

Reduction of the Carbon Footprint of Thermal Power Plants Through the Implementation of Energy-Efficient Technologies

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Abstract: The article addresses the issue of high greenhouse gas emissions in Kazakhstan, where the energy sector - primarily based on coal-fired thermal power plants - accounts for up to 80% of total emissions. Data are presented on CO₂ emission dynamics, along with the methodology for their calculation in accordance with international standards such as the GHG Protocol and ISO 14064 (Scope 1–3 categories). Special attention is given to the assessment of the carbon footprint of thermal power plants and the necessity of reducing emissions in order to meet the nationally determined contributions under the Paris Agreement. The paper highlights the worn-out condition of most power plant equipment and the resulting increase in carbon load. Modernization pathways are discussed, including improvements in thermal efficiency, the implementation of cogeneration and waste heat recovery systems, process digitalization, and the transition to cleaner types of fuel. The conclusion emphasizes that reducing the carbon footprint of thermal power plants is a key prerequisite for the sustainable development of Kazakhstan's energy sector and requires comprehensive measures, including international investment, the deployment of renewable energy technologies, and the training of qualified personnel for the new energy industry.

1 INTRODUCTION

The global transition toward low-carbon development presents Kazakhstan with both a challenge and an opportunity to modernize its industrial and energy systems. Decarbonization today is not only a response to environmental imperatives but also a strategic pathway for technological renewal, competitiveness, and economic diversification. In this context, studying advanced international practices - such as carbon capture, utilization and storage (CCUS), hydrogen energy, and clean industrial technologies - provides valuable guidance for shaping Kazakhstan's sustainable energy trajectory.

Thermal power plants remain the backbone of Kazakhstan's power system and, simultaneously, the primary source of anthropogenic carbon dioxide emissions. The country's historical reliance on abundant coal reserves ensured energy independence but created a generation structure with high carbon

intensity. Coal-based plants, often equipped with outdated technologies and low efficiency, produce the majority of national emissions. Reducing their carbon footprint is therefore critical for achieving the country's long-term climate goals and ensuring energy security.

Under the Paris Agreement, Kazakhstan has pledged to cut its greenhouse gas emissions by 15% by 2030 (unconditionally) and by up to 25% with international support. Fulfilling these commitments requires systematic modernization of the thermal power sector through the introduction of energy-efficient technologies, the integration of renewable sources, and the implementation of digital management systems. These steps can significantly reduce specific emissions even within the existing fuel structure.

The national energy transition must balance ecological and economic priorities. On one hand, stable electricity generation is essential for industrial growth and social well-being; on the other, the

sector's transformation is indispensable for meeting global sustainability standards. Modernization efforts should therefore combine technical upgrading - improving turbine and boiler efficiency, deploying waste-heat recovery, and introducing cogeneration schemes - with organizational and regulatory measures that stimulate investment in cleaner production.

The objective of this research is to assess the carbon footprint of Kazakhstan's thermal power plants, identify the principal factors influencing its scale, and propose effective technological solutions that ensure emission reduction without compromising the reliability of energy supply. The study employs internationally recognized methodologies for greenhouse gas accounting (GHG Protocol and ISO 14064) and draws on national statistical and regulatory data. Its findings are intended to support evidence-based policy decisions for the modernization of Kazakhstan's power sector and contribute to the country's progress toward a low-carbon economy [1].

2 MATERIALS AND METHODS

As the primary basis for this study, official statistical materials of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan [1], the Ministry of Energy of the Republic of Kazakhstan [2], as well as data from national and international reports on climate and energy [4]–[6], were used. The analysis employed methodological approaches regulated by international greenhouse gas accounting standards: the GHG Protocol (developed by WRI and WBCSD) and ISO 14064 [7].

3 RESULTS AND DISCUSSIONS

Kazakhstan, despite its relatively small population, is among the countries with the highest levels of greenhouse gas emissions per capita. In 2024, total emissions amounted to about 380 million tons of CO₂-equivalent, making Kazakhstan the largest emitter of greenhouse gases in Central Asia. The main contributors to emissions are the energy sector (around 80% of all emissions), industry, and transport [1]. A particularly significant share comes from thermal power plants that operate primarily on coal with high ash content and low calorific value. According to the Ministry of Energy of the Republic of Kazakhstan [2], electricity production in the

country is carried out by 158 power plants, with 70% of total generation coming from coal-fired TPPs. The fuel balance is largely based on lignite and hard coal mined in the Karaganda and Pavlodar regions. Such dependence on carbon-intensive fuels predetermines the high level of greenhouse gas emissions, especially carbon dioxide (CO₂). According to the results of research conducted by scientists from Uzbekistan, the optimized design of a trench-type solar greenhouse makes it possible to reduce the specific heating load by 50% compared to the original design and decrease CO₂ emissions by 75% [3]. Excessive greenhouse gas emissions intensify the natural greenhouse effect, leading to global warming - a gradual increase in the Earth's average surface temperature.

The consequences of global climate change in Kazakhstan are becoming increasingly tangible. In recent decades, the country has experienced an increase in the average annual air temperature by 0.3–0.4 °C per decade [4], which is nearly twice the global rate; longer drought periods; reduced snow cover and glacier melting in mountainous regions; and a rise in extreme weather events, including droughts, dust storms, and sudden floods.

According to the National Climate Report [5] (prepared by the Ministry of Ecology of the Republic of Kazakhstan and Kazhydromet), if the current level of emissions is maintained, by the middle of the 21st century Kazakhstan may face a reduction of water resources by up to 30% in the southern regions; degradation of pastures and agricultural land; a decline in the yields of major crops; and an increase in the frequency of power supply disruptions due to rising summer temperatures and growing loads on energy networks. Thus, the impact of greenhouse gas emissions is not limited to the environmental dimension - it directly affects the country's economic resilience, as well as its food and energy security. Under these conditions, reducing emissions, particularly in the energy sector, becomes not only an international obligation but also an internal necessity.

Kazakhstan, as a full participant in the global climate process, signed and ratified the Paris Agreement in 2016 [6], thereby confirming its readiness to contribute to limiting global warming. In accordance with the provisions of the agreement, each country develops and submits so-called nationally determined contributions (NDCs) - voluntarily declared targets for reducing greenhouse gas emissions. In its updated NDC, Kazakhstan has committed to: reducing net greenhouse gas emissions by 15% by 2030 compared to 1990 levels (unconditional target); and up to 25% subject to external support (conditional target). These

commitments cover all sectors of the economy, including energy, industry, transport, agriculture, and waste.

The main source of emissions in Kazakhstan is the energy sector ($\approx 79.9\%$ of total GHG). Overall CO₂ emissions show three key phases: 1990–1999 - a sharp decline of almost 50% due to the collapse of the USSR and industrial downturn (minimum ~ 116 Mt CO₂ in 1999). 2000–2013 - economic recovery and rising emissions, peaking in 2013 (~ 263 Mt CO₂). 2014–2019 - stabilization and a slight decrease at a high level (~ 200 – 250 Mt CO₂). 2020–2023 - a temporary drop in 2020 (COVID-19), followed by gradual recovery by 2023. 2024 - official data have not yet been published; according to global estimates, the trend is upward again.

Kazakhstan’s total gross greenhouse gas emissions average 348.844 million tons of CO₂-eq per year [1]. The dynamics of carbon dioxide emissions in Kazakhstan for 1990–2024, thousand tons of CO₂, are shown in Figure 1.

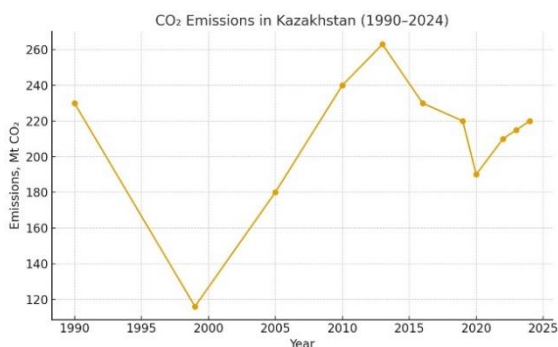


Figure 1: Dynamics of carbon dioxide emissions in Kazakhstan, 1990–2024, thousand tons of CO₂.

The carbon footprint of thermal power plants (TPPs) represents the total volume of greenhouse gas emissions, expressed in CO₂-equivalent, generated in the process of electricity production. In the context of growing attention to sustainable development and climate responsibility, this indicator has become a key criterion for assessing the environmental efficiency of energy facilities.

At present, various standards for greenhouse gas accounting have been developed, but the fundamental ones are the GHG Protocol and the ISO 14064 standard [7]. The GHG Protocol was developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). It provides guidance on how to properly structure emission sources and clarify what is included or excluded in the assessment. The protocol

recognizes a methodology for calculating emissions across three categories:

- Scope 1 – direct emissions under the direct control of an organization. These typically include process emissions, stationary fuel combustion, mobile fuel combustion, fugitive emissions, etc.;
- Scope 2 – indirect energy emissions (purchased electricity, heat, steam);
- Scope 3 – other indirect emissions that result from an organization’s activities but occur from sources owned or controlled by other entities [8].

Greenhouse gas emissions under Scope 1 can be determined either by calculation or by instrumental measurement, although the calculation method is most commonly used. In this case, actual organizational data on fuel consumption are combined with greenhouse gas emission factors for different fuels and processes.

A general formula for the calculation is:

$$\text{CO}_2\text{-eq emissions (kg)} = \text{Consumption} \times \text{Emission factor}$$

Each type of activity has its own emission factor (EF), which indicates how much CO₂-equivalent is released when using 1 unit of a resource.

Let us give an example of a Scope 1 emissions calculation for a coal-fired combined heat and power plant (CHP). For instance, the annual consumption of hard coal is 100,000 tons; the lower heating value is 25 MJ/kg; the carbon content of the fuel is 60%; and the carbon oxidation factor is 0.98 (i.e., 98% of the carbon is oxidized to CO₂).

Step 1. Determining the mass of carbon in the fuel:

$$M_C = M_{fuel} \cdot C_{content} \quad (1)$$

Step 2. Considering the carbon oxidation factor:

$$M_{C,ox} = M_C \cdot O_{factor} \quad (2)$$

Step 3. Conversion to CO₂ (each 1 kg of C gives CO₂):

$$M_{CO_2} = M_{C,ox} \cdot \frac{44}{12} \quad (3)$$

The presented calculation example shows that, with known values of fuel consumption, carbon content, and the carbon oxidation factor, it is possible to accurately determine the mass of CO₂ emitted [9].

The methodology is based on simple stoichiometric relationships and is the standard for accounting direct Scope 1 emissions in the energy sector. It makes it possible to: link the

physicochemical characteristics of fuel with actual emissions; take into account incomplete combustion of carbon through the oxidation factor; provide a reliable basis for reporting under international standards (GHG Protocol, ISO 14064) [10].

Thus, even a simplified calculation clearly demonstrates how strongly coal-based power generation influences the carbon footprint of the energy sector and why this sector is the key source of emissions in Kazakhstan. For example, a CHP plant burning 100,000 tons of hard coal annually emits approximately 215,764 tons of CO₂ per year under Scope 1 [9]-[13].

Reducing the carbon footprint of thermal power plants is a key priority in Kazakhstan's energy decarbonization strategy. The introduction of energy-efficient technologies, the digitalization of generation management, the transition to cleaner fuels, and equipment modernization make it possible to achieve a sustainable balance between the country's energy needs and environmental protection goals [14].

For effective CO₂ reduction in Kazakhstan, it is necessary to consider the technical condition of thermal power plants (TPPs), evaluate modernization potential, analyze the experience of other countries in the region, and stimulate private sector involvement. The average age of TPPs in Kazakhstan is 61 years, with about 76% of them operating for more than 50 years. The average wear of equipment reaches 66%, and in some cities such as Oral, Stepnogorsk, Taraz, Kyzylorda, and Kentau, this figure exceeds 80% [9].

The transition to low-carbon energy is impossible without comprehensive modernization of thermal power plants, especially given their dominant role in Kazakhstan's power system. The implementation of energy-efficient technologies at existing TPPs makes it possible to significantly reduce specific greenhouse gas emissions without a fundamental change in the fuel base, which is particularly relevant in conditions of high dependence on coal [15].

Several key areas of energy-efficient modernization of TPPs in Kazakhstan can be highlighted:

- 1) Improving the thermal efficiency of power equipment. Most Kazakhstani TPPs were built during the Soviet period, and today their efficiency often does not exceed 30–35%. An increase in efficiency by even 2–3% can lead to a significant reduction in specific CO₂ emissions. This can be achieved by: replacing or modernizing turbines and boilers; optimizing the operation of regenerative heaters; improving thermal insulation of pipelines and elements of

thermal circuits; and applying intelligent control systems for operating modes [16].

- 2) Implementation of low-grade heat recovery systems. Waste heat recovery from flue gases, the use of waste heat boilers, and the introduction of cogeneration schemes (combined production of heat and electricity) improve the energy efficiency of units.
- 3) Replacement and automation of auxiliary equipment.** The introduction of variable-frequency drives for pumps, draft fans, and blowers reduces auxiliary electricity consumption, which at old TPPs can reach 8–10% of generation. Transitioning to high-efficiency pumping units and ventilation control systems saves fuel and reduces emissions [17].
- 4) Intelligent control and monitoring systems. Modern digital solutions, such as automatic combustion control (ACC) systems, allow real-time optimization of the fuel combustion process, reducing overconsumption and emissions.
- 5) Conversion of boiler units to cleaner fuels. Switching from coal to natural gas in regions with available infrastructure makes it possible to cut the specific carbon footprint nearly in half [18].

4 CONCLUSIONS

Kazakhstan remains one of the largest greenhouse gas emitters in Central Asia despite its relatively small population, due to the country's high dependence on coal-fired thermal power plants. This structure of the fuel balance not only results in a significant carbon footprint but also exacerbates climate risks, including rising temperatures, reduced water resources, and land degradation [18].

Fulfilling the commitments under the Paris Agreement requires comprehensive measures, with the modernization of thermal power plants (TPPs) playing a central role. Increasing the thermal efficiency of equipment, implementing cogeneration and heat recovery systems, digitalizing combustion processes, switching to natural gas, and adopting energy-efficient equipment can significantly reduce specific CO₂ emissions even without a complete phase-out of coal.

However, the long-term sustainability of the energy sector is possible only through a gradual transition to renewable energy sources and the attraction of international investments and technologies. An important condition for the

successful implementation of the energy transition is the consideration of social impacts and the training of personnel for the emerging low-carbon economy.

Thus, the modernization of thermal power plants is not only an environmental but also a strategic economic necessity, ensuring Kazakhstan's energy and climate security.

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