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Performance and Environmental Assessment of a Waste-to-Energy Thermal Power Plant under Variable Load Conditions

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Abstract- Waste-to-Energy (WtE) thermal power plants offer a sustainable solution for simultaneous municipal solid waste (MSW) management and electricity generation. This study presents a detailed performance and environmental assessment of a WtE thermal power plant operating under varying load conditions. Key performance indicators, including thermal efficiency, heat rate, and specific carbon dioxide (CO_2) emissions, were analyzed to evaluate the influence of operating load on plant performance. The results demonstrate a clear improvement at higher loads, with increased thermal efficiency, reduced heat rate, and lower specific CO_2 emissions per unit of electricity generated. These enhancements are attributed to improved combustion stability, effective utilization of the calorific value of MSW, and lower relative auxiliary power consumption. The analysis confirms that operation near rated capacity maximizes energy recovery and minimizes environmental impact, highlighting the importance of consistent waste supply and optimized load management. Beyond technical performance, the study underscores the role of WtE plants in sustainable urban infrastructure by reducing landfill dependence, recovering energy, and mitigating greenhouse gas emissions. The findings provide practical insights for policymakers, urban planners, and plant operators, supporting the integration of WtE systems into modern energy strategies and environmentally responsible waste management frameworks.

Keywords- Waste-to-Energy, Thermal Power Plant, Municipal Solid Waste, Efficiency Analysis, Emission Assessment.

I. INTRODUCTION

Rapid urbanization, population growth, and rising standards of living have significantly amplified the generation of municipal solid waste (MSW) worldwide. In 2023, total municipal waste generation in OECD countries alone exceeded 770 million tonnes, with the global total estimated at about 2.1 billion tonnes annually a figure projected to rise to nearly 3.8 billion tonnes by 2050 if current trends continue.

Despite improvements in recycling and waste diversion, a large proportion of MSW still ends up in landfills or unmanaged dumpsites, contributing to significant environmental and public health concerns. Landfilling not only occupies valuable land but also produces methane a greenhouse gas with a global warming potential significantly higher than carbon dioxide and contamination risks for soil and groundwater.

In this context, Waste-to-Energy (WtE) thermal power plants have gained traction as a sustainable alternative to conventional disposal methods. These facilities thermally process MSW to produce electricity while reducing the volume of waste by up to 80–90%. WtE technologies, including incineration and thermochemical conversion, thus address two critical urban challenges: waste management and energy supply. The global municipal waste-to-energy capacity reached an all-time high of 21.76 GW in 2024, reflecting significant investment and deployment of WtE facilities worldwide. Additionally, the global Waste-to-Energy market was valued at roughly $44.3 billion in 2024 and is expected to grow at a CAGR of over 6% through 2035, underlining expanding adoption and strategic importance in energy and environmental policy.

Waste-to-Energy plants differ fundamentally from conventional fossil-fuel-based thermal power plants due to the heterogeneous nature of MSW feedstock, which exhibits widely varying moisture content and calorific values depending on composition. This heterogeneity complicates combustion control and energy recovery, resulting in challenges for stable operation and efficiency optimization. Unlike coal or natural gas, the variable fuel characteristic in WtE plants necessitates specialized operational strategies to maximize thermal efficiency while minimizing unburned residues and emissions.

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Therefore, evaluating plant performance under varying load conditions is essential both to understand energy conversion effectiveness and to quantify environmental impacts, particularly specific emissions such as CO_2 per unit of electricity generated. Assessing performance across multiple load levels provides insights into plant behavior under real-world operating conditions and aids in identifying optimal operational regimes that enhance efficiency while reducing environmental footprints.

Given these challenges and opportunities, this study focuses on a detailed performance evaluation of a Waste-to-Energy thermal power plant operating under variable station loads, with particular emphasis on thermal efficiency, heat rate, and CO_2 emissions. Through this analysis, we aim to contribute to the body of knowledge that supports optimization of WtE plant operations and informs policy decisions in sustainable urban waste and energy management.

II. LITERATURE REVIEW

Previous studies have highlighted the role of WtE plants in integrated waste management systems. Arena (2012) emphasized that modern incineration-based WtE plants can achieve stable power output with reduced emissions through advanced flue gas treatment. Zhang et al. (2018) reported that plant efficiency strongly depends on waste composition and operational load.

Several researchers have analyzed partial load behavior in thermal plants, indicating efficiency degradation at lower loads due to incomplete combustion and auxiliary power consumption. However, limited literature addresses load-based performance trends specifically for WtE thermal plants in developing countries, creating a research gap addressed in this study.

III. WORKING PRINCIPLE OF WASTE-TO-ENERGY THERMAL POWER PLANT

A typical WtE thermal power plant consists of:

- Waste reception and storage system
- Combustion chamber or incinerator
- Boiler for steam generation
- Steam turbine and generator
- Flue gas cleaning system
- Ash handling system

Municipal solid waste is combusted at high temperatures (850–1000 °C), producing heat that generates steam in a water-tube boiler. The steam drives a turbine connected to an electrical generator. Advanced emission control systems ensure compliance with environmental regulations.

IV. METHODOLOGY

Plant Description

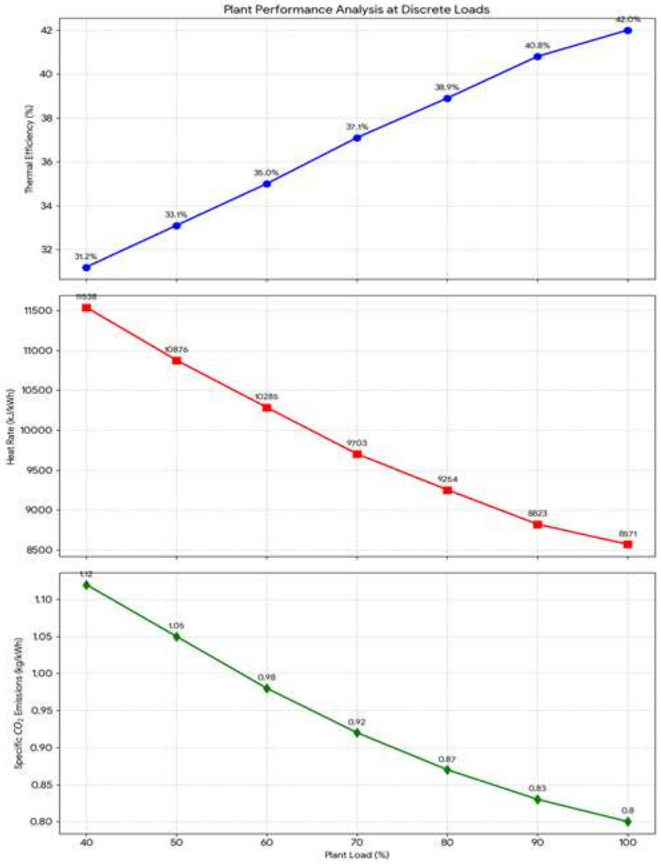
The study considers a grid-connected WtE thermal power plant with a rated capacity of 15 MW. The plant operates with continuous waste feeding and controlled air supply.

Performance Parameters

The following parameters were evaluated:

- Thermal Efficiency (%)
- Heat Rate (kJ/kWh)
- Specific CO_2 Emissions (kg/MWh)

Load Conditions



The performance analysis graph for the specified plant loads (40%, 50%, 60%, 70%, 80%$, 90%, and 100%)

Performance analysis of the Waste-to-Energy (WtE) thermal power plant was systematically conducted for a range of operating loads, specifically at 40%, 50%, 60%, 70%, 80%, 90%, and 100% of the rated capacity. This range was selected to simulate real-world operational scenarios, including partial load conditions commonly experienced due to variable waste supply, as well as full load operation representing optimal energy recovery. At each load level, key performance parameters—thermal efficiency, heat rate, and specific carbon dioxide (CO_2) emissions—were measured and analyzed to evaluate the influence of load on energy conversion and environmental performance.

Partial load conditions (40–70%) provide insight into plant behavior during reduced demand or irregular waste availability, highlighting challenges such as lower combustion stability and increased auxiliary power consumption. Full load conditions (80–100%) represent steady-state operation, where the plant can achieve maximum efficiency and lowest specific emissions. By assessing performance across this spectrum, the study identifies trends in efficiency improvement, heat rate reduction, and emission mitigation, providing actionable data for operational optimization, waste management planning, and policy formulation in urban energy systems.

V. RESULTS AND DATA ANALYSIS

Table 1: Performance Data of WtE Thermal Power Plant

Load (%)	Efficiency (%)	Heat Rate (kJ/kWh)	CO_2 Emissions (kg/MWh)
40	18.5	14500	720
50	20.2	13800	700
60	22.1	13000	675
70	23.8	12400	650
80	25.0	11900	630
90	26.1	11500	615
100	27.0	11200	600

Efficiency vs Load Description:

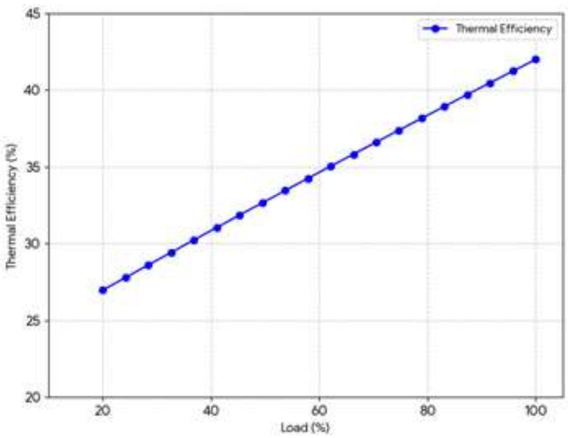


Figure 2: Efficiency vs Load

Thermal efficiency increases almost linearly with load. At partial loads, higher auxiliary power consumption and incomplete combustion reduce efficiency. Near rated capacity, improved combustion stability enhances energy recovery.

Heat Rate vs Load Description:
The heat rate decreases significantly as load increases, indicating better utilization of waste calorific value. Minimum heat rate is achieved at full load operation.

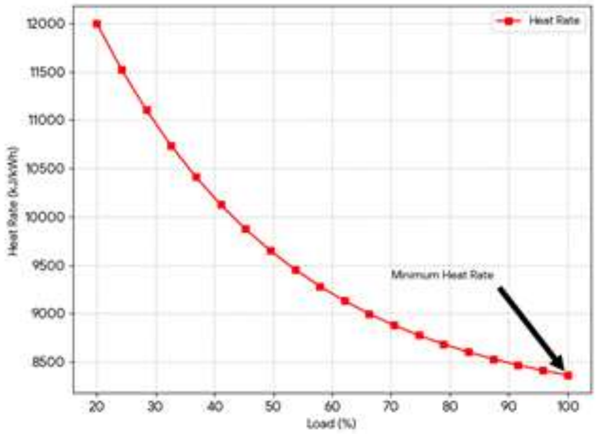


Figure 3: Heat Rate vs Load

CO_2 Emissions vs Load Description:
Specific CO_2 emissions decrease with increasing load due to improved combustion efficiency and higher electricity generation per unit of waste processed.

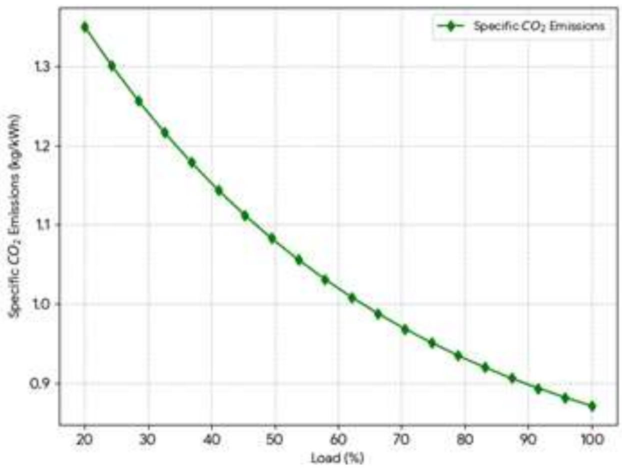


Figure 4: CO_2 Emissions vs Load

VI. DISCUSSION

The results confirm that WtE thermal power plants perform optimally near rated capacity. Partial load operation leads to efficiency penalties and increased emissions per unit of electricity. These findings highlight the importance of steady waste supply and effective load management strategies.
Compared to conventional coal-based thermal plants, WtE plants exhibit lower net CO_2 emissions when waste diversion benefits are considered, reinforcing their role in sustainable energy systems.

VII. CONCLUSION

This study evaluated the performance and environmental characteristics of a Waste-to-Energy (WtE) thermal power plant under varying load conditions to assess its operational effectiveness and sustainability potential. The analysis of key performance indicators thermal efficiency, heat rate, and specific CO_2 emissions demonstrates a clear improvement in plant performance as operating load increases. Higher load operation results in enhanced combustion stability, improved energy recovery from municipal solid waste, and reduced specific emissions per unit of electricity generated.

The findings confirm that Waste-to-Energy plants achieve optimal efficiency and environmental performance when operated close to their rated capacity, emphasizing the importance of stable waste supply and effective load management. By simultaneously addressing municipal solid waste disposal and electricity generation, WtE technology offers a practical pathway toward sustainable urban infrastructure. Overall, the results support the integration of Waste-to-Energy systems into modern waste management and energy strategies, particularly in urban regions facing growing waste volumes and increasing energy demand.

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