Comparative Performance Analysis of Coal-Fired and Natural Gas Power Plants with Carbon Capture Integration

Power Plant Engineering Sessional Project

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Abstract

Growing electricity demand and climate change concerns have intensified the need for cleaner and more efficient power generation technologies. This project presents a comparative performance analysis of a 500 MW coal-fired power plant and a 400 MW natural gas combined cycle (NGCC) power plant, with and without carbon capture integration. Thermodynamic performance, fuel consumption, carbon dioxide emissions, efficiency penalties, variable load behavior, and economic feasibility are evaluated using given operational data and standard engineering correlations. The results indicate that natural gas power plants exhibit higher efficiency, lower emissions, and superior operational flexibility compared to coal-fired plants. Although carbon capture significantly reduces CO_2 emissions (up to 90%), it introduces efficiency penalties of 8–12% and increases the levelized cost of electricity. The study highlights the trade-offs involved in adopting carbon capture technologies for conventional thermal power plants.

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Chapter 1

Introduction

Electric power systems play a crucial role in economic development and industrial growth. A typical power system consists of electricity generation, transmission, and distribution. Among various generation technologies, thermal power plants remain dominant due to their reliability and ability to supply base-load power.

However, fossil-fuel-based power plants are major contributors to greenhouse gas emissions, particularly carbon dioxide (CO_2). To mitigate environmental impacts while maintaining energy security, carbon capture and storage (CCS) has emerged as a promising solution. This project compares the performance of coal-fired and natural gas power plants under CCS integration using engineering analysis.

1.1 Objectives

- To compare thermodynamic performance of coal-fired and NGCC power plants.
- To evaluate fuel consumption and heat rate.
- To quantify CO_2 emissions with and without carbon capture.
- To analyze efficiency penalties and auxiliary power requirements.
- To assess economic performance using LCOE.

Chapter 2

Overview of Power Generation Technologies

2.1 Global Power Generation Scenario

Globally, electricity is generated using coal, natural gas, hydro, nuclear, and renewable energy sources. Despite rapid growth in renewables, coal and gas power plants still supply a significant portion of base-load electricity due to their dispatchability.

2.2 Power Plants in Bangladesh

Bangladesh's power generation mix is dominated by natural gas-based plants, followed by furnace oil, diesel, coal, and hydroelectric power. Recent additions include coal-fired plants and the Rooppur Nuclear Power Plant, highlighting diversification efforts.

2.3 Thermal Power Plants

Thermal power plants convert chemical energy of fuel into electrical energy through thermodynamic cycles such as Rankine and Brayton cycles. Combined cycle plants improve efficiency by utilizing exhaust heat from gas turbines.

Chapter 3

Description of Power Plant Systems

3.1 Coal-Fired Power Plant

The coal-fired plant considered has a net capacity of 500 MW and operates on a Rankine cycle. Pulverized coal is burned in a boiler to generate superheated steam that expands through a steam turbine.

3.1.1 Given Data

- Net output: 500 MW
- Net efficiency: 42%
- Coal lower heating value (LHV): 25 MJ/kg
- CO_2 emission factor: 94 kg/GJ

3.2 Natural Gas Combined Cycle Power Plant

The NGCC plant has a net capacity of 400 MW and consists of a gas turbine, HRSG, and steam turbine.

3.2.1 Given Data

- Net output: 400 MW
- Net efficiency: 55%
- Natural gas LHV: 50 MJ/kg
- CO_2 emission factor: 56 kg/GJ

Chapter 4

Carbon Capture Technology

Post-combustion carbon capture using amine-based solvents is considered for both plants. The process involves absorption of CO_2 from flue gas, solvent regeneration, and compression of captured CO_2 for transport and storage.

4.1 Efficiency Penalty

Carbon capture systems require additional energy for:

- Solvent regeneration
- CO_2 compression
- Auxiliary equipment

Typical efficiency reduction ranges from 8–12%.

Chapter 5

Thermodynamic and Performance Calculations

5.1 Thermal Input and Heat Rate

5.1.1 Coal Plant

$$\dot{Q}_{in} = \frac{P_{net}}{\eta} \tag{5.1}$$

$$\dot{Q}_{in} = \frac{500}{0.42} = 1190.48 \text{ MW}_{th}$$

Heat rate:

$$HR = \frac{3600}{0.42} = 8571 \text{ kJ/kWh}$$

Coal flow rate:

$$\dot{m}_{coal} = \frac{1190.48}{25} = 47.6 \text{ kg/s}$$

5.1.2 NGCC Plant

$$\dot{Q}_{in} = \frac{400}{0.55} = 727.27 \text{ MW}_{th}$$

$$\dot{m}_{gas} = \frac{727.27}{50} = 14.55 \text{ kg/s}$$

Chapter 6

CO_2 Emissions Analysis

6.1 Without Carbon Capture

Coal plant:

$$\dot{m}_{CO_2} = 94 \times 1.19048 = 111.9 \text{ kg/s}$$

$$I_{CO_2} = 805 \text{ kg/MWh}$$

NGCC plant:

$$\dot{m}_{CO_2} = 56 \times 0.72727 = 40.7 \text{ kg/s}$$

$$I_{CO_2} = 366 \text{ kg/MWh}$$

6.2 With Carbon Capture (90% Capture)

Coal plant:

$$I_{CO_2} = 80.5 \text{ kg/MWh}$$

NGCC plant:

$$I_{CO_2} = 36.6 \text{ kg/MWh}$$

Chapter 7

Efficiency Penalty and Auxiliary Power

Coal plant with 10% penalty:

$$\eta_{CCS} = 0.378$$

Additional thermal input:

$$\Delta Q = 132 \text{ MW}_{th}$$

Equivalent auxiliary load $\approx$ 35 MW.

Chapter 8

Variable Load Performance

Thermal power plants experience efficiency degradation at part-load operation. NGCC plants show better load-following capability due to faster gas turbine response and lower thermal inertia compared to coal-fired plants.

At 60% load, coal plant efficiency drops to approximately 39–40%, increasing fuel consumption and emissions per unit electricity.

Chapter 9

Economic Analysis

9.1 LCOE Formulation

$$LCOE = \frac{CRF \cdot CAPEX + OPEX}{E_{annual}} + Fuel$$

9.2 Illustrative Results

Table 9.1: LCOE Comparison

Plant Type	Without CCS ($/MWh)	With CCS ($/MWh)
Coal-fired	60	95
NGCC	50	80

Chapter 10

Environmental Impact

In addition to CO_2, coal plants emit SO_x, NO_x, and particulate matter. Natural gas plants have significantly lower non-CO_2 emissions. CCS reduces CO_2 but does not eliminate other pollutants, highlighting the importance of fuel selection.

Chapter 11

Discussion

Natural gas combined cycle plants outperform coal-fired plants in efficiency, emissions, and flexibility. Although CCS enables deep CO_2 reductions, its energy and cost penalties remain significant. NGCC with CCS represents a more viable transitional technology toward low-carbon power generation.

Chapter 12

Conclusion

The comparative analysis demonstrates that:

- NGCC plants achieve higher efficiency and lower emissions.
- Carbon capture reduces CO_2 emissions by up to 90%.
- Efficiency penalties of 8–12% are observed.
- CCS significantly increases LCOE.

Future work may include dynamic simulation, alternative capture technologies, and integration with renewable energy systems.