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Performance Assessment of Cogeneration-Based Energy Systems for Improving Energy Efficiency and Reducing Air Emissions in Petroleum Refineries

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***Abstract*—Petroleum refineries are among the most energy-intensive industrial sectors, requiring substantial quantities of thermal energy and electrical power for continuous operation. Increasing fuel costs, environmental concerns, and stricter emission regulations have motivated the adoption of high-efficiency energy systems. Cogeneration, also known as Combined Heat and Power (CHP), offers a practical solution by simultaneously producing electricity and process steam from a single fuel source. This study evaluates the performance of a gas turbine-based cogeneration system proposed as a replacement for conventional steam boilers and purchased grid electricity in a refinery. The investigation focuses on thermal efficiency, carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x) emissions under Indian environmental regulations prescribed by the Central Pollution Control Board (CPCB) and Ministry of Environment, Forest and Climate Change (MoEFCC). Results indicate that the proposed CHP system improves overall energy efficiency from 60.91% to 77.51%, while reducing annual CO_2 emissions by approximately 24% and NO_x emissions by nearly 70%. The study demonstrates that cogeneration technology can significantly contribute to industrial sustainability and energy conservation objectives in India.**

***Index Terms*—Cogeneration, Combined Heat and Power, Energy Efficiency, Petroleum Refinery, Air Emissions, CO_2 Reduction, CHP, Environmental Compliance**

I. INTRODUCTION

India is the third-largest consumer of energy in the world and continues to experience rapid industrial growth. Petroleum refineries play a critical role in meeting transportation and industrial fuel demands. However, refinery operations require substantial amounts of process steam and electrical power, resulting in high fuel consumption and significant greenhouse gas emissions.

Traditionally, steam is generated through boilers while electricity is purchased from external utilities. This approach often results in lower overall energy utilization due to transmission losses and independent generation processes. Cogeneration technology has emerged as an effective alternative capable of simultaneously generating electricity and useful thermal energy from a single fuel source.

Combined Heat and Power (CHP) systems improve fuel utilization by recovering waste heat from power generation and using it for process heating applications. Such systems can achieve overall efficiencies exceeding 75%, compared with efficiencies ranging from 50–65% in conventional separate generation systems.

The present study investigates the implementation of a gas turbine-based cogeneration facility for refinery applications and evaluates its impact on energy efficiency and environmental emissions under Indian industrial conditions.

II. LITERATURE REVIEW

Several researchers have examined the benefits of cogeneration systems in industrial applications.

Smith et al. reported that CHP installations in petroleum industries improve energy efficiency by 15–30% compared to conventional utility systems.

International Energy Agency studies indicate that industrial cogeneration can reduce greenhouse gas emissions by 20–30% through improved fuel utilization.

Bureau of Energy Efficiency (BEE) reports have identified CHP technology as one of the most effective energy conservation measures under India's Perform, Achieve and Trade (PAT) scheme.

Research conducted in process industries has further demonstrated significant reductions in NO_x emissions through the application of Selective Catalytic Reduction (SCR) technology integrated with Heat Recovery Steam Generators (HRSGs).

Although CHP systems offer considerable environmental benefits, sulfur emissions remain a challenge when refinery off-gases containing sulfur compounds are used as fuel.

III. OBJECTIVES OF THE STUDY

The objectives of this research are:

1. To evaluate the thermal efficiency of conventional and cogeneration-based utility systems.
2. To compare annual CO_2 emissions for both systems.
3. To analyze NO_x and SO_x emissions under Indian environmental standards.
4. To assess the suitability of CHP systems for refinery applications.
5. To identify operational and environmental benefits associated with cogeneration implementation.

IV. METHODOLOGY

A. Existing Refinery Utility System

The existing refinery utility configuration consists of:

- Two steam boilers operating at 85.1% efficiency.
- Purchased electricity from the utility grid.
- High-pressure and medium-pressure steam generation.

The refinery requires:

- Electrical Power = 85 MW
- HP Steam = 194,000 lb/hr
- MP Steam = 213,000 lb/hr

B. Proposed Cogeneration System

The proposed CHP system consists of:

- Two gas turbines
- Two Heat Recovery Steam Generators (HRSG)
- Supplemental duct firing
- Selective Catalytic Reduction (SCR)

The CHP plant produces:

- Net Power Output = 95.5 MW
- Process Steam = Complete refinery requirement

C. Performance Evaluation Parameters

The following parameters are evaluated:

- Thermal efficiency
- CO_2 emissions
- NO_x emissions
- SO_x emissions
- Environmental compliance

V. THERMODYNAMIC ANALYSIS

A. Overall Efficiency

The efficiency of the utility system is calculated as:

η = Useful Energy Output / Fuel Energy Input × 100

Existing System

$\eta = 60.91\%$

Proposed CHP System

$\eta = 77.51\%$

Percentage Improvement

Efficiency Improvement = $((77.51 - 60.91)/60.91) \times 100$

Efficiency Improvement = 27.25%

B. Carbon Dioxide Emission Reduction

CO_2 Reduction (%) = ((CO_2 Existing − CO_2 CHP) / CO_2 Existing) × 100

CO_2 Reduction (%) = $((675576 - 513531)/675576) \times 100$

CO_2 Reduction = 24.0%

VI. RESULTS

Table 1. Energy and Environmental Performance Comparison

Parameter	Existing System	CHP System
Energy Efficiency (%)	60.91	77.51
CO_2 from Steam (t/year)	278,425	220,476
CO_2 from electricity (t/year)	397,151	293,055
Total CO_2 (t/year)	675,576	513,531
NO_x (t/year)	286	86
SO_x (t/year)	151	168

Table 2. Improvement Achieved

Parameter	Improvement
Energy Efficiency	27.25%
CO_2 Reduction	24.00%
NO_x Reduction	69.93%
Grid Dependency	Eliminated

VII. RESULTS AND DISCUSSION

The proposed cogeneration facility demonstrates a substantial improvement in overall refinery energy performance. The increase in efficiency from 60.91% to 77.51% is primarily attributed to the utilization of waste heat from gas turbine exhaust gases for steam generation through HRSG units.

Carbon dioxide emissions show a significant reduction of approximately 24%, highlighting the effectiveness of CHP technology in lowering greenhouse gas emissions. The reduction is achieved because electricity and steam are produced simultaneously from the same fuel input, minimizing energy losses associated with separate generation.

Nitrogen oxide emissions are reduced by nearly 70% due to the incorporation of SCR technology. This contributes significantly toward compliance with CPCB emission control requirements and improves local air quality.

Although overall environmental performance improves, sulfur oxide emissions remain a challenge. The sulfur compounds present in refinery off-gas contribute to SO_2 formation, requiring additional sulfur removal technologies to satisfy stringent emission standards.

The results indicate that CHP systems offer a technically feasible and environmentally beneficial solution for Indian refineries seeking to improve energy efficiency and reduce carbon emissions.

VIII. COMPLIANCE WITH INDIAN ENVIRONMENTAL REGULATIONS

The proposed CHP system was evaluated considering Indian environmental guidelines including:

CPCB Requirements

- Continuous Emission Monitoring Systems (CEMS)
- NO_x control requirements
- SO_2 monitoring requirements

MoEFCC Requirements

- Environmental Clearance Compliance
- Air Pollution Control Standards
- Industrial Emission Reporting

BEE PAT Scheme

The improved efficiency achieved through CHP implementation supports energy conservation objectives established under India's Perform, Achieve and Trade (PAT) scheme.

IX. CONCLUSION

The study demonstrates that gas turbine-based cogeneration technology provides significant advantages for petroleum refinery operations. The CHP system improves overall energy efficiency by 27.25%, reduces annual carbon dioxide emissions by approximately 24%, and decreases NO_x emissions by nearly 70%.

The results confirm that CHP technology can support India's industrial sustainability goals while improving refinery energy performance. However, sulfur emission control remains an important consideration requiring additional fuel treatment or desulfurization systems.

Future work should include detailed techno-economic analysis, life-cycle assessment, and integration of sulfur recovery technologies to further enhance environmental performance.

FUTURE SCOPE

- Integration of carbon capture systems.
- Advanced sulfur recovery technologies.
- Hydrogen-enriched fuel utilization.
- AI-based energy management systems.
- Economic feasibility studies for Indian refineries.

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