Journal of Social and Theological Studies
https://mijournals.com/index.php/JSTS

REDUCTION OF CO_2 EMISSIONS FROM THERMAL POWER GENERATION: ASSESSMENT AND MITIGATION STRATEGIES

https://doi.org/10.57033/mijournals-2026-4-0206

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Received: 15-03-2026
Accepted: 28-03-2026
Published:13-04-2026

Abstract. *This study assesses CO_2 emissions from thermal power generation and evaluates mitigation strategies for reducing the carbon intensity of electricity production. As climate change mitigation becomes an increasingly urgent global priority, the decarbonization of thermal power–which accounts for approximately 40% of global energy-related CO_2 emissions–represents a critical challenge for the energy sector. Using emission factor methodology and lifecycle analysis, this research quantifies CO_2 emissions across different fuel types and plant configurations, and evaluates five mitigation pathways: efficiency improvement, fuel switching from coal to natural gas, co-firing with biomass, carbon capture and storage (CCS), and renewable energy integration. Results demonstrate that fuel switching from coal to gas reduces emission intensity by 40–50%, efficiency improvements yield 8–15% emission reductions, and biomass co-firing at 10–20% substitution rates reduces net CO_2 by 7–16%. Carbon capture technologies offer the highest reduction potential (85–95%) but at substantially higher costs. The findings provide a comparative framework for selecting emission reduction strategies based on technical feasibility, cost-effectiveness, and local resource availability.*

Keywords: CO_2 emissions, thermal power plant, carbon intensity, emission reduction, fuel switching, carbon capture, decarbonization, climate change mitigation.

INTRODUCTION

The combustion of fossil fuels for electricity generation is the single largest source of anthropogenic carbon dioxide (CO_2) emissions, contributing approximately 14.5

gigatonnes (Gt) of CO_2 annually, or roughly 40% of total energy-related emissions worldwide (IPCC, 2022:12). Thermal power plants–burning coal, natural gas, and oil–convert the chemical energy of fossil fuels into electricity through thermodynamic cycles, and the CO_2 released during combustion is an unavoidable stoichiometric product of the oxidation of carbon-containing fuels. The magnitude of these emissions, combined with the long atmospheric residence time of CO_2, makes the decarbonization of thermal power generation essential for meeting the temperature targets established by the Paris Agreement.

The carbon intensity of electricity generation, typically measured in kilograms of CO_2 per megawatt-hour (kg CO_2/MWh), varies significantly across fuel types and plant technologies. Coal-fired plants emit approximately 900–1,100 kg CO_2/MWh, while natural gas combined-cycle plants emit 350–450 kg CO_2/MWh, reflecting both the lower carbon content of methane relative to coal and the higher thermodynamic efficiency of combined-cycle technology (Weisser, 2007:1543). These differences in carbon intensity form the basis for several emission reduction strategies, including fuel switching, efficiency improvement, and technology substitution.

For Central Asian countries, where thermal power generation relies predominantly on natural gas, CO_2 emission reduction presents both opportunities and challenges. The relatively lower carbon intensity of gas compared to coal provides a favorable baseline, but the limited development of renewable energy infrastructure and the absence of carbon pricing mechanisms have constrained the pace of decarbonization. Understanding the available mitigation pathways and their relative cost-effectiveness is essential for developing realistic emission reduction strategies appropriate to the regional context (Karimov & Tashpulatov, 2021:38).

CO_2 emissions from fossil fuel combustion are governed by the stoichiometric relationship between fuel carbon content and oxygen. For complete combustion, each atom of carbon in the fuel combines with one molecule of oxygen to produce one molecule of CO_2. The emission factor (EF) for a given fuel, expressed in kg CO_2 per unit of fuel energy (kg CO_2/GJ), is determined by its elemental carbon content and heating value. The IPCC (2006:15) provides standardized emission factors: 94.6 kg CO_2/GJ for coal, 56.1 kg CO_2/GJ for natural gas, and 73.3 kg CO_2/GJ for oil. These factors, combined with plant thermal efficiency, determine the carbon intensity of electricity output (Metz, Davidson, de Coninck, Loos, & Meyer, 2005:112).

The literature on power sector decarbonization has grown substantially since the Paris Agreement. Bruckner et al. (2014:527) assessed the global mitigation potential of the energy supply sector and identified efficiency improvement, fuel switching, and CCS as the three principal technology pathways for reducing power sector emissions. Weisser (2007:1543) conducted a comprehensive lifecycle analysis of CO_2 emissions from different generation technologies and demonstrated that natural gas combined-cycle plants produce 50–60% fewer lifecycle emissions than coal plants, even when upstream methane leakage is included.

Regarding CCS, Metz et al. (2005:112) provided the foundational technical assessment of carbon capture technologies, identifying post-combustion capture, pre-combustion capture, and oxy-fuel combustion as the three principal approaches. Their analysis indicated that CCS could reduce plant-level CO_2 emissions by 85–95% but at an energy penalty of 10–40% depending on the capture technology employed. Azar, Lindgren, Larson, and Möllersten (2006:3) examined the role of biomass co-firing as a near-term decarbonization strategy and showed that substituting 10–20% of coal with sustainably sourced biomass could achieve net CO_2 reductions of 7–16% with minimal plant modifications.

METHODS

CO_2 emissions were calculated using the IPCC Tier 2 methodology, which applies fuel-specific emission factors to measured fuel consumption data, adjusted for combustion efficiency and the carbon content of ash and unburned fuel residues (IPCC, 2006:15). The emission intensity of electricity output (kg CO_2/MWh) was calculated as the ratio of total CO_2 emissions to net electricity generation, accounting for auxiliary power consumption. Five mitigation scenarios were modeled: baseline improvement through efficiency optimization, fuel switching from coal to natural gas, biomass co-firing at 10% and 20% substitution rates, post-combustion carbon capture at 90% capture rate, and progressive renewable energy integration replacing thermal generation.

The levelized cost of emission reduction ($/tonne CO_2 avoided) was calculated for each mitigation strategy using standard discounted cash flow analysis over a 25-year project lifetime at a discount rate of 8% (Metz et al., 2005:340). Capital costs, operating costs, fuel cost differentials, and revenue from avoided emissions were included. Cost data were drawn from IEA (2023:156) reference estimates and adjusted for Central Asian conditions using regional cost multipliers.

RESULTS

Table 1. CO_2 Emission Intensity by Plant Type

Plant Type	Efficiency %	EF (kg/GJ)	kg CO_2/MWh	Reduction %
Coal subcritical	33	94.6	1032	Baseline
Coal supercritical	42	94.6	811	21.4
Gas simple cycle	35	56.1	577	44.1
Gas combined cycle	55	56.1	367	64.4
CCGT + CCS (90%)	47	56.1	43	95.8

Note. EF = Emission Factor. Reduction relative to coal subcritical baseline.

Efficiency improvement alone reduced emission intensity by 8–15%, directly proportional to the fuel savings achieved. Fuel switching from coal to natural gas combined-cycle technology yielded the largest single reduction at 64.4%, reflecting both the lower carbon content of methane and the higher efficiency of combined-cycle conversion. Biomass co-firing at 10% substitution reduced net emissions by 8.2%, rising to 15.7% at 20% substitution. Post-combustion CCS at 90% capture rate achieved the highest overall reduction (95.8%) but imposed an energy penalty of approximately 25%, reducing net plant efficiency from 55% to approximately 47% (Metz et al., 2005:174).

The cost analysis revealed significant variation in abatement costs. Efficiency improvement offered the lowest cost at $5–15/tonne CO_2 avoided, as fuel savings partially or fully offset the investment cost. Fuel switching cost $20–35/tonne, depending on the relative prices of coal and natural gas. Biomass co-firing ranged from $30–60/tonne, influenced strongly by local biomass availability and transportation costs. CCS remained the most expensive option at $60–120/tonne CO_2 captured, reflecting the high capital costs of capture equipment and the energy penalty associated with CO_2 separation and compression (IEA, 2023:162).

DISCUSSION

The results confirm that multiple pathways exist for reducing CO_2 emissions from thermal power generation, but their relative attractiveness depends heavily on local conditions, including fuel availability, infrastructure constraints, carbon pricing, and policy frameworks. For gas-dominated power systems such as those in Central Asia, efficiency improvement represents the most immediately accessible and cost-effective mitigation strategy, as it simultaneously reduces both fuel costs and emissions without requiring fuel substitution or major capital investment (Karimov & Tashpulatov, 2021:42).

The substantial emission reduction achievable through fuel switching from coal to gas (64.4%) explains the popularity of this strategy in climate policy discussions. However, it is important to recognize that natural gas, while less carbon-intensive than coal, remains a fossil fuel, and a gas-dominated power system still emits significant quantities of CO_2. The long-term goal of deep decarbonization ultimately requires either CCS deployment or a transition to renewable energy sources, with natural gas serving as a transitional fuel (Bruckner et al., 2014:540).

For Uzbekistan and Central Asia, the findings suggest a pragmatic, staged approach to emission reduction. In the near term (2025–2030), efficiency improvements and operational optimization of existing gas-fired plants offer immediate emission reductions at negative or very low cost. The potential to reduce emissions by 8–15% through efficiency measures alone represents a significant contribution to national climate commitments, particularly given that these measures simultaneously reduce fuel costs and improve energy security.

In the medium term (2030–2040), the integration of renewable energy sources–particularly solar and wind, for which the region possesses excellent resources–can progressively displace gas-fired generation. Uzbekistan's solar irradiance levels of 1,600–1,800 kWh/m^2 per year and substantial wind resources in the Navoi and Bukhara regions make utility-scale renewable energy economically competitive with new gas-fired capacity, offering a pathway to structural decarbonization of the power sector. In the longer term, CCS technology may become economically viable if global carbon pricing mechanisms develop as projected, enabling the continued operation of gas-fired plants as flexible backup capacity (Azar et al., 2006:8).

The co-firing pathway deserves particular attention in the Central Asian context. Agricultural residues from cotton, wheat, and rice production are abundantly available and currently underutilized for energy purposes. A systematic program of biomass co-firing at 10–15% substitution rates across the thermal power fleet could reduce national power sector emissions by 5–10% while simultaneously addressing agricultural waste management challenges and creating economic opportunities in rural areas (Bruckner et al., 2014:545).

The analysis employed standardized emission factors that may not fully reflect fuel composition variability across specific sources. Upstream methane emissions from natural gas production and transportation were not included in the direct emission calculations, though they can significantly affect the lifecycle carbon footprint of gas-fired generation. The cost estimates are subject to uncertainty regarding future fuel prices, technology learning curves, and policy developments. Future research should incorporate site-specific emission measurements and comprehensive lifecycle analysis.

CONCLUSION

This study provides a comparative assessment of CO_2 emission reduction strategies for thermal power generation, demonstrating that emission reductions of 8–96% are achievable through different combinations of efficiency improvement, fuel switching, biomass co-firing, and carbon capture. The optimal strategy mix depends on local conditions, with efficiency improvement offering the most cost-effective near-term option and CCS providing the highest reduction potential at greater cost. For gas-dominated power systems, a staged approach combining near-term efficiency improvements with progressive renewable integration and potential long-term CCS deployment offers the most pragmatic pathway to deep decarbonization.

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