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ASSESSMENT OF THE IMPACT OF ENERGY EFFICIENCY IMPROVEMENTS IN THERMAL POWER PLANTS OF UZBEKISTAN ON ELECTRICITY GENERATION AND CO_2 EMISSIONS

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Abstract: This article analyzes the impact of improving energy efficiency in thermal power plants of Uzbekistan on electricity generation volume and carbon dioxide (CO_2) emissions. The study investigates the technical and economic performance indicators of thermal power plants, which constitute the main generation capacity within the country's power system. The relationship between thermal efficiency, fuel consumption, and electricity generation was evaluated using mathematical methods. The findings demonstrate that increasing energy efficiency reduces natural gas consumption and, consequently, decreases CO_2 emissions. Furthermore, the effects of modern combined-cycle gas turbine (CCGT) units, high-efficiency turbines, and digital control technologies on energy efficiency were assessed. The results indicate that modernizing thermal power plants in Uzbekistan plays a crucial role in strengthening energy security, ensuring the rational use of fuel resources, and reducing atmospheric greenhouse gas emissions.

Keywords: Thermal power plant, electric power engineering, energy efficiency, efficiency coefficient, combined-cycle gas turbine, natural gas consumption, electricity generation, carbon dioxide emissions, modernization.

Introduction

In the Republic of Uzbekistan, several state programs are being implemented to modernize the electric power sector and accelerate "green transformation" processes. Specifically, during 2025–2027, a total of 23 low-efficiency units with a combined capacity of 3,257 MW are planned to be decommissioned and mothballed in stages. These measures aim to cut fuel consumption, increase production efficiency, and reduce greenhouse gas emissions. In particular, modernizing existing power units and implementing combined-cycle gas turbine (CCGT) units represent key directions for enhancing electricity generation efficiency [5, 7].

Talimarjan Thermal Power Plant is one of Uzbekistan's largest power producers, operating both traditional steam turbine units and modern CCGT units side by side. This setup provides an opportunity to evaluate the actual operational relationships between energy efficiency, electricity generation volume, and CO_2 emissions. Moreover, modernization efforts carried out between 2021 and 2025 establish a scientific basis for comparing changes in technical and energy indicators.

The primary objective of this study is to evaluate the impact of improving energy efficiency on electricity generation and CO_2 emissions using Talimarjan TPP as a case study, mathematically model the correlations between efficiency, fuel consumption, and emission rates, and quantitatively determine the technical and environmental gains achieved through modernization.

The research utilized technical data from Talimarjan TPP (2021–2025), official corporate reports, and international methodology documents using mathematical modeling, energy balance analysis, and comparative-statistical methods. The calculations allow for a quantitative evaluation showing that increasing energy efficiency enhances generation performance while reducing natural gas consumption and CO_2 emissions.

Literature Review

Global research extensively covers energy efficiency improvements, fuel consumption reduction, and generation efficiency enhancement in thermal power plants. According to International Energy Agency data, combined-cycle power units feature significantly higher efficiencies compared to traditional steam-turbine units, reaching up to 55–62% in modern facilities. Higher thermal efficiency directly reduces the fuel required per unit of electricity generated, leading to lower carbon dioxide (CO_2) emissions [1].

Reports from the International Renewable Energy Agency and the Intergovernmental Panel on Climate Change highlight energy efficiency improvements in electric utilities as one of the most cost-effective strategies for greenhouse gas mitigation. These reports emphasize a direct functional dependency between thermal efficiency gains, specific fuel consumption, and CO_2 emissions. Thus, energy efficiency not only lowers power production costs but also noticeably boosts environmental performance [3].

In recent years, Uzbekistan has systematically pursued state policies to modernize its thermal power plants. State programs prioritize replacing outdated equipment with modern CCGT units to boost efficiency and lower carbon emissions, focusing primarily on technological solutions, technical characteristics, and fuel economy [4].

Research Methodology

The research object comprises the technical and energy performance metrics of Talimarjan TPP during 2021–2025. Parameters analyzed include electricity generation volume, installed capacity, efficiency coefficient (η), specific natural gas consumption (b_g), and carbon dioxide (CO_2) emissions. Initial data were gathered from the Ministry of Energy, JSC "Thermal Power Plants," and open technical reports. Missing indicators were determined using mathematical modeling and engineering calculations [6].

The research was conducted in three stages:

Stage 1. Energy Performance Assessment

Thermal efficiency was evaluated via the efficiency coefficient (η) and specific standard fuel consumption (b_{sh}). Utilizing the heat equivalent of electricity (860 kcal/kWh) and the lower heating value of standard fuel (7000 kcal/kg), the following international thermal engineering equation was applied:

$$\eta = \frac{123}{b_{sh}} \times 100\% \quad (1)$$

Where:

- η — Efficiency coefficient (%);
- b_{sh} — Specific standard fuel consumption per 1 kWh of electricity (*g*/kWh);
- 123 — Energy conversion constant coefficient.

Formula (1) serves as the primary metric for determining thermal power plant efficiency based on the First Law of Thermodynamics and energy conservation principles, describing the conversion rate of thermal fuel energy into electricity.

Stage 2. Fuel Consumption Assessment

To calculate natural gas consumption required for power generation, the following energy balance relationships were used:

$$b_g = \frac{b_{sh}}{1.15 \times 1000} \quad \text{and} \quad FC = b_g \times E \times 10^{-9} \quad (2)$$

Where:

- b_g — Specific natural gas consumption (m^3/kWh);
- FC — Total annual natural gas consumption (billion m^3/year);
- E — Annual electricity generation (billion kWh/year);
- 1.15 — Equivalent factor for converting Uzbekistan natural gas to standard fuel.

This model reflects the functional relationship between output electricity, efficiency coefficient, and natural gas usage. Under constant generation levels, increasing thermal efficiency directly decreases overall fuel consumption.

Stage 3. CO_2 Emission Assessment

To compute carbon dioxide emissions, emission factor methods and national reporting parameters were combined:

$$M_{CO_2} = E \times EF_{CO_2} \times b_g \times 10^{-9} \quad (3)$$

Where:

- M_{CO_2} — Total carbon dioxide emitted (million tons CO_2/year);
- E — Annual electricity generation (billion kWh/year);
- b_g — Specific natural gas consumption (m^3/kWh);
- EF_{CO_2} — Carbon dioxide emission factor for natural gas (kg CO_2/m^3) [15].

Based on local natural gas chemical compositions and station technical reports, EF_{CO_2} was set at 1.90 kg CO_2/m^3, allowing accurate predictions of emitted CO_2 relative to fuel usage [11].

Results and Discussion

Calculations confirmed that improving energy efficiency at Talimarjan TPP significantly affects electricity output, natural gas usage, and carbon emissions. Based on 2021–2025 operational metrics and mathematical calculations, the relationships between thermal efficiency, fuel consumption, and CO_2 emissions were evaluated. Modernization efforts, including the addition of modern CCGT units totaling 1065 MW capacity, directly contribute to efficiency gains [9].

Table 1. Main Technical Indicators of Talimarjan TPP (2021–2025)

Year	Installed Capacity (MW)	Electricity Generation (Billion kWh)	Modernization Status
2021	1700	10.84	Existing units operating
2022	1700	9.60	Existing units operating
2023	1700	7.50	Construction of 1065 MW CCGT began
2024	1700	7.90	Construction continued
2025	1700	8.20	Final stage

- **2021–2022:** Electricity output declined from 10.84 to 9.60 billion kWh. This was caused by long-term planned overhaul on Unit 1 (800 MW) and load reallocations following new PPP power plants joining the grid.
- **2023:** Output reached its lowest level (7.50 billion kWh), though achieving 108.7% of its target forecast. This temporary drop was due to starting the construction of a major $771.8 million project (CCGT-3 and CCGT-4, 1065 MW combined) and technical integration of existing units [10].
- **2024–2025:** Generation recovered to 7.90 and 8.20 billion kWh. Growth was driven by energy-saving technologies implemented on active units and testing/commissioning phases conducted in partnership with Mitsubishi Corporation (Japan) and Intecsa Ingeniería Industrial (Spain) [12].

Table 2. Efficiency Dynamics at Talimarjan TPP (2021–2025)

Year	Specific Standard Fuel Consumption (bsh, g/kWh)	Specific Natural Gas Consumption (bg, m3/kWh)	Calculated Thermal Efficiency (η, %)	CO2 Emission Factor (EFCO2, kg/m3)	Total Calculated CO2 Emissions (MCO2, Million Tons)
2021	270.0	0.235	45.7	1.90	4.84
2022	266.5	0.232	46.3	1.90	4.23
2023	262.0	0.228	47.1	1.90	3.25
2024	258.5	0.225	47.7	1.90	3.38
2025	252.6	0.220	48.8	1.90	3.43

Calculations in Table 2 demonstrate that due to higher operational shares of high-efficiency CCGT-1 and CCGT-2 technologies, average plant thermal efficiency is projected to grow from 45.7% in 2021 to 48.8% by 2025. Consequently, specific natural gas consumption per kWh drops from 0.235 m^3 down to 0.220 m^3. This aligns with national decarbonization strategies by lowering carbon intensity per unit of electricity through fuel savings [2].

Graph 1. Dynamics of Generation (E), Thermal Efficiency (η), and Carbon Emissions (M_{CO_2}) at Talimarjan TPP (2021–2025)

The system of equations in the methodology aligns fully with parameters across all tables. Results derived from equations (1), (2), and (3) directly correspond to Table 2 data. Modernization projects at Talimarjan TPP—including commissioning 1065 MW of new CCGT capacity—prove to be essential in boosting overall plant efficiency, saving fuel, and reducing carbon emissions [13].

Conclusion

This study evaluated the impact of energy efficiency improvements in Uzbekistan's thermal power plants on power output and CO_2 emissions through mathematical modeling and energy balance analysis. Focusing on Talimarjan TPP (2021–2025), results show modernization increased plant efficiency from 45.7% in 2021 to 48.8% in 2025. Concurrently, specific natural gas

consumption decreased from 235 g/kWh (0.235 m^3/kWh) to 220 g/kWh (0.220 m^3/kWh), ensuring cleaner, more efficient resource utilization.

The mathematical models confirmed an inverse relationship between thermal efficiency gains and greenhouse gas emissions: every percentage increase in efficiency leads to measurable reductions in natural gas consumption and CO_2 emissions. The energy balance and emission calculation models applied here can be used for predicting economic and environmental performance during future thermal power plant modernizations.

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