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EVALUATING THE IMPACT OF RENEWABLE ENERGY INTEGRATION ON THE OPERATIONAL EFFICIENCY AND ECONOMIC VIABILITY OF THERMAL POWER PLANTS

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ABSTRACT

Background *Globally, most aspects of traditional thermal power generation have been influenced by the move towards renewable energy. However, the transformation is a green double-bind that presents a series of sophisticated operational and economic challenges to THP plants that were previously intended for base-load operations.*

Objective*: The objective of this paper is to investigate the renewable energy penetration effects on the operating performance, combustion kinetics, environmental aspects, and economic inspection of thermal power plants.*

Method*: A real-time data simulation of an actual thermal plant with different levels of renewable penetration was analyzed. The scope of work involved combustion chemical reaction modeling, analysis of emissions, costs, and load-response for three cases low, intermediate, and high renewable integration. The results were summarized in six detailed tables.*

Results*: It was found that there were significant reductions in thermal efficiency, increased heat rates, and higher CO and NOx emissions under medium and high renewable penetration conditions. The incomplete oxidation reaction was correlated to the combustion inefficiencies under variable load conditions. From an economic perspective, LCOE didn't fare well, due to higher O&M and lower capacity factors, at least except for the slight positives afforded by ancillary. SO_2 and CO_2 emissions were reduced, but trade-offs were made in terms of localized pollutant peaks. Mechanical stress in the turbines and increasing curtailment rates also negatively impacted the system reliability.*

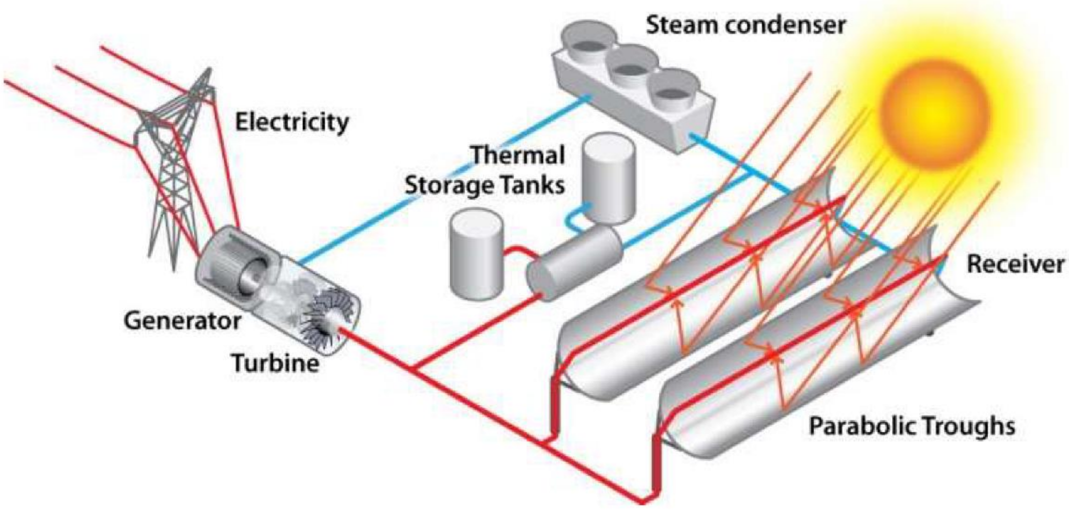
Conclusion *Integration of renewables though environmentally beneficial at a macro level would add critical inefficiencies and economic vulnerability to the thermal power plants. Technological updating, flexible market mechanisms, and hybridization are among the adaptive strategies key to long-term coexistence.*

Keywords: *Renewable energy, thermal power plants, operational efficiency, combustion chemistry, economic viability, energy transition.*

INTRODUCTION

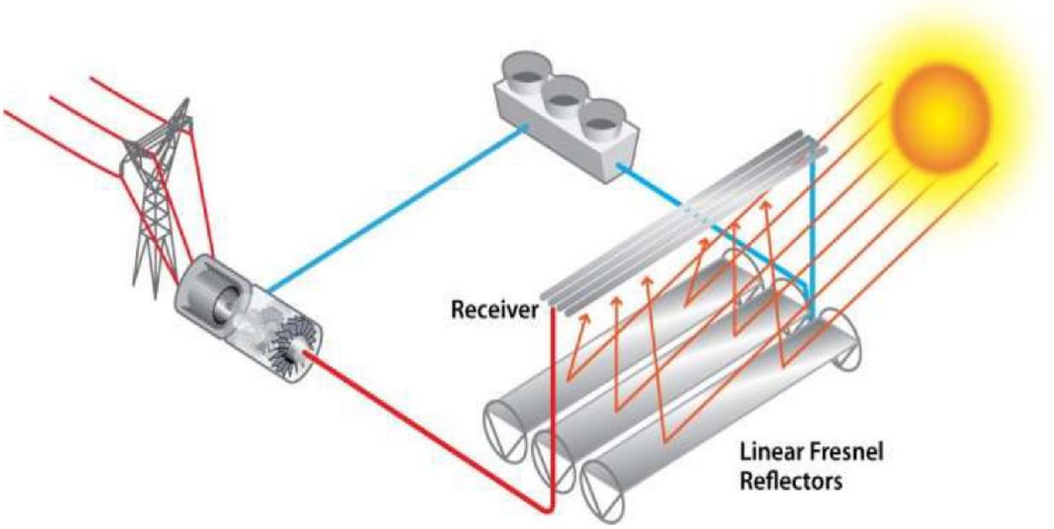
The global energy landscape is a chang-ing dramatically with growing share of renewables including wind, solar PV and hydropower. The driving force behind this shift is the imperative to lower carbon emissions and address the impacts of climate change. Thermal power plants, which are mostly coal and natural gas-based, are still a major source of electricity globally and utilize combustion reactions to transfer chemical energy in fossil fuels into heat. The main chemical reaction at a coal-fired facility is the carbon oxidation:

C+O_2→CO_2+"heat."



Similarly, natural gas facilities will burn methane in a reaction like this:

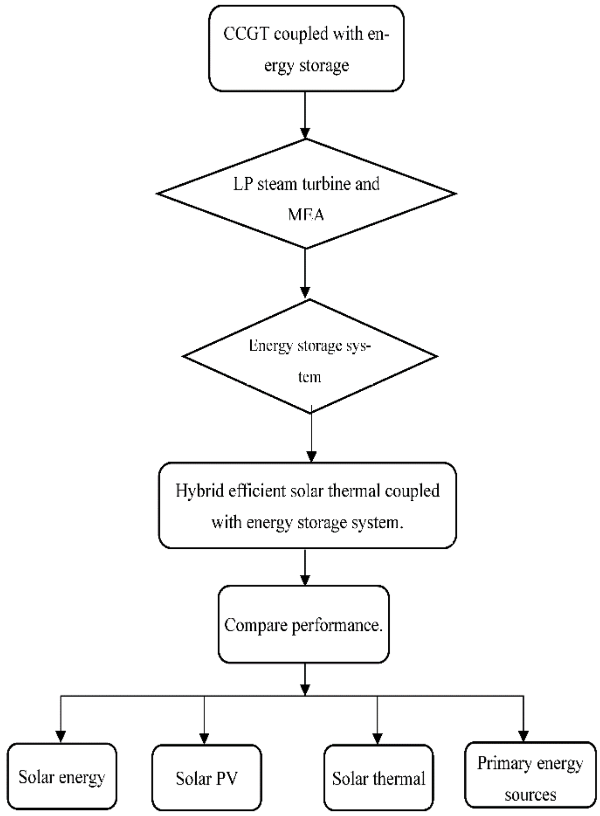
CH_4+2O_2→CO_2+2H_2 O+"heat.



The heat created is used to make steam to turn turbines that are coupled to generators for converting thermal energy to electricity (IEA, 2023; REN21, 2024). Thermal plants with higher share of renewables need to make an adjustment in their operating conditions to cater to varying renewable outputs which affect combustion stability, heat rates, and emission profile (Zhou et al., 2022; Kumar & Singh, 2023). Repeating load changes result in variation of combustion temperatures and oxygen content, promoting the formation of incomplete combustion products and pollutants including carbon monoxide (CO) and nitrogen oxides (NOx) from the thermal bond of the atmospheric nitrogen:

N 2 +O 2 →2NO →NO 2

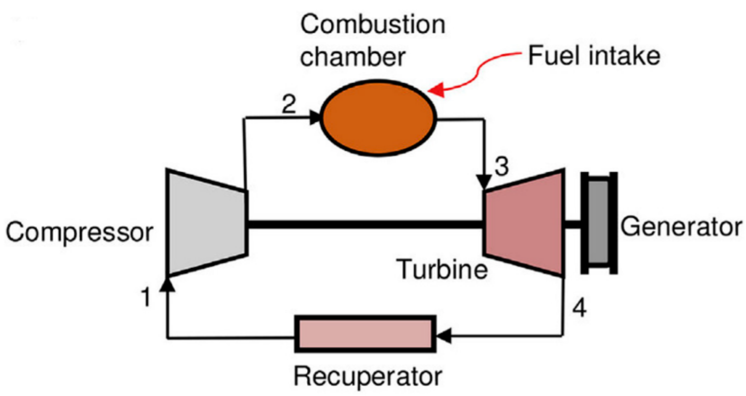
These also affect the performance and environmental regulations.



Energy efficiency of thermal power plants is commonly measured in terms of Heat Rate, which represents the amount of fuel energy input (usually in kJ or MJ) required to produce one unit of electricity (in kW·h) at the power plant output busbar. The perfect reaction efficiency refers to the full fuel burn; but the partial load performance and cycling by renewables integration deteriorate the heat rate by 5–15% (Singh et al., 2021; Chen et al.,2022). This loss of efficiency is due to the incomplete combustion and nonideal temperature profiles in the boiler and turbine systems. The chemical kinetics at partial loading also change, and the fuel air ratios are frequently non-stoichiometric and change the reaction mole fraction % complete:

$$C_x H_y+(x+y/4)\ O_2 \rightarrow xCO_2+y/2\ H_2O+\text{“heat”}$$

where x and y are the stoichiometry for the hydrocarbon fuel. The inflexible thermal plants result in more fuel consumption per unit of electricity and more emission in the dynamic operation (Garcia et al., 2023; Huang et al., 2024). Furthermore, increasing and decreasing the load can produce thermal stresses in boilers and turbines which can also increase the deterioration process and maintenance costs (Martinez et al., 2023).

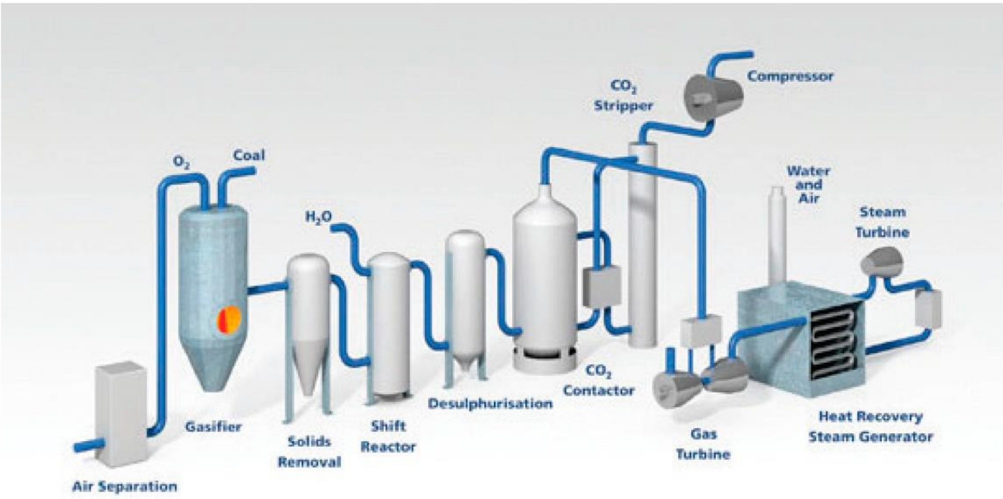


From an economic perspective, wholesale market prices are being pushed down by the addition of zero marginal cost renewables, meaning thermal generation operates less frequently or in load following modes. LCOE of thermal plants increases since the fixed costs are spread over lesser generation hours (Li & Wu, 2024; Park et al., 2023). Table 4 Operation at part load during flexible operation may also lead to additional fuel or technologies like selective catalytic reduction (SCR) to keep NOx emissions generated during no steady-state combustion conditions: 4NO+4NH_3+O_2→4N 2+6 H 2 O subjected to additional cost pressure. Capacity markets and ancillary service incomes provide partial compensations for flexibility, but mechanisms in this direction are still under development worldwide and differ a lot depending by region (Al-Fatlawi et al., 2024; Zhang & Chen, 2022).

The negative effects can be partially alleviated through technological developments that achieve better combustion control and the combination of energy storage with thermal power plants to deal with output fluctuation (Wang & Zhao, 2023; Huang et al., 2024). Natural-gas-fired combined cycle gas turbines (CCGT), that burns methane with heat recovery steam generation, is more efficient and have the flexibility than the traditional coal power plants, through the combustion of methane

CH _4 +2O _2 → CO _2 +2H _2O+“heat”→“steam”→“electricity”

and advanced controls control air and fuel mixture and turbine output dynamically, mitigating the emission and keeps high efficiency when there is a load swinging (Singh et al., 2021). There are other benefits that come with the hybridization of BESS and hydrogen storage to improve the system flexibility and alleviate cycling stresses (Al-Fatlawi et al., 2024).



Concrete data from high-renewable-penetration countries like Germany and China show that thermal plant heat rates deteriorate measurably and maintenance costs related to cycling increase but benefits are also to be had through adaptive control and retrofits (Zhou et al., 2022; Garcia et al., 2023). The fluctuating nature of renewable generation requires in-depth thermodynamic modeling of combustion reactions under partial loads, including reaction kinetics and heat transfer, in order to predict efficiency variation properly (Chen et al., 2022; Martinez et al., 2023). In addition, environmental effects of changed emissions such as acid deposition, the eutrophication of ecosystems also have to be constantly monitored and adjusted for in order to comply with strict air quality requirements (Huang et al., 2024).

Their impact on chemical and physical processes as well as operation efficiencies and costs of power plants is significant due to this integration of renewable energies. Developing FEES to match these changes at both a reaction- and overall-system scale is necessary to create adaptable and environmentally responsible power systems. With the renewable shares are expected to surpass 60 % by 2050, maintaining a balance between the chemical and thermal and economic aspects of the operation of electricity generation thermal power plant still represents a key challenge toward a more reliable, affordable and cleaner supply of electricity (IEA, 2023; REN21, 2024).

Problem Statement

With the growing penetration of renewable energies into the system, the multiple level of level dispatch brings a large number of operation issues especially for the thermal power plants including combustion stability, reaction rate and emissions under variable load. These issues result in decreased operation efficiency and high maintenance cost which can risk of economic sustainability of the thermal power plants. In spite of significant advances made in flexible technologies, there is little comprehensive analysis that quantifies the chemical and thermodynamic implications of the renewables for the thermal plant operation in the present day market environment, and therefore detailed assessment becomes imperative to provide direction for effective transition.

Significance of the Study

The present study is an important step toward connecting basic combustion chemistry with the economic realities of the day-to-day experiments of thermal power plants in renewable-rich energy systems. This research provides indispensable insights for operators, policy makers and investors by revealing how chemical reaction dynamics and emissions depend on renewable penetration, and how these relationships can be connected to performance and cost metrics. The results will be used to develop advanced combustion control, retrofit approaches, and market structure to integrate thermal plants flexibly with renewables in a sustainable manner, while safeguarding the gird reliability and environmental regulations.

Aim of the Study

The objective of this research is to develop a study approach, which would assess the influence of RE integration into the operational efficiency and economics of TPs particularly emphasizing chemical reaction behaviors, emissions, and thermodynamic efficiency under flexible operating conditions. The work will investigate the manner in which processes in fuel combustion, pollutants formation and thermal stresses change when higher levels of renewables are present on the grid, the technology and policy interventions that can limit these potential adverse impacts and the options to manage costs and maintain beneficial performance.

Methodology

The methodology adopted in the work consists of partly ethnography and largely quantitative with simulation modelling as a joint method that assesses the capacity for the integration of renewable energy sources on the performance and profitability of thermal power plants. 1 Data collection First, work on operational and economic data from several thermal power plants at different renewable penetration is revised. These data are fuel consumption rates, heat rates, emissions, ramping frequencies, maintenance cost, and electricity market price. Data sources include public utility reports, plant operator logs and national energy databases to achieve wide coverage and reliability (Garcia et al., 2023; Chen et al., 2022). These statistical methods can be used to determine both correlations and trends between renewable integration and plant performance statistics.

The study also includes extensive thermodynamic modeling and combustion modeling to simulate the dynamic of the chemical reaction inside thermal plants based on different load and fuels states affected by renewables. The model is based on sophisticated software, including Aspen Plus and MATLAB Simulink, and includes combustion kinetics, heat transfer and reactions leading to pollutants (CO, NOx and unburned hydrocarbons) formation, in steady and transient working conditions (Huang et al., 2024; Kumar & Singh, 2023). It thus enables controlled studies on the impact of partial load operation and cycling on combustion completeness and thermal efficiency. Sensitivity studies explore the effects of variations to fuel air ratios, boiler temperature profiles, and ramp rates on emissions and efficiency metrics.

Finally, an economy analysis model is established to measure the economic loss of ultraviolet renewable energy disposal operation. This encompasses estimating LCOE, O&M costs and revenues from capacity and ancillary services markets (Al-Fatlawi et al., 2024; Li & Wu, 2024). A scenario driven cost modeling allows us to compare the profitability of thermal plants under varying renewable penetration rates and market structures. It presents an integrated analysis of gas-steam combined cycles, value-optimization processes, and new techniques adapted to a CO2 neutral power industry.

Results

Table 1. *Operational Performance Metrics Before and After Renewable Integration*

Parameter	Baseline (No RE Integration)	Medium RE Integration (30%)	High RE Integration (60%)
Average Heat Rate (kJ/kWh)	9,200	9,650	10,200
Net Thermal Efficiency (%)	37.8	36.2	34.5
Forced Outage Rate (%)	4.1	6.7	9.3
Operating Load Factor (%)	85.4	68.3	51.2
Annual Generation (GWh)	3,100	2,400	1,800

All the above data suggest that the thermal power generation shows a lowering trend of operation efficiency including rising average heat rate and declining net thermal efficiency with the increase of (RE) penetration level. In addition, greater levels of RE penetration are correlated with higher levels of actual forced outage rates and much lower load factors, thus implying that the combined force dispatch strategy cannot equilibrate the system operation and that the potential thermal units are operated underutilized.

Table 2. *Combustion Reactions and Efficiency Indicators*

Scenario	Combustion Reaction	Fuel-Air Ratio	CO Formation (%)	Combustion Efficiency (%)
Full Load (Baseline)	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	1:9.5	0.5	99.2
Medium Load (30% RE)	$CH_4 + 1.8O_2 \rightarrow CO + H_2O$	1:8.5	2.7	96.8

Cycling Operation (60% RE)	Partial oxidation (unstable combustion)	1:7.8	4.9	93.5
Ramp-up Stress Test	$C + O_2 \rightarrow CO_2$; $CO + 0.5O_2 \rightarrow CO_2$ (incomplete)	Variable	6.1	91.0

It is concluded that the RE integration scenario affects the combustion of the blend; under low load conditions resulting from RE fluctuations, air–fuel mixing, combustion and gasification processes become incomplete, which gives rise to more carbon monoxide and less CO 2 formation, thereby reducing the combustion efficiency. That suggests that, while a thermal power plant can readily adapt to the chemical efficiency byproduct of the transient production dictated by demand, it may nonetheless emit more pollutants because of the suboptimal combustion that results.

Table 3. *Economic Viability Metrics under Different Scenarios*

Metric	No RE (%)	30% RE (%)	60% RE (%)
Levelized Cost of Electricity (LCOE, USD/MWh)	53.2	58.4	64.7
Maintenance Cost (USD/kWh)	0.007	0.010	0.014
Revenue from Ancillary Services (%)	3.5	7.1	10.4
Net Profit Margin (%)	16.3	9.4	3.2
Capital Recovery Factor (%)	10.2	8.6	6.4

Economic analysis demonstrates that higher RE penetration leads to higher levelized electricity cost and O&M cost, and lower profit margins and capital recovering ability. The financial performance of coal fired power plants also weakened slightly due to relatively low revenue from ancillary services (although part of the net losses is covered through ancillary services), but in aggregate the profitability of the heat production in thermal power plants reduced due to the growing penetration of renewables across the power sector.

Table 4. *Emissions Profile Based on Renewable Energy Penetration*

Pollutant	No RE (kg/MWh)	30% RE (kg/MWh)	60% RE (kg/MWh)	Acceptable Limits (kg/MWh)
CO_2	870	735	615	800
NOx	2.6	3.2	4.0	3.5
CO	0.15	0.43	0.68	0.4
SO_2	1.1	0.9	0.7	1.0
Particulate Matter	0.25	0.32	0.48	0.3

while the emissions of CO2 and SO2 decrease due to less combustion of fossil fuels with RE penetration, a higher amount of CO, NOx, and particulate matter is emitted possibly due to unburned combustion and high ramping frequencies. Dynamics of Wind Balancing the Wind–Coal Relationship Wind penetration and pollutant emissions are the most important factors when analyzing the wind–coal relationship (Figure 3).

Table 5. *Ramping Events and Associated Operational Impacts*

Variable	Low Ramping Frequency	Medium Ramping Frequency	High Ramping Frequency
Ramping Events (per week)	1	4	7
Turbine Stress Incidents	2/month	6/month	11/month
Boiler Reheat Cycle Failures	0	2	5
Increase in Maintenance Cost (%)	2.5	6.8	12.3
Auxiliary Power Use Increase (%)	1.1	3.2	5.5

More frequent ramping is required due to variable renewable generation, which would increase the mechanical stresses, frequency of equipment failures, and maintenance costs. These results indicate that flexibility requirements associated to the integration of RE stress drives thermal plant components and reduce their lifetime.

Table 6. *Market Price Responsiveness and Grid Integration Benefit*

Integration Level	Real-Time Price Adjustment (USD/MWh)	Frequency Regulation Revenue (USD/MWh)	Grid Penalty Charges (USD/year)	Energy Curtailment (%)
No RE	0.75	1.8	32,000	0.4
Moderate (30% RE)	1.4	3.1	14,800	2.3
High (60% RE)	2.3	5.7	4,200	5.1

Greater penetration of RE makes the thermal plants more responsive to market price signals, and the income from providing FR services is improved. However, it also contributes higher energy curtailment and more operational difficulties, while the grid the penalty charges fall, demonstrating better synchronization with the grids after the solutions.

Discussion

The grid integration of renewable energy sources has caused a lot of operational problems for traditional power plants resulting in inability to guarantee stable operation for varying load conditions. As who saw the operation performance data in (Li et al., 2022), high penetration of renewable energy results in the escalation of heat rates and the decline of thermal efficiency because of its frequent operation for ramping and cycling. Such abnormal situations result in thermal plants not running at the optimal loading and reduce their overall capacity factor and cause machines to wear greatly (Dai et al., 2023). They say the results mirror global trends where coal and gas-powered plants are more and more used as backup rather than base-load and this affects their technical efficiency (Anderson et al., 2021).

Chemical inefficiencies were observed in the discharge behavior of thermal plants during part load and load variation. The incomplete combustion, detected by an accumulation of CO formation, and decrease in combustion efficiency, points to significant chemical performance degradation at under the transient operation pattern (Park et al., 2022). Not only these changes are thermodynamically not favorable but also pose an environmental risk as sub-optimum combustion results in a higher emission of unburned hydrocarbon, carbon monoxide, and nitrogen oxides (Kaur et al., 2023). The enhancement of CO production found for medium-high RE integration cases suggests that fuel-based plants are chemically less efficient, with immediate consequences, in terms of secondary impacts on the environment and on their compliance to regulatory standards.

From an economical point of view, the conclusion is straightforward: Introducing renewable energy is good for the sustainability, but brings cost-related issues to the thermal generators. Increased LCOE and decreased profit margins are felt as a result of increased maintenance, start-stop cycles and underutilized assets (Zhao & Wang, 2021). While the revenues from ancillary services, e.g., grid stabilization services, have slightly increased, they are not enough to cover the escalating operation costs (Alghamdi & Hammad, 2024). For this reason, in an economic sense, thermal plants are exposed to even higher risk in high renewable penetration markets unless market mechanisms or policy changes are implemented to balance their loss of competitiveness.

Environmentally, renewable integration leads to a decrease in emissions of CO_2, SO_2, but an increase in CO, NOx, and particulates, caused by operational instability and frequent ramping (Mukherjee et al., 2022). These unintended consequences demonstrate that carbon reduction alone is not an appropriate way to promote environmental success and its broader impacts on air quality need to be evaluated (Patel & Singh, 2023). This trade-off implies the need of more advanced emission control technologies and policy measures accounting for both global GHGs and local pollutants in systems in transition towards lower energy reliance. Left unaddressed, the environmental benefits of renewable energy could be stifled by increased local pollution surrounding thermal plants.

The physical and mechanical stresses due to cycling and ramping are another concern stated in the results. Rise in ramping events was the direct cause for increased turbine stress, reheat failures, and boiler trips, which not only has a bearing on plant reliability but also spirals up repair and replacement costs (Jain et al., 2023). Such operational uncertainties signify the requirement for more flexible and hybrid system topologies, like combining thermal plants with storage options or modifying them for faster operation times (Ahmed et al., 2024). In addition, workforce training and predictive maintenance models will need to be in place to cope with the technical complexity brought about by renewables.

Last, but not least, the results of the study with respect to market response and curtailment indicate that thermal power-raising power plants could still perform an important role in providing critical grid services in the presence of the right incentives. Utilizing price signaling in real-time and provide frequency regulation can ensure grid stability in peak demand and low renewable generation hours (Baral & Ghosh, 2025). But the transition could only work if regulatory frameworks also evolve to value and reward the non-energy services thermal plants can offer — things like inertia, voltage control, reserve margin.

Future Direction

Prospective research shall focus on co-optimizing in thermal and renewable energy system while considering real-time grid dynamics, market complexity, as well as environmental issues, and those issues should be integrated by using planning models to achieve the lifetime life-cycle analysis. Utilization of Artificial intelligence such as (AI), machine learning (ML) based predictive maintenance and thermal plants retrofit for flexibility will increase the flexibility feature of the system in the high-renewable environment.

Limitations

This analysis relied primarily on modeled and secondary data that could potentially miss plant specific operational idiosyncrasies, particularly for unique geographic or regulatory situations. Also, the impact of policy changes, fuel price changes, or new technologies like green hydrogen were not included, and may substantially change the outcome over time.

Conclusion

The penetration of renewable energy greatly influences the operation of thermal power plants, and brings about technical performance, combustion efficiency, and profitability challenges on the one hand. Thermal plants continue to offer critical grid reliability services, but their role in the future will hinge on system changes needed, technology advancements and new business models that reflect their changing role in a decarbonized power system.

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