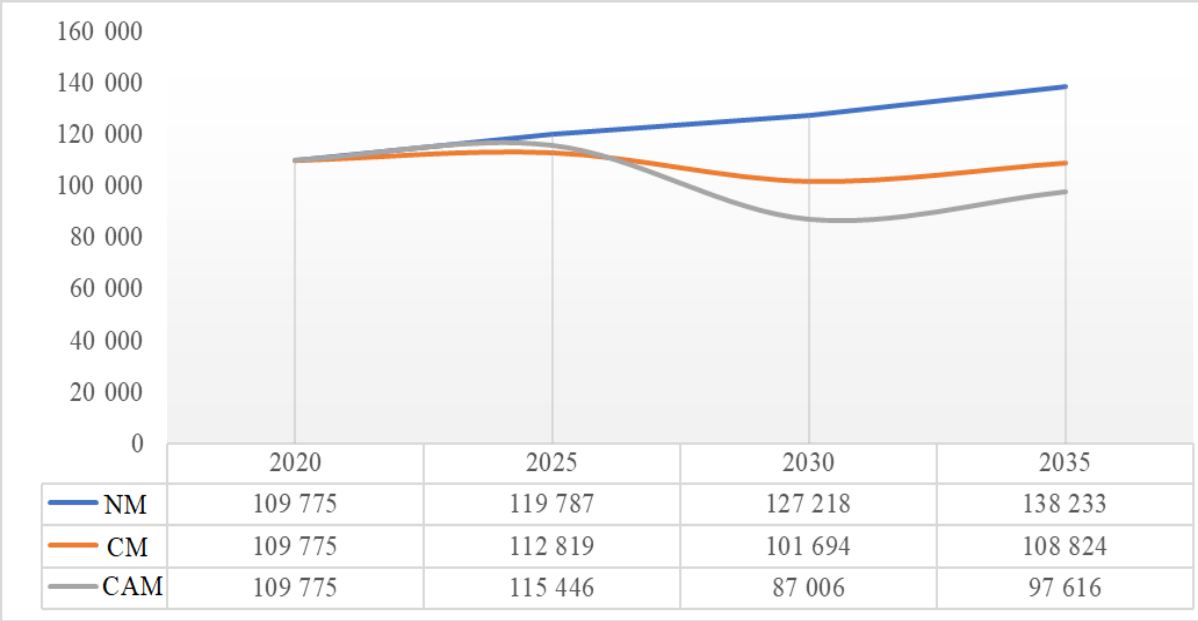


Fig. 1. Scenarios of greenhouse gas emission trends in the electricity production sector, ktCO2e.

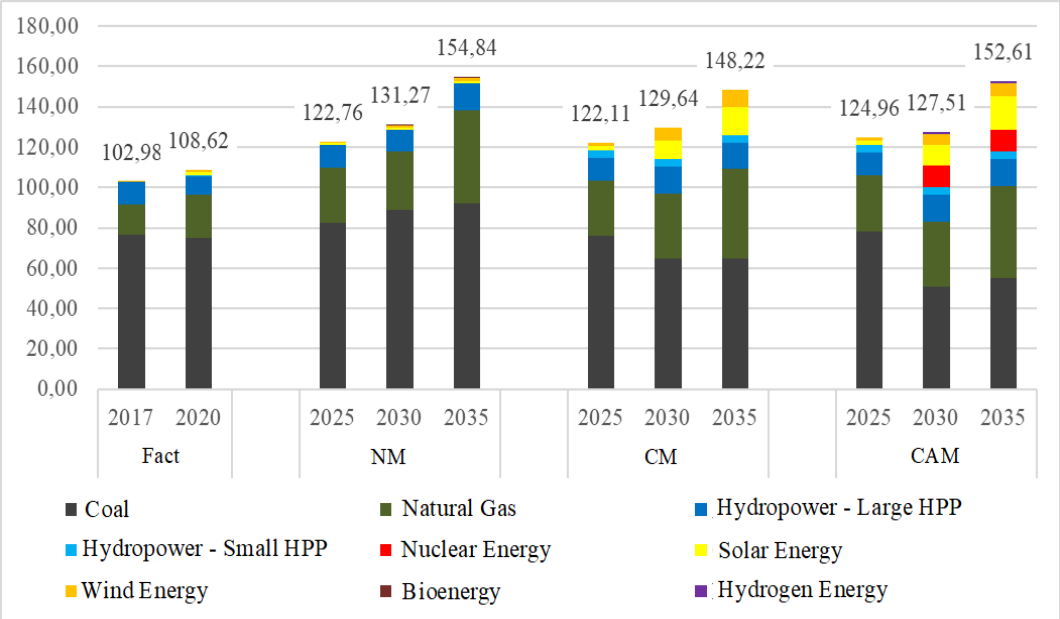


Fig. 2. Scenarios of electricity generation trends, billion kWh.

Electricity generation increases in all scenarios by around 20%, 30%, and 50% compared to 2017 levels in the years 2025, 2030, and 2035, respectively. In the scenario with measures, these levels reach 122.11, 129.64, and 148.22 billion kWh.

Electricity generation from coal in the scenarios with measures and additional measures is lower compared to the scenario without measures. In these scenarios, coal-based generation decreases, while generation from natural gas, hydropower, solar, and wind energy increases.

In the scenario with additional measures, energy from nuclear power plants (included in the scenario) and hydrogen energy is also present.

The structure of electricity generation in Table 2 by scenario shows that the share of coal in generation decreases in all scenarios. The increase in the scenario without measures is due to the faster growth rate of electricity generation from natural gas compared to coal.

Table 2. Structure of Electricity Generation, %

	Fact		NM			CM			CAM		
	2017	2020	2025	2030	2035	2025	2030	2035	2025	2030	2035
Coal	74.1	69.1	67.0	67.9	59.4	62.4	49.8	43.6	62.6	40.0	36.1
Natural Gas	14.7	19.5	22.5	21.7	30.0	22.5	25.0	30.0	22.5	25.0	30.0
Hydropower - Large HPP	10.8	8.4	9.1	8.5	8.6	9.1	10.2	9.0	8.9	10.4	8.7
Hydropower - Small HPP	0.0	0.7	0.0	0.0	0.0	3.0	3.0	2.6	3.1	3.0	2.5
Nuclear Energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.6	7.0
Solar Energy	0.0	1.2	0.8	0.7	0.6	1.5	7.0	9.4	1.5	8.0	10.9
Wind Energy	0.3	1.0	0.7	0.6	0.9	1.5	5.0	5.5	1.4	3.9	4.1
Bioenergy	0.0	0.0	0.0	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen Energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.7
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Share of RES	0.4	3.0	1.5	1.9	2.1	6.0	15.0	17.5	6.0	15.0	17.5

Table 3. Installed Power Plant Capacity, GW

	Fact		NM			CM			CAM		
	2017	2020	2025	2030	2035	2025	2030	2035	2025	2030	2035
Coal	16.3	14.7	15.2	16.6	17.6	15.2	16.8	19.1	15.2	16.6	17.6
Natural Gas	3.1	4.0	5.6	5.6	8.6	5.8	6.6	9.5	5.8	6.8	10.4
Hydropower - Large HPP	2.6	2.8	2.6	2.6	3.1	2.6	3.1	3.1	2.6	3.1	3.1
Hydropower - Small HPP	0.0	0.2	0.0	0.0	0.0	0.9	0.9	0.9	0.9	0.9	0.9
Nuclear Energy	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5
Solar Energy	0.1	0.9	0.6	0.6	0.6	1.1	5.3	8.0	1.1	5.9	9.5
Wind Energy	0.1	0.5	0.3	0.3	0.5	0.6	2.5	3.1	0.6	1.7	2.1
Bioenergy	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen Energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.5
Total	22.2	24.2	24.3	25.8	30.7	26.2	35.2	43.8	26.2	36.8	45.6

As seen from the Table 3, the increase in renewable capacity contributes more to the overall capacity growth than traditional types of power plants. In the scenarios with measures and additional measures, the level of installed capacity is higher by approximately 10 and 15 GW in 2030 and 2035, respectively.

In the heat production sector, emissions from boilers are presented, as emissions from combined heat and power (CHP) plants are included in the electricity production sector. Below are the GHG emissions from boilers by scenario. As shown, emissions decrease in all scenarios, which is due to the significant shift towards heat supply from CHP plants.

When comparing GHG emissions between scenarios, it can be observed that emissions with additional measures are higher than in the scenario with measures. This is because the increase in the share of electricity generation from nuclear power plants and the reduction in coal-based electricity generation lead to a decrease in the share of CHP plants and, consequently, the heat they provide. This is replaced by an increase in the use of heat from boilers in the scenario with additional measures.

4.2 Linear regression results

Figure 3 shows the GHG emissions forecast under the Current Measures Scenario (CM) in the IPPU category for the years 1990–2019 and the projection up to 2030, broken down by subcategory. As seen from the graph, the primary drivers of GHG emissions growth are the metallurgy sector and mineral production. In 2019, emissions from the IPPU sector exceeded the 1990 base year level by 24.2% (Table 4).

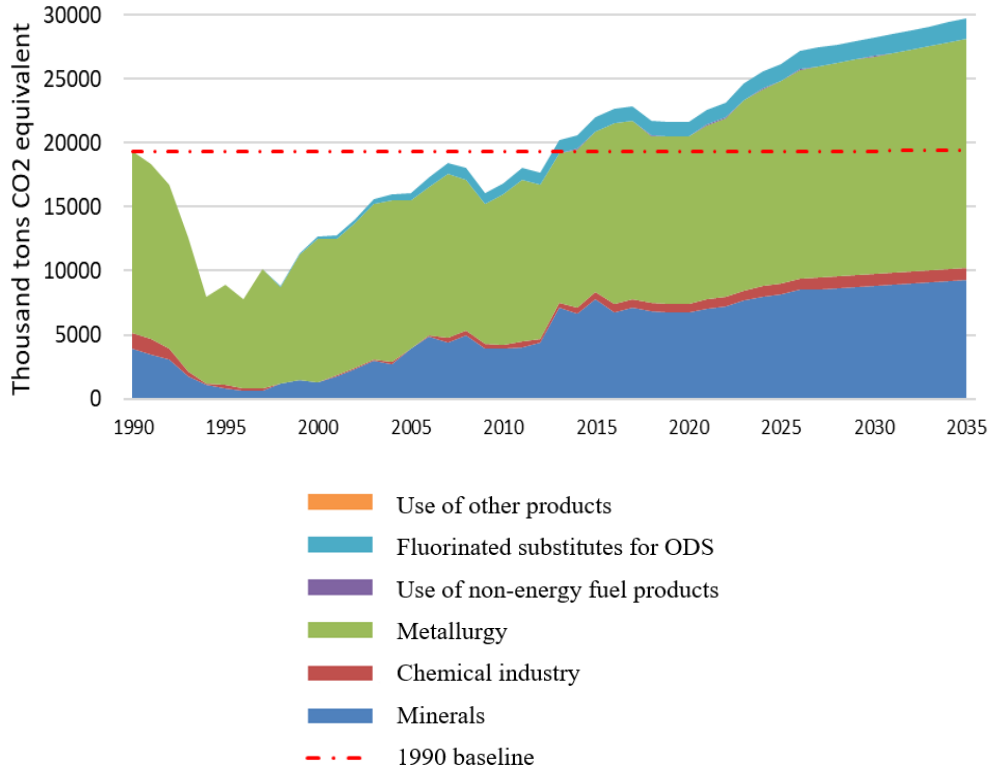


Fig. 3. Forecast of GHG emissions in the IPPU sector up to 2035 with current measures.

Table 4. Increase in emissions in the IPPU category in 2019 relative to the 1990 base year

GHG source and sink categories, (kt) CO2 eq	1990 Base Year	2019	Change from base to latest reported year of NIR, %
Industrial Processes	19405.85	21678.15	11.71
A. Mineral industry	3876.59	6,778.39	74.85
B. Chemical industry	1234.17	674.58	-45.34
C. Metal industry	14292.73	13,064.47	-8.59
D. Non-energy products from fuels and solvent use	2.36	18.83	697.67
F. Product uses as ODS substitutes	NO	1,139.56	100.00
G. Other product manufacture and use	NO, NE	2.32	100.00

The positive growth rate of GHG emissions is associated with the expansion of the construction industry and increased demand for cement (clinker), along with a rise in metallurgy production to the base year level.

The GHG forecasts under the No Measures Scenario (NM) and the Additional Measures Scenario (CAM) are shown in Figure 4. In the forecasted years, the emissions in the Current Measures Scenario (CM) are on the rise. With the implementation of additional measures starting from 2023, there is a possibility to reduce emissions by 10%, but they remain above the base level throughout the entire forecast period. As seen from the graph, under the No Measures Scenario (NM), emission levels exceed those in the CM Scenario by 5%.

The calculations for assessing the impacts of mitigation measures show that the policies and measures adopted by Kazakhstan to reduce GHG emissions partially decrease emissions in this category. In all scenarios, total GHG emissions exceed the 1990 base year level. Therefore, it is necessary to reduce specific emissions in the industrial sector through a transition to newer technologies (as described above). Figure 5 and Table 5 present the projected values of emissions for the industry/industrial processes sector across different scenarios.

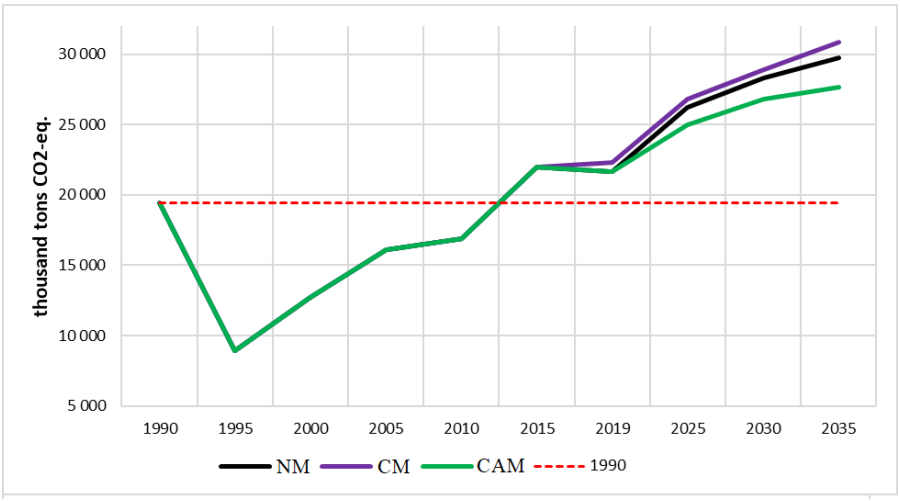
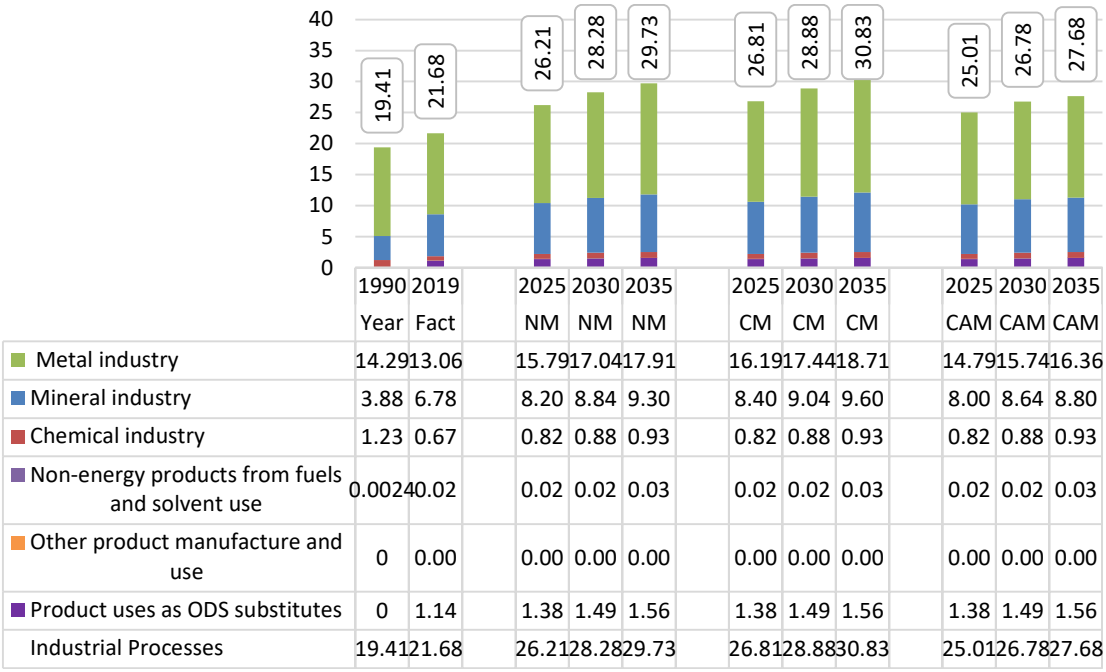


Fig. 4. Comparative graph of scenario analysis: Actual and projected emission levels in the IPPU category for 1990–2035.



	1990 Year	2019 Fact	2025 NM	2030 NM	2035 NM	2025 CM	2030 CM	2035 CM	2025 CAM	2030 CAM	2035 CAM
Metal industry	14.29	13.06	15.79	17.04	17.91	16.19	17.44	18.71	14.79	15.74	16.36
Mineral industry	3.88	6.78	8.20	8.84	9.30	8.40	9.04	9.60	8.00	8.64	8.80
Chemical industry	1.23	0.67	0.82	0.88	0.93	0.82	0.88	0.93	0.82	0.88	0.93
Non-energy products from fuels and solvent use	0.0024	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.03
Other product manufacture and use	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Product uses as ODS substitutes	0	1.14	1.38	1.49	1.56	1.38	1.49	1.56	1.38	1.49	1.56
Industrial Processes	19.41	21.68	26.21	28.28	29.73	26.81	28.88	30.83	25.01	26.78	27.68

Fig. 5. Emissions in the IPPU sector by scenario up to 2035, Mt CO2e.

Table 5. Emissions in the IPPU sector by scenario up to 2035, Mt CO2e

	Year	Fact		NM	NM	NM		CM	CM	CM		CAM	CAM	CAM
	1990	2019		**2025**	**2030**	**2035**		**2025**	**2030**	**2035**		**2025**	**2030**	**2035**
Mineral industry	3.88	6.78		8.20	8.84	9.30		8.40	9.04	9.60		8.00	8.64	8.80
Chemical industry	1.23	0.67		0.82	0.88	0.93		0.82	0.88	0.93		0.82	0.88	0.93
Metal industry	14.29	13.06		15.79	17.04	17.91		16.19	17.44	18.71		14.79	15.74	16.36
Non-energy products from fuels& solvent use	0.0024	0.02		0.02	0.02	0.03		0.02	0.02	0.03		0.02	0.02	0.03
Product uses as ODS substitutes	NO	1.14		1.38	1.49	1.56		1.38	1.49	1.56		1.38	1.49	1.56
Industrial Processes	**19.41**	**21.68**		**26.21**	**28.28**	**29.73**		**26.81**	**28.88**	**30.83**		**25.01**	**26.78**	**27.68**

5. Discussion

To achieve a reduction in greenhouse gas emissions from the energy sector to below 15% of the 1990 level (within the energy sector), additional measures are required. In this work, such measures include reducing the share of coal in electricity generation to 40% by 2030 (and no more than 40% after 2030), commissioning a nuclear power plant with a capacity of 1.5 GW in 2030, and introducing a carbon tax on greenhouse gas emissions from non-capped sectors. The carbon tax rates are set at $2 per ton of CO2 in 2023, with an annual increase of $2 per ton of CO2 from 2024 to 2030 (reaching $16 per ton of CO2 in 2030). From 2031 to 2035, the carbon tax will increase by $2.50 annually and will cover not only CO2 but also methane and nitrous oxide, reaching $29 per ton in 2035.

The majority of steel production in Kazakhstan is carried out using integrated coke-chemical, blast furnace, and converter technology (ArcelorMittal Temirtau LLP, hereafter referred to as AMT). This technology is characterized by significant greenhouse gas emissions (around 2.0 tons of CO_2 equivalent per ton of steel), yet it will continue to remain the primary method of steel production globally in the coming years. According to OECD forecasts, the share of steel produced using this method is expected to decrease from the current 70% to 60% by 2030. Moreover, this production method complies with the European Union's Best Available Techniques Reference Document (BREF EU). Specific GHG emissions in local integrated electric steel production significantly exceed those of similar enterprises worldwide. One of the main reasons for this is the lack of access to natural gas at the ArcelorMittal Temirtau (AMT) metallurgical plant. The production of electricity and heat (for both the plant's own needs and the city of Temirtau) is based on the combustion of coal and fuel oil.

It is assumed that all the increase in steel production in the country by 2030 will be based on the use of electric arc furnace (EAF) technology using scrap metal (a combination of energy efficiency measures, renewable energy sources, and waste recycling). The implementation of this measure requires the development of a national program to encourage the collection and recycling of ferrous scrap, which will meet the production needs for scrap of the required quality.

Choosing technologies for reducing emissions from industrial processes is crucial for Kazakhstan, especially in the production of pig iron and steel. The use of Direct Reduction of Iron (DRI) with natural gas already reduces emissions by 30% compared to blast furnaces and by 42% compared to coal-based DRI. The application of hydrogen for DRI in combination with electric arc furnaces powered by renewable energy could enable carbon-neutral steel production. In aluminum production, effective recycling could reduce the demand for primary aluminum and cut emissions by 27% by 2050. The use of inert anodes in aluminum production can reduce emissions by 15%. In the cement industry, changes in cement composition and the production of carbon-cured concrete could cut emissions by 48%.

6. Conclusion

The scenario analysis of Kazakhstan's energy sector reveals a shift towards cleaner energy sources, with growing investments in renewables and nuclear power, especially under the Current Measures (CM) and Current and Additional Measures (CAM) scenarios. The CAM scenario presents a more ambitious strategy to reduce coal reliance and increase renewable and nuclear energy, but introduces complexities in emission patterns, particularly in heat production. The analysis highlights the need for a balanced approach, targeting a significant GHG emissions reduction below 15% of 1990 levels. Relying solely on renewables is insufficient; additional measures are necessary to meet ambitious emission targets. Integrating these measures with renewable energy expansion is key to achieving a comprehensive reduction in GHG emissions and a lower-carbon future.

In the industrial sector, economic growth, especially in metallurgy and mineral industries, is driving emissions upward. Under the CM scenario, emissions rise through 2035, exceeding the 1990 baseline, with the No Measures (NM) scenario projecting even higher emissions. However, the CAM scenario shows advanced technologies, such as hydrogen-based steel production, could cut emissions by half by 2035. Despite these efforts, emissions remain above the 1990 baseline, underscoring the need for further adoption of low-carbon technologies and modernization of industrial processes. Continued investment in new technologies and stricter policies is essential for Kazakhstan to meet its climate commitments and reduce long-term emissions, particularly in key industrial sectors.

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