**Digital Transformation of CO₂ Emission Monitoring in Thermal Power Plants: Methodologies, Algorithms and Practical Implications**

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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**

Under the conditions of global climate change, the management of greenhouse gas emissions especially CO₂ remains one of the most pressing challenges. Thermal power plants are considered one of the main sources of CO₂ emissions worldwide. International reports for the end of 2025 indicate that total global emissions have remained at a high level.

In 2024, energy-related CO₂ emissions amounted to 37,8 billion tons, whereas forecasts for 2025 showed emissions reaching one of the highest levels in history. In other words, global CO₂ emissions rose to a record annual level. 38,1 billion tons. This demonstrates that compared to 2024, emission growth remains stable, highlighting the need to further strengthen international climate efforts.

The growth of CO₂ emissions is driven by a combination of economic, technological, demographic, and environmental factors. One of the primary drivers is **economic growth**, which is accompanied by increasing production volumes, the expansion of large industrial enterprises, and the rapid development of the energy sector. As industrial output and electricity generation increase, fossil-fuel consumption rises accordingly, leading to higher carbon emissions. Another significant factor is the **structure of energy supply and fuel consumption**. The continued reliance on fossil fuels such as coal, oil, and natural gas remains a dominant source of CO₂ emissions, while the share of renewable energy sources is still insufficient to offset growing energy demand. This imbalance in the energy mix directly contributes to the persistence of high emission levels. **Transport and logistics** also play a notable role in emission growth. The continuous increase in the number of vehicles, particularly those powered by internal combustion engines, leads to higher fuel consumption and associated emissions, especially in urban areas and major transport corridors. **Population growth and urbanization** further intensify CO₂ emissions. High population density in cities increases demand for electricity, heating, cooling, and transportation services. As urban infrastructure expands, energy consumption rises, resulting in additional emissions from power generation and district heating systems. The **agricultural sector** contributes to greenhouse gas emissions through methane release from livestock and carbon emissions related to soil management practices. Although these emissions are not solely in the form of CO₂, they significantly influence overall greenhouse gas balances and climate impacts. **Deforestation** represents another critical driver of emission growth. The reduction of forested areas leads to a decline in oxygen generation and the loss of natural carbon sinks that would otherwise absorb atmospheric CO₂. As a result, deforestation exacerbates the accumulation of greenhouse gases in the atmosphere. Finally, **industrial production processes** significantly contribute to CO₂ emissions, particularly in energy-intensive sectors such as cement, chemical, and metallurgical industries. In addition, the growing production of electronics and household equipment increases energy demand across manufacturing supply chains, further amplifying carbon emissions.

Production of electronics and household equipment

According to the World Meteorological Organization (2025), record growth in atmospheric CO₂ concentration was also observed. Compared to 2024, the increase amounted to 3.5 ppm — the largest annual rise ever recorded [1,2,3,8].

**TABLE 1.** Approximate CO₂ emissions by region (2024/2025)

|  |  |  |  |
| --- | --- | --- | --- |
| **№** | **Countries** | **CO₂ emissions (billion tons – Gt)** | **Share of global CO2 (%)** |
|  | **World total** | **≈ 38.0 Gt** | **100%** |
| 1 | China | ≈ 12.5 Gt | 33% |
| 2 | United States | ≈ 5.0 Gt | 13% |
| 3 | India | ≈ 3.2 Gt | 8% |
| 4 | European Union (27) | ≈ 2.7 Gt | 7% |
| 5 | Uzbekistan | ≈ 0.207 Gt (207 mln t) | 0.5% |
| 6 | Other countries | ≈ 14.5-15,0 Gt | 39% |

In 2025, within the framework of the Paris Agreement, Uzbekistan adopted its new Third Nationally Determined Contribution (NDC) strategy, which sets a target of reducing CO₂ emissions per unit of nominal GDP by up to 50% by 2035.

In 2024, total greenhouse gas emissions in Uzbekistan were approximately 207 million tons of CO₂-equivalent.

The main contributing sectors are:

|  |  |  |  |
| --- | --- | --- | --- |
| **Sector** | **Emissions**  **(tons CO₂-eq.)** | **Share (%)** | **Notes** |
| Energy (TPPs, heating, etc.) | ~157,320,000 | ~65% | Main CO₂ source |
| Industry & Construction | ~37,260,000 | ~18% | CO₂ and other GHG |
| Agriculture | ~33,120,000 | ~16% | Includes CH₄ and N₂O |
| Waste & Other | ~2,070,000 | ~1% | Small share |

**TABLE 2.** Sectors with the largest atmospheric impact.

Emissions from the electric power sector were recorded at 157.3 million tons of CO₂-equivalent in 2024, confirming the dominant share of the energy industry.

Global emission growth continued in 2025 — especially in the energy and transport sectors — leading to increased emissions from thermal power plants, largely due to [6]:

* rising energy demand
* continued reliance on fossil fuels
* commissioning of new industrial capacity

Uzbekistan’s expansion of renewable energy (over 9 billion kWh of green electricity produced in 2025) and the implementation of emission-reduction strategies are contributing to emission stabilization or reduction.

**METHODOLOGY**

This study examines the dynamics of CO₂ emissions in Uzbekistan with a specific focus on the energy sector, particularly thermal power plants. The methodology is based on quantitative analysis of verified national and international datasets covering the period 2010–2025. Statistical analysis tools are applied to identify emission trends, sectoral contributions, and macroeconomic relationships [7].

Data Sources — The primary datasets were obtained from:

* International Energy Agency (IEA),
* Global Carbon Project,
* World Bank Development Indicators (WDI),
* EDGAR Emissions Database,

These data contain national greenhouse‑gas emissions, GDP indicators, electricity production, and fossil‑fuel consumption.

Time Frame — The analytical period covers the years 2010–2025. This time frame allows evaluation of long‑term changes during the period of economic reform and power‑sector modernization in Uzbekistan [5].

Trend Analysis — Emission dynamics are evaluated using time‑series trend modeling. A linear regression trend is constructed according to

(1)

where Y denotes CO₂ emissions and X denotes the corresponding year. The parameter b expresses the average annual rate of change. Polynomial and logarithmic models are applied for robustness comparison.

**Correlation Analysis** — Pearson correlation coefficients are calculated to assess the statistical strength of relationships between CO₂ emissions and GDP, electricity consumption, and population growth. A correlation matrix is constructed to identify the dominant drivers of emission growth.

(2)

r – value of Correlation,

0-0,3 – weak,

0,3-0,7 – moderate,

0,7-1,0 - strong

Regression Modeling — Elasticities are quantified using simple and multiple linear regression models. In the baseline model, GDP serves as the principal explanatory variable. A multi‑factor model incorporates electricity consumption and population as additional predictors. Model parameters are evaluated using standard significance testing.

Multivariate regression

(3)

GDP — (Gross Domestic Product)

b > 0 → positive effect

p < 0.05 → statistically significant

Monitoring and quantitative assessment of carbon dioxide (CO₂) emissions in thermal power plants represent one of the key components of environmental control in the energy sector. In practical applications, several technical and analytical approaches are commonly used to determine CO₂ emission levels and evaluate their dynamics.

The fuel-based emission calculation method is one of the most widely applied approaches for estimating CO₂ emissions in thermal power plants. In this method, the total amount of carbon dioxide released into the atmosphere is determined on the basis of the quantity of fuel consumed and its specific carbon content. The general relationship can be expressed as

(4)

Here, fuel consumption represents the volume or mass of the fuel used (e.g., cubic meters, kilograms, or tons), while the emission factor denotes the specific CO₂ generation coefficient associated with a given fuel type. For instance, in the case of natural gas, the emission factor typically ranges from 1.9 to 2.1 tCO₂/MWh, depending on the chemical composition of the fuel and the efficiency of the combustion process.

Another important approach is the efficiency-based emission assessment, which considers the inverse relationship between CO₂ emissions and the overall efficiency of the power plant. In this case, the amount of emitted CO₂ is inversely proportional to the thermal and electrical efficiency of the generating unit:

(5)

where denotes the plant efficiency coefficient. An increase in operational efficiency leads to reduced fuel consumption per unit of generated energy and, consequently, to a decrease in CO₂ emissions. This approach highlights the critical role of efficiency improvement measures in achieving emission reductions.

In modern thermal power plants, continuous emission monitoring systems (CEMS) are increasingly employed to ensure real-time measurement and control of gaseous pollutants. These systems provide continuous monitoring of CO₂ concentration, nitrogen oxides (NOₓ), sulfur dioxide (SO₂), oxygen content, flue-gas temperature, and volumetric flow velocity. The measured data are automatically transmitted to supervisory control and data acquisition (SCADA) or distributed control systems (DCS), where they are processed, visualized, archived, and used for operational decision-making and regulatory reporting.

The algorithmic calculation procedure for determining CO₂ emissions typically follows a structured sequence of steps. Initially, fuel consumption is measured, followed by the determination of fuel composition and its lower heating value. Based on these parameters, the released thermal energy is calculated, after which the corresponding CO₂ emission factor is applied. The results are then normalized to standard indicators such as tCO₂/MWh, and comprehensive analytical reports and summaries are prepared for operational analysis and compliance purposes.

The introduction of advanced digital platforms significantly enhances the accuracy, transparency, and operational efficiency of CO₂-emission monitoring in thermal power plants. Digitalization minimizes the influence of human factors, enables real-time data acquisition, and supports data-driven environmental management. As a result, emission control becomes more reliable and responsive to changing operating conditions.

From a systems perspective, a conceptual digital monitoring architecture for CO₂ emissions typically comprises distributed emission sensors and CEMS analyzers, data acquisition and transmission units, a centralized analytical software platform, forecasting and optimization modules, KPI-monitoring dashboards, and automated reporting and compliance tools. All these modules operate within an integrated environment, ensuring continuous and reliable data flow from measurement points to decision-support systems.

A key advantage of such systems is the capability for real-time data analytics. Operational data are collected continuously with high temporal resolution, often at intervals of up to one second. Visualization dashboards present real-time emission trends, key operational parameters, and alarm notifications. Early detection of anomalies—such as sudden load changes, incomplete fuel combustion, or instrumentation faults—enables preventive and corrective actions to be implemented before emission limits are exceeded.

In addition, AI-based predictive modeling can be integrated into digital monitoring platforms to forecast CO₂ emissions as a function of key operating variables:

Such predictive models support fuel-consumption optimization, minimization of CO₂ intensity, and identification of the most energy-efficient operating regimes. Consequently, the digital platform functions not only as a monitoring tool, but also as an effective optimization instrument.

The integration of emission-monitoring platforms with Smart Grid infrastructure further expands their capabilities. This integration enables load balancing to reduce peak-period emissions, facilitates wider penetration of renewable energy sources, improves generation scheduling stability, and enhances demand-side management. Collectively, these measures contribute to a gradual transition toward a lower-carbon power-system structure.

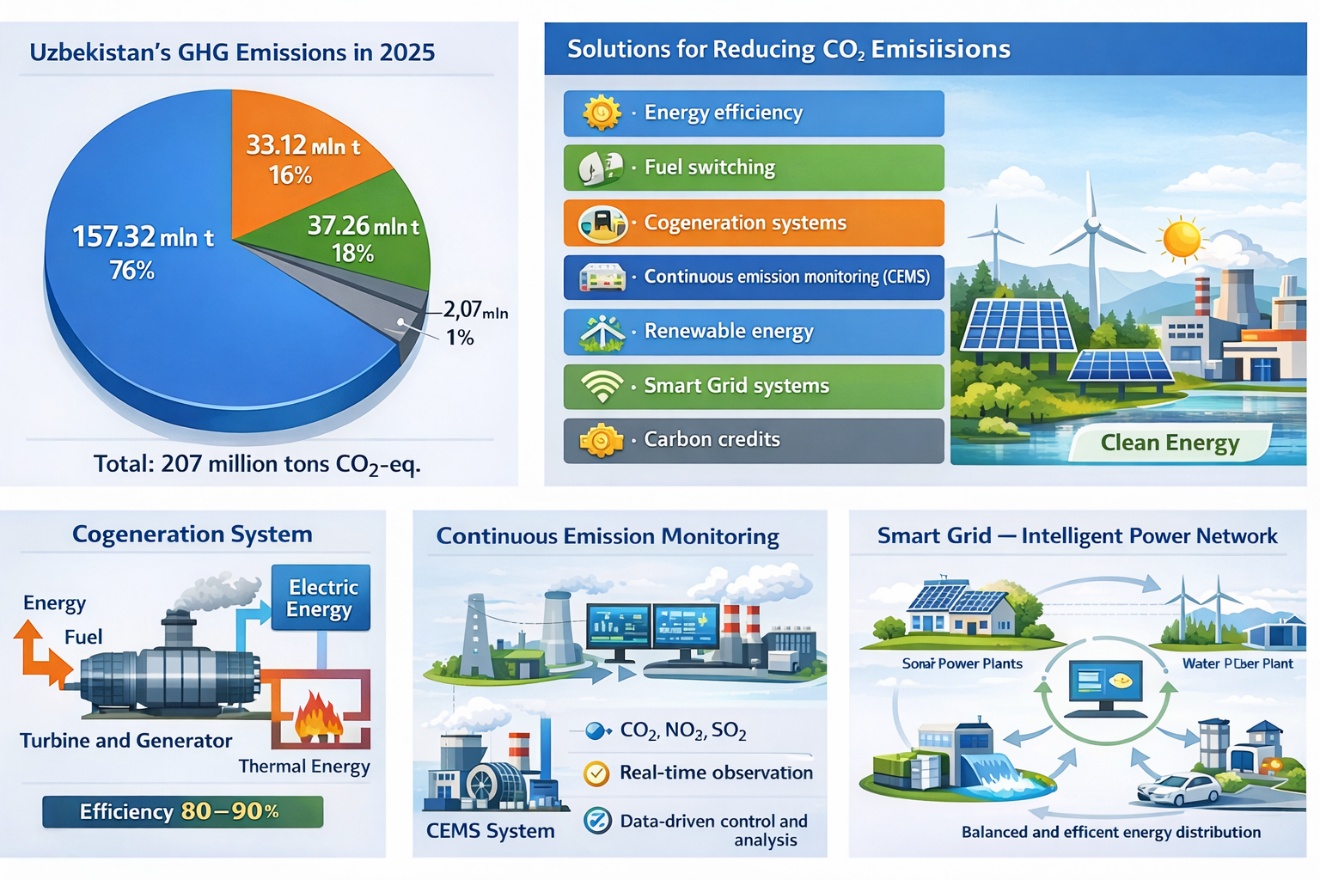
Finally, digital emission-monitoring platforms can serve as a core component of an ISO 50001-compliant energy-management system. In this context, they support the tracking of energy performance indicators (EnPIs), facilitate internal energy audits, document continuous improvement measures, and ensure transparent and traceable reporting for regulatory authorities and stakeholders. This integration strengthens both environmental performance and energy-management governance.

**TABLE 3.** Key performance indicators

|  |  |
| --- | --- |
| KPI | Meaning |
| tCO₂/MWh | Carbon-intensity index |
| Fuel consumption per MWh | Specific fuel rate |
| Plant efficiency (%) | Overall energy efficiency |
| Peak-emission index | Maximum short-term emission rate |
| Compliance rate (%) | Share of time within environmental limits |

Key performance indicators (KPIs) play a crucial role in evaluating the effectiveness of CO₂-emission management at both unit and plant levels. These indicators provide quantitative metrics that allow objective assessment of environmental and operational performance. Commonly used KPIs include the carbon-intensity index expressed in tCO₂/MWh, which reflects the amount of carbon dioxide emitted per unit of generated energy; fuel consumption per MWh, indicating the specific fuel rate; overall plant efficiency expressed as a percentage; the peak-emission index, which characterizes maximum short-term emission levels; and the compliance rate, representing the share of operating time during which emissions remain within established environmental limits. Together, these indicators form an integrated performance-evaluation framework (Table 3). The implementation roadmap for a digital CO₂-emission monitoring system should follow a structured and phased approach. Typically, the process begins with a comprehensive system audit to assess existing instrumentation, data availability, and regulatory requirements. This is followed by the installation of measurement devices and data-transmission infrastructure, ensuring reliable acquisition of emission and operational parameters. The next phase focuses on data integration and validation, during which collected data are harmonized and checked for consistency. Subsequently, AI-based analytical and forecasting modules are deployed to enable advanced data analysis and predictive capabilities. Staff training and operational testing are then conducted to ensure correct system usage and acceptance. Finally, certification and regulatory alignment are achieved, after which continuous monitoring and ongoing system improvement become part of routine operation.

The expected outcomes of deploying an advanced digital CO₂-monitoring system are multifaceted. Practical experience and analytical studies indicate that such systems can enable a reduction of CO₂ emissions by approximately 5–15%, primarily through improved efficiency and optimized operating regimes. Additional benefits include measurable fuel savings, enhanced operational safety, increased transparency and reliability of environmental reporting, and closer alignment with international best-practice standards in emissions management and energy efficiency.



**FIGURE 1.** Practical measures to achieve CO2 emissions.

From a scientific and practical perspective, several measures can be implemented to reduce CO₂ emissions in thermal power plants. One of the most effective approaches is the optimization of combustion processes, which involves ensuring complete fuel combustion in boilers, automatic control of air–fuel ratios, and minimization of heat losses. These measures directly increase efficiency and reduce fuel consumption and associated CO₂ emissions. Another important direction is improving overall energy efficiency through modernization of turbines and generators, improved thermal insulation, and the use of energy-efficient auxiliary equipment.

The deployment of continuous emission monitoring systems (CEMS) enables real-time emission control and accurate accounting, providing a reliable basis for operational optimization. In parallel, the application of Smart Grid technologies allows optimized load management and increased integration of renewable energy sources, thereby reducing excess generation and carbon intensity. Furthermore, digital management and AI-based solutions—including advanced data analytics and predictive modeling—help identify emission risks in advance and optimize operating regimes. Finally, institutional measures, such as the implementation of ISO 50001 energy-management systems, regular environmental audits, and systematic staff training, play a significant role in sustaining long-term emission reductions and ensuring regulatory compliance.

Figure 1 illustrates the main practical measures and technological pathways for reducing CO₂ emissions in the energy sector, with a particular focus on the case of Uzbekistan. The upper-left diagram presents the structure of greenhouse gas (GHG) emissions in 2025, indicating that the energy sector accounts for the dominant share of emissions, amounting to approximately 157.32 million tons or 76% of total CO₂-equivalent emissions. Other sectors contribute comparatively smaller shares, highlighting the critical role of power generation and fuel combustion processes in national emission reduction strategies.

Continuous digital monitoring, intelligent power-network management, and large-scale deployment of renewable energy sources.

The upper-right panel summarizes key solution domains for mitigating CO₂ emissions, including energy efficiency improvement, fuel switching, cogeneration systems, continuous emission monitoring systems (CEMS), renewable energy integration, smart grid technologies, and carbon credit mechanisms. These measures collectively form a comprehensive framework that combines technological, digital, and regulatory approaches to decarbonization.

The lower-left panel demonstrates the concept of a cogeneration (combined heat and power) system, in which a single fuel input simultaneously produces electrical and thermal energy. By utilizing waste heat from electricity generation, overall system efficiency can reach 80–90%, significantly reducing specific fuel consumption and associated CO₂ emissions compared to conventional separate generation.

The lower-middle panel illustrates the role of continuous emission monitoring systems (CEMS), which enable real-time measurement of key pollutants such as CO₂, NO₂, and SO₂. The integration of CEMS with digital control platforms allows continuous observation, data-driven analysis, and timely operational adjustments, thereby enhancing emission transparency and regulatory compliance.

The lower-right panel represents the Smart Grid concept, showing the interaction between renewable energy sources (such as solar and wind power), conventional power plants, and end users. Smart Grid technologies enable balanced and efficient energy distribution, improved load management, and higher penetration of renewable energy sources, all of which contribute to lowering carbon intensity and enhancing system flexibility.

Overall, Figure 1 demonstrates that effective CO₂-emission reduction requires an integrated approach that combines high-efficiency generation technologies

**CONCLUSION**

This study has demonstrated that thermal power plants remain the dominant source of national greenhouse gas emissions in Uzbekistan, accounting for the majority of total CO₂ output. Statistical analysis confirms that emission dynamics are closely linked to macroeconomic growth, electricity demand and the fossil-fuel structure of power generation. Temporal analysis further shows that emissions display seasonal fluctuations, with pronounced peaks occurring during winter high-load periods.

At the same time, the results indicate that a combination of technological modernization and digital transformation enables sustainable emission reduction. Continuous emission monitoring systems (CEMS), AI-based analytical tools, Smart-Grid integration and the expansion of cogeneration capacity play a key role in decreasing emission intensity while maintaining reliable electricity supply. Improvements in plant-level efficiency, fuel-mix optimization and the gradual scaling-up of renewable-energy generation were identified as the most effective decarbonization pathways.

Overall, the findings support the conclusion that Uzbekistan’s ongoing energy-sector reforms — including modernization of thermal power plants, deployment of digital monitoring platforms and implementation of energy-management standards — create a solid foundation for achieving long-term emission-reduction targets within the framework of national climate-policy commitments. Future research may incorporate plant-level operational datasets and scenario-based modeling to more precisely quantify the emission-reduction potential under alternative policy and technological pathways.

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