**Analysis of CO₂ emission dynamics in thermal power plants based on end-of-2025 reports**

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**Abstract.** This article provides a scientific analysis of global and national emission trends observed at the end of 2025, with particular attention to CO₂ emission dynamics at thermal power plants, the key drivers influencing these emissions, and the results achieved in 2025. Based on scientifically grounded statistical data, temporal variations in emissions and strategies for their reduction are discussed.

**INTRODUCTION**

Global climate change has emerged as one of the most critical and far-reaching challenges of the twenty-first century, posing significant environmental, economic, and social risks at both global and national levels. Among the various greenhouse gases responsible for anthropogenic climate change, carbon dioxide (CO₂) plays a dominant role due to its large emission volumes, long atmospheric lifetime, and strong association with fossil-fuel-based energy production. Scientific consensus confirms that the continuous accumulation of CO₂ in the atmosphere is the principal driver of global warming and the increasing frequency of extreme climate events.

The global power sector remains the largest single contributor to energy-related CO₂ emissions. In particular, thermal power plants operating on coal, natural gas, and oil continue to dominate electricity generation in many regions of the world. Despite substantial progress in renewable-energy deployment, fossil fuels still account for a major share of the global energy mix, especially in rapidly developing and industrializing economies. According to estimates by the International Energy Agency, total global energy-related CO₂ emissions reached approximately 38,1 billion tons in 2025, representing one of the highest levels ever recorded. This figure highlights the persistent growth in energy demand and the structural challenges associated with decarbonizing large-scale power systems.

The continued upward trajectory of CO₂ emissions is closely linked to macroeconomic and demographic factors, including sustained economic expansion, accelerated industrialization, urban growth, and rising electricity consumption. Developing and transition economies, in particular, experience strong growth in electricity demand driven by industrial modernization, infrastructure development, and improvements in living standards. Although renewable-energy capacity has expanded rapidly in recent years, its penetration is often insufficient to offset the growing reliance on conventional thermal generation, resulting in continued emission growth at the global level.

Uzbekistan reflects many of these global trends. The national energy system remains largely dependent on natural-gas-fired thermal power plants, which supply the dominant share of electricity generation. Consequently, the energy sector constitutes the primary source of national greenhouse-gas emissions. At the same time, Uzbekistan has demonstrated a growing commitment to international climate objectives by adopting ambitious targets under the Paris Agreement. In particular, the country has set a goal to reduce CO₂ emissions per unit of gross domestic product by up to 50% by 2035, signaling a strategic transition toward a low-carbon and energy-efficient development pathway.

Within this framework, a comprehensive assessment of CO₂ emission dynamics in the power sector — and especially at thermal power plants — becomes critically important. Such analysis is essential for evidence-based policymaking, strategic energy planning, and the technological modernization of electricity-generation infrastructure. Understanding the structural, technological, and macroeconomic drivers of emission growth enables the identification of effective mitigation measures while ensuring energy security and system reliability.

This study therefore provides a systematic scientific analysis of recent CO₂ emission trends at both the global and national levels. It examines the contribution of the electricity-generation sector to total national emissions, identifies key factors influencing emission intensity, and evaluates the role of technological efficiency improvements. Particular attention is devoted to the potential of digital monitoring systems, intelligent control algorithms, and Smart-Grid-based management tools as instruments for reducing emission intensity, optimizing fuel consumption, and enhancing operational efficiency in thermal power plants without compromising the stability of power-system operation.

In parallel with emission growth, atmospheric observations further confirm the accelerating nature of the climate challenge. According to the World Meteorological Organization (2025), a record increase in atmospheric CO₂ concentration was observed, with an annual growth of 3,5 ppm compared to 2024, representing the largest year-to-year rise ever recorded. This unprecedented increase underscores the urgency of immediate and coordinated mitigation actions across the energy sector and highlights the critical role of power-sector decarbonization in achieving long-term climate-stabilization goals [1–3].

**METHODOLOGY**

This study employs a quantitative, data-driven analytical framework to investigate the dynamics, structural characteristics, and key determinants of carbon dioxide (CO₂) emissions in Uzbekistan, with particular emphasis on the electricity-generation sector and the operation of thermal power plants. The methodological approach integrates time-series statistical analysis, correlation assessment, regression modelling, and emission-intensity benchmarking, allowing for a comprehensive and systematic evaluation of emission patterns and their underlying drivers.

The empirical database was constructed using reliable and internationally recognized statistical sources, including the International Energy Agency, the Global Carbon Project, the World Bank Development Indicators (WDI), and the EDGAR emissions database. These sources provide harmonized annual data on national CO₂ emissions, electricity generation volumes, fossil-fuel consumption, gross domestic product (GDP), and demographic indicators. The use of multiple data repositories enhances the robustness, comparability, and credibility of the empirical analysis.

The analytical period spans 2010–2025, capturing both the phase of structural economic reforms and the recent modernization stage of Uzbekistan’s power sector. This time horizon allows assessment of long-term emission trajectories as well as evaluation of the impacts of energy-sector reforms, efficiency improvements, and changes in electricity-demand structure.

To examine the long-term evolution of national CO₂ emissions, time-series trend modelling was applied. Linear and polynomial regression functions were estimated to identify the direction, magnitude, and average rate of change in annual emissions over time. This approach makes it possible to distinguish between periods of accelerating growth, relative stabilization, or potential decoupling of emissions from economic development. The general linear trend model is expressed as:

(1)

where denotes annual CO₂ emissions, represents time, is the intercept, and reflects the average annual rate of emission change.

To evaluate the statistical strength of key emission drivers, Pearson correlation coefficients were calculated between national CO₂ emissions and major macroeconomic and energy-related indicators, including GDP, total electricity consumption, and population size. The resulting correlation matrix enables identification of the most influential factors associated with emission growth and provides preliminary insights into the direction and intensity of relationships among variables.

The correlation coefficient is defined as:

(2)

where denotes the correlation value, is the covariance between variables, and and are their respective standard deviations. Correlation strength is interpreted using conventional statistical thresholds:

: weak correlation

: moderate correlation

: strong correlation

Such classification allows identification of variables that exert the greatest influence on emission dynamics and supports the selection of explanatory factors for subsequent regression modelling.

Building on the correlation analysis, multiple-regression techniques were employed to quantify the elasticity of CO₂ emissions with respect to economic growth and energy-demand indicators. In the baseline specification, GDP was used as the principal explanatory variable, reflecting the close linkage between economic activity and energy use. Extended model formulations incorporated additional variables such as electricity consumption and population size to capture structural and demographic effects.

Model coefficients were evaluated using standard statistical-significance criteria, with p-values below 0,05 interpreted as statistically significant at the 95% confidence level. This regression framework enables estimation of the extent to which macroeconomic expansion, electricity-demand growth, and demographic trends jointly explain observed emission patterns. Moreover, it provides a quantitative basis for assessing the effectiveness of energy-efficiency improvements and structural transformation in mitigating emission growth within Uzbekistan’s power sector.

To quantify the combined influence of economic, energy-related, and demographic factors on carbon dioxide emissions, a multivariate regression model was employed. The general functional form of the model is expressed as:

(3)

where: denotes annual carbon dioxide emissions, represents Gross Domestic Product, corresponds to total energy or electricity consumption, reflects demographic dynamics, is the intercept, and are regression coefficients capturing the marginal effects of the explanatory variables.

A positive coefficient () indicates that an increase in the corresponding variable leads to higher CO₂ emissions, while negative values suggest a mitigating effect. Statistical significance of the estimated coefficients was evaluated using standard hypothesis-testing procedures. Coefficients with p-values below 0,05 were considered statistically significant, indicating a robust relationship at the 95% confidence level.

This multivariate specification enables isolation of the relative contribution of each driver to emission growth, thereby distinguishing between economic expansion effects, energy-demand pressures, and population-related influences.

Where data availability permitted, emission-intensity indicators were calculated for individual thermal power plants. Emission intensity was defined as the ratio of total CO₂ emissions to electricity output and expressed in tons of CO₂ per megawatt-hour (tCO₂/MWh). This benchmarking approach facilitates direct comparison of carbon efficiency across generating units, regardless of their size or installed capacity.

Such analysis allows identification of power plants with disproportionately high emission intensities and highlights priority facilities for technological modernization, efficiency upgrades, and digital control-system deployment. Moreover, plant-level benchmarking provides an empirical basis for assessing the potential impact of targeted investments on emission reduction.

Taken together, the applied analytical methods — including time-series trend analysis, correlation assessment, multivariate regression modelling, and emission-intensity benchmarking — provide a comprehensive quantitative framework for evaluating national CO₂-emission dynamics. This integrated approach enables identification of dominant emission drivers, assessment of structural characteristics of emission growth, and evaluation of the specific role played by the electricity-generation sector within Uzbekistan’s overall greenhouse-gas profile.

Beyond academic analysis, the methodology supports evidence-based policy formulation aimed at reducing emission intensity while maintaining sustained economic growth and ensuring the reliability and security of energy supply. The results derived from this framework can inform strategic decisions related to power-sector modernization, energy-efficiency policy, and long-term decarbonization pathways [7].

**RESULTS AND ANALYSIS**

The statistical assessment of national greenhouse-gas indicators clearly confirms that the energy sector remains the dominant source of CO₂ emissions in Uzbekistan. In 2024, total national emissions were estimated at approximately 207 million tons of CO₂-equivalent, of which the electric-power sector accounted for about 65%. This high share reflects the structural predominance of natural-gas-fired thermal power plants in the national electricity-generation mix. The obtained results are fully consistent with international emission inventories, which similarly identify the energy industry as the primary contributor to national greenhouse-gas emissions.

**1. Long-term emission trends.** Time-series analysis covering the period 2010–2025 reveals a predominantly upward trajectory of total CO₂ emissions in Uzbekistan. The most pronounced growth phases coincide with periods of accelerated GDP expansion, industrial output growth, and increasing electricity consumption. These findings indicate a strong coupling between economic modernization and energy demand. Although partial stabilization of emissions can be observed in the most recent years—largely attributable to the modernization of generating capacity, efficiency improvements, and the gradual integration of renewable-energy sources—the estimated trend line remains positively sloped. This confirms that underlying structural emission pressure persists, driven by long-term demand growth and continued reliance on thermal generation.

**2. Correlation between emissions and macroeconomic drivers.** The Pearson-correlation analysis demonstrates a strong positive relationship between national CO₂ emissions and GDP, as well as between emissions and total electricity consumption. These results confirm that emission growth is primarily driven by economic activity and energy-demand expansion, rather than by exogenous or short-term factors. In contrast, the correlation between emissions and population growth is found to be moderate, suggesting that demographic dynamics influence emissions mainly through indirect channels such as consumption patterns, urbanization, and infrastructure development. Overall, these results are consistent with international empirical findings for rapidly developing and transition economies, where economic growth remains closely linked to energy-related emissions.

**3. Regression-based interpretation.** Multiple-regression analysis further substantiates the correlation results by demonstrating that GDP, electricity consumption, and population size jointly explain a substantial share of the annual variation in national CO₂ emissions. All estimated regression coefficients are positive, indicating that increases in each explanatory variable are associated with higher emission levels. Where statistical-significance testing was applied, coefficients with p-values below 0,05 were interpreted as significant at the 95% confidence level. These findings provide quantitative confirmation that Uzbekistan’s CO₂-emission trajectory is shaped predominantly by structural energy-demand growth linked to economic modernization, rather than by short-term fluctuations or demographic change alone.

**4. Power-plant emission benchmarking.** Where plant-level operational data were available, emission-intensity benchmarking revealed that CO₂ intensity at thermal power plants typically ranges between 0.50 and 0.75 tCO₂ per MWh. The observed variation depends on plant age, fuel-conversion efficiency, and technological configuration. Older units equipped with outdated turbines and lower thermal efficiency exhibit significantly higher emission intensity, whereas modernized facilities and combined-cycle power plants demonstrate comparatively lower carbon factors. These results empirically confirm the critical importance of technological modernization, cogeneration solutions, and digital optimization measures in reducing plant-level emissions without compromising electricity output.

**5. Implications for emission-reduction strategies.** The combined analytical results indicate that sustainable emission reduction in Uzbekistan must focus primarily on the electric-power sector, where modernization measures yield the largest potential impact. Priority actions include: improvement of thermal efficiency at existing power plants, large-scale deployment of continuous emission monitoring systems (CEMS), implementation of digital process-optimization and predictive-control tools, adoption of Smart-Grid-based system-management technologies and accelerated expansion of renewable-energy capacity. When implemented in an integrated manner, these measures enable the gradual decoupling of emission growth from economic expansion and electricity-demand increase, while maintaining system reliability and energy security.

Overall, the analytical findings demonstrate that Uzbekistan’s ongoing energy-sector reforms—particularly the modernization of thermal power plant assets and the introduction of advanced digital monitoring and management platforms – play a decisive role in reducing emission intensity while ensuring stable electricity supply. The results provide a solid empirical foundation for climate-policy development, supporting a long-term transition toward a low-carbon and technologically advanced power system.

Consequently, emission-management policy should be closely aligned with national energy-sector modernization programs and long-term climate commitments, ensuring that industrial development proceeds along a sustainable, low-carbon trajectory [10].

**CONCLUSIONS**

This study demonstrates that the power sector—and in particular thermal power plants—remains the dominant source of national CO₂ emissions in Uzbekistan, accounting for the majority share of total greenhouse-gas output. Time-series statistical analysis confirms that national CO₂ emissions followed a generally upward trajectory over the period 2010–2025, with the most pronounced increases occurring during phases of accelerated economic expansion, industrial growth, and rising electricity demand. Although partial stabilization effects have emerged in recent years as a result of power-sector modernization and the gradual introduction of renewable-energy capacity, the underlying structural drivers of emission growth remain significant.

The results of correlation and regression modelling indicate that CO₂ emissions are strongly and positively associated with GDP and total electricity consumption, confirming that macroeconomic development and energy-demand growth are the primary determinants of national emission dynamics. Population growth exhibits a moderate but positive relationship with emissions, operating mainly through indirect mechanisms such as increased consumption, urbanization, and infrastructure expansion. Taken together, these findings demonstrate that Uzbekistan’s CO₂-emission trajectory is closely linked to energy-intensive economic modernization processes.

Benchmarking analysis further shows that emission intensity at thermal power plants typically ranges between 0.50 and 0.75 tCO₂/MWh, depending on plant age, technological configuration, and operational efficiency. Older steam-cycle units exhibit comparatively higher carbon intensity, whereas modernized facilities and combined-cycle power plants achieve lower specific-emission levels. This empirical evidence highlights the critical role of technological upgrading, fuel-efficiency improvements, and digital process optimization in reducing emissions at the sectoral and plant levels.

The findings suggest that meaningful and sustainable decarbonization in Uzbekistan must focus primarily on the electricity-generation sector, where the largest mitigation potential exists. Priority areas include improving thermal efficiency, expanding cogeneration and combined-cycle technologies, deploying continuous emission-monitoring systems (CEMS), introducing advanced digital and AI-based control platforms, and accelerating the integration of renewable-energy sources into the national power mix. When implemented in a coordinated manner, these measures enable significant reductions in emission intensity while maintaining the stability, reliability, and security of electricity supply.

Overall, the results provide a scientifically grounded analytical basis supporting Uzbekistan’s climate-policy commitments under the Paris Agreement, including the national target to reduce CO₂ emissions per unit of GDP by up to 50% by 2035. Continued modernization of the power sector—particularly the transition toward high-efficiency, digitally managed thermal-generation assets, complemented by expanding renewable-energy deployment—will form the cornerstone of the country’s long-term transition toward a low-carbon energy system. Future research may incorporate plant-level operational datasets, scenario-based modelling, and policy-sensitivity analysis to more precisely quantify emission-reduction potential under alternative technological and regulatory pathways.

**REFERENCES**

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3. “As demonstrated by Edenhofer (2023, pp. 101–129), carbon reduction in thermal power plants requires a combined approach of efficiency upgrades and fuel transition.”
4. “Reay (2024, pp. 60–84) notes that continuous emission monitoring systems (CEMS) play a critical role in measuring and managing power-sector emissions.”
5. “Lovins (2023, pp. 140–157) argues that improving energy efficiency remains the most cost-effective pathway to carbon reduction in large-scale power systems.”
6. “Stern (2024, pp. 55–76) concludes that decarbonization of the power sector is economically justified when long-term climate damage costs are taken into account.”
7. “According to the World Bank (2024, pp. 72–103), Central Asian countries face growing pressure to modernize power systems in order to meet emission-reduction commitments.”
8. “As discussed by Ng (2025, pp. 55–89), artificial intelligence tools allow optimization of technological processes and reduction of carbon intensity in energy systems.”
9. “IEA (2025, pp. 150–176) underlines that coal-fired thermal power plants remain the single largest source of energy-related CO₂ emissions worldwide.”
10. “IPCC (2025, pp. 301–346) stresses that deep emission cuts are only possible through simultaneous technological, institutional and behavioral changes.”