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INTEGRATED RENEWABLE ENERGY MODELING AND SCENARIO ANALYSIS FOR ACHIEVING A LOW-CARBON ENERGY MIX IN CHHATTISGARH

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Abstract

Chhattisgarh, a resource-rich state in central India, plays a pivotal role in national energy production due to its vast coal reserves and rapidly expanding industrial sectors such as steel, mining, cement, and thermal power generation. While this industrialization has ensured strong energy availability and economic growth, it has simultaneously intensified environmental challenges, including rising carbon emissions, air pollution, and ecological degradation. With a population of nearly 30 million and a climate characterized by high solar insolation and abundant biomass resources, the state possesses significant potential for renewable energy development. This study presents an integrated renewable energy modeling and scenario analysis framework aimed at achieving a low-carbon energy mix in Chhattisgarh by 2035. Using statistical datasets and simulated projections, three scenarios Business-as-Usual (BAU), Moderate Transition (MT), and Aggressive Green Transition (AGT) were constructed to assess renewable integration pathways and their environmental impact. Results indicate that the AGT scenario, supported by large-scale solar expansion, biomass utilization, and energy storage deployment, can reduce carbon emissions by 48–55% while increasing the renewable share to 60–65% of the total energy mix. The findings demonstrate that a structured shift toward renewable energy can mitigate industrial pollution, enhance long-term energy security, and support India's national goal of achieving net-zero emissions by 2070. The study provides policymakers with a strategic roadmap for optimizing renewable resources, reducing coal dependency, and enabling sustainable industrial growth in Chhattisgarh.

Keywords: *Renewable Energy[1], Energy Modeling[2], Low-Carbon Transition[3], Chhattisgarh[4], Scenario Analysis[5].*

1. Introduction

Chhattisgarh, situated in the geographic center of India, spans 135192 square kilometers and houses a population of nearly 30 million, making it one of the country's most resource-abundant yet rapidly developing states. The demographic profile is predominantly rural, with over 75% of the population dependent on agriculture, forestry, and allied sectors. Simultaneously, the state has undergone significant industrial expansion over the past two decades, emerging as a national hub for steel, thermal power generation, mining, cement, aluminum processing, and heavy engineering. This industrialization supported by vast coal reserves and continuous electricity availability has strengthened the regional economy but has also increased energy consumption and placed severe stress on environmental systems [1]. Chhattisgarh's energy landscape remains heavily dominated by coal-based thermal power, contributing approximately 82% of the total installed capacity. Although this reliance ensures continuous energy availability for industry and urban centers, it leads to substantial greenhouse gas emissions, coal ash generation, particulate pollution, and degradation of land and water resources. Industrial districts such as Korba, Raigarh, Bhilai, and Raipur frequently report high pollution loads, reflecting the urgent need for sustainable energy diversification. Climatically, the state experiences a tropical wet and dry climate, with temperatures ranging from 12°C in winter to over 42°C in summer. Average annual rainfall of 1200 to1600 mm and high solar insolation of 5 to 5.5 kWh/m²/day position Chhattisgarh favorably for large-scale solar deployment. Additionally, extensive agricultural and forest-based activities generate significant biomass resources, offering opportunities for biomass energy production and decentralized renewable systems [2]. Given India's national commitment to achieving net-zero emissions by 2070, Chhattisgarh's transition toward clean energy is not only desirable but essential. The state possesses the technical potential and resource base to shift from a coal-dependent structure to a low-carbon, diversified energy portfolio. This research develops a comprehensive renewable energy modeling and scenario analysis framework, aiming to evaluate feasible pathways for enhancing renewable integration, reducing industrial emissions, and achieving a sustainable energy mix for Chhattisgarh by 2035 [3].

2. Literature Review

The transition toward a low-carbon energy system has become a central theme in global sustainability research. Numerous studies highlight that shifting from fossil-fuel dependence to renewable energy can significantly reduce greenhouse gas emissions, improve energy security, and support economic resilience (IEA, 2022). India, as one of the world's fastest-growing economies, has placed strong emphasis on renewable energy expansion, aiming for 500 GW of installed non-fossil capacity by 2030 and net-zero by 2070. This national vision forms the backdrop for state-level research, including studies focused on Chhattisgarh an energy-surplus yet coal-dependent state [4].

National-Level Renewable Energy Studies

Several national analyses have assessed India's renewable potential and low-carbon pathways. According to the Central Electricity Authority (2023), India has the technical potential of generating 748 GW from solar, 120 GW from wind, 25 GW from biomass, and 10 GW from small hydro. Research by Pandey et al. (2020) and Bhatia & Gupta (2021) underscores that achieving 50% renewable penetration by 2035 is economically feasible due to falling solar LCOE (₹2.5 to ₹3.0/kWh) and improving storage technologies. Furthermore, the International Renewable Energy Agency (IRENA, 2022) highlights that India can reduce its power-sector emissions by up to 44% through accelerated renewable deployment [5].

Regional-Level Studies on Central India

Central Indian states such as Chhattisgarh, Odisha, and Madhya Pradesh possess some of the richest coal reserves, making them industrial hotspots. Rao and Singh (2019) conducted a regional modeling study showing that central India's high solar insolation (5 to 6 kWh/m²/day) and biomass output can replace 35 to 40% of thermal generation by 2040. A study by Kumar et al. (2021) found that regions like Korba (Chhattisgarh) and Talcher (Odisha) face severe degradation due to coal mining, reporting PM2.5 levels frequently exceeding the national limit of 60 µg/m³, reinforcing the need for renewable alternatives [6].

Studies Focused on Chhattisgarh

Research specifically examining Chhattisgarh's renewable energy landscape is comparatively limited but highly relevant. Sharma et al. (2023) assessed the state's solar potential at 24 to 26 GW, primarily concentrated in Janjgir-Champa, Bilaspur, Raipur, and Baloda Bazar. MNRE (2024) data indicates that Chhattisgarh produces 6 to 7 million tonnes of agricultural residue annually, supporting an estimated biomass generation potential of

1200 to 1500 MW. Studies on environmental impacts of industrialization in Chhattisgarh provide crucial context. According to the Central Pollution Control Board (CPCB, 2022), industrial clusters such as Korba, Raigarh, and Bhilai rank among India's most polluted areas, with high SO_2, NOx, and particulate emissions predominantly from thermal plants and metallurgical industries. A study by Swain & Kumar (2022) linked thermal power operations in Korba to a 20 to 30% increase in respiratory illnesses in surrounding populations [7].

Technological and Policy Perspectives

Several authors have also explored policy frameworks and technological considerations for state-level renewable transitions. Singh and Reddy (2020) argue that India's Renewable Purchase Obligation (RPO) and Green Energy Open Access Rules can accelerate adoption in industrial states. Meanwhile, studies on energy storage (Verma & Thomas, 2021) emphasize that battery integration is crucial for achieving >50% renewable penetration in coal-dependent grids. Research on decentralized systems by Johar & Meena (2021) demonstrates that biomass gasifiers and rooftop solar can significantly benefit rural and tribal regions of Chhattisgarh, improving energy access and economic opportunities [8]. These findings align with global studies advocating decentralized renewable energy as a foundation for just transitions (World Bank, 2023).

Identified Research Gaps

Despite existing literature, several key gaps remain:

1. Lack of integrated energy modeling specifically tailored to Chhattisgarh's demographic, industrial, and environmental context.
2. Absence of scenario-based evaluations comparing BAU, moderate, and aggressive renewable expansion pathways for the state.
3. Insufficient assessment of industrial decarbonization potential through renewable energy integration.
4. Limited combined analysis of solar, biomass, hydro, and storage potential using statistical projections.

This study addresses these gaps by offering a comprehensive, data-driven, scenario-based modeling framework for achieving a low-carbon energy mix in Chhattisgarh [9].

3. Methodology

This study adopts a structured, multi-layered methodological approach to evaluate the feasibility of a low-carbon energy transition in Chhattisgarh. The methodology integrates statistical data analysis, renewable resource estimation, energy demand forecasting, optimization modeling, and scenario simulation [10]. The approach combines both primary-region insights and secondary datasets from national energy agencies to ensure accuracy and reliability.

Research Framework and Design

This study adopts a comprehensive quantitative research framework that integrates statistical data analysis, renewable resource assessment, energy demand forecasting, and scenario-based modeling to evaluate pathways for achieving a low-carbon energy mix in Chhattisgarh [11]. The methodological design is structured into four key phases: assessing the state's current energy landscape, estimating future energy demand based on demographic and industrial growth, developing three alternative energy transition scenarios, and applying optimization models to identify the most cost-effective and environmentally sustainable energy configuration. This multi-layered approach ensures that both technical feasibility and socio-economic conditions are incorporated into the modeling process.

Data Sources and Collection

Data for the study were compiled from multiple government, institutional, and technical sources to ensure accuracy and reliability. Official datasets from the Central Electricity Authority (CEA), Ministry of New and Renewable Energy (MNRE), and Chhattisgarh State Electricity Board (CSEB) provided information on installed capacity, energy generation, and district-level consumption. Climate parameters such as solar irradiance, temperature, and rainfall were obtained from NASA-SSE and India Meteorological Department (IMD) databases, while GIS-based land-use maps and forest cover data were integrated to assess spatial suitability for renewable installations. Since long-term official projections were limited, future estimates for biomass availability, electricity demand, and renewable deployment were generated using regression-based simulation models and historical growth trends, such as a 5.1% average annual rise in industrial electricity demand [12].

Renewable Resource Assessment

Renewable resource assessment involved evaluating the technical potential of solar, biomass, small hydro, and wind energy across different districts of Chhattisgarh. Solar energy potential was calculated using global horizontal irradiance (GHI) values, with most districts receiving 5 to 5.5 kWh/m²/day, indicating suitability for utility-scale solar parks and rooftop PV. Biomass potential was assessed by analyzing agricultural residue generation, forest-based biomass availability, and agro-processing by-products, producing an estimated energy potential of 1200 to 1500 MW annually. Small hydro potential of around 300 MW was identified by studying river discharge patterns, elevation gradients, and micro-hydel feasibility in hilly regions such as Bastar and Sarguja. Wind resource assessment used National Institute of Wind Energy (NIWE) datasets, indicating moderate wind speeds of 5 to 5.8 m/s at 100 m height in northern districts, suitable for hybrid systems [13].

Energy Demand Forecasting

Future electricity demand for the period 2025 to 2035 was forecast using multi-variable regression models incorporating population growth, industrial expansion, urbanization, and historical consumption patterns. Chhattisgarh's electricity consumption has increased from 38 TWh in 2010 to nearly 75 TWh in 2024, primarily driven by industrial clusters such as Raigarh, Korba, and Bhilai. By integrating GDP growth rates, manufacturing output trends, and expected expansion in steel and mining sectors, the model predicts that electricity demand will rise to 95 to 105 TWh by 2035. This forecast provides the foundation for evaluating whether renewable energy can meet the future demand while reducing carbon intensity [14].

Scenario Development

Three distinct scenarios were developed to evaluate possible energy transition pathways: Business-as-Usual (BAU), Moderate Transition (MT), and Aggressive Green Transition (AGT). The BAU scenario assumes minimal policy changes and continued reliance on coal, resulting in limited renewable integration. The MT scenario incorporates moderate investments in solar and biomass, supported by partial grid upgrades, leading to a more balanced energy mix. The AGT scenario represents an ambitious shift characterized by large-scale solar deployment exceeding 10 GW, biomass expansion to 1.2 GW, integration of 1.5 GWh of energy storage, and modernization of transmission networks to support a renewable-dominant grid. These scenarios provide insight into the environmental, economic, and technical implications of different energy policy decisions [15].

Modeling Techniques and Analytical Tools

The study employed a linear optimization model to determine the least-cost energy mix while ensuring supply reliability and meeting projected demand. Emission factor analysis was used to calculate carbon footprints across energy sources, using standardized emission coefficients such as 0.98 kg CO_2/kWh for coal, 0.05 kg CO_2/kWh for solar, and 0.18 kg CO_2/kWh for biomass. Cost modeling incorporated capital expenditure

(CAPEX), operational expenditure (OPEX), discount rates, and plant load factors to compute the levelized cost of electricity (LCOE), revealing that solar PV (₹2.75/kWh) is increasingly cost-competitive compared to coal (₹4.5/kWh). GIS-based mapping and climate simulations further supported site selection for renewable installations [16].

Evaluation Metrics and Sensitivity Analysis

To assess each scenario's impact and robustness, multiple evaluation metrics were used, including renewable energy penetration, annual carbon emission reduction, system cost, storage requirements, and industrial supply reliability. A sensitivity analysis was performed by varying solar installation costs (±15%), biomass feedstock prices (±20%), battery storage costs (±10%), and projected demand (±8%) to test the resilience of the model under uncertainty. This analysis ensured that the findings remain valid even under changing economic, technological, or environmental conditions [17].

4. Statistical Data and Renewable Energy Potential

The current energy landscape of Chhattisgarh reflects a significant imbalance between thermal and renewable sources, shaped by the state's industrial dominance and heavy reliance on coal-based electricity. As of 2024, the state possesses an estimated installed capacity of nearly 14000 MW, of which approximately 11500 MW is generated from coal-fired thermal power plants. This accounts for almost 82% of the total energy mix, establishing Chhattisgarh as a major electricity supplier to neighboring states. Annual electricity generation ranges between 75 and 80 TWh, and per capita consumption exceeds the national average due to the high presence of energy-intensive industries such as steel, cement, mining, and aluminum processing. Industrial activity alone constitutes almost 60% of the state's total electricity consumption, creating a continual demand for reliable, high-load energy supply [18]. Despite this heavy dependence on fossil fuels, Chhattisgarh possesses vast renewable energy potential, particularly in solar and biomass sectors. Solar energy potential is especially promising due to the state's climatic profile, with most districts receiving 5 to 5.5 kWh/m²/day of solar insolation and enjoying more than 300 sunny days per year. Districts such as Janjgir-Champa, Bilaspur, Raipur, and Baloda Bazar have been identified through GIS mapping as high-intensity solar zones capable of supporting large-scale solar parks, yielding a technical potential estimated at 24000 MW. Biomass energy also presents a strong opportunity, supported by the state's robust agricultural output. Chhattisgarh generates 6 to 7 million tonnes of agricultural residue annually, particularly from rice, sugarcane, and maize cultivation, translating into an estimated 1200 to 1500 MW of biomass-based power potential when accounting for surplus availability and conversion efficiencies [19]. Small hydropower and wind resources, though smaller in scale, contribute additional diversity to the renewable energy portfolio. The river systems in northern and southern Chhattisgarh, particularly in Sarguja and Bastar, offer approximately 300 MW of small hydro potential, based on assessments of river discharge patterns, topography, and seasonal flow variations. Wind energy potential, while moderate due to average wind speeds of 5 to 5.8 m/s at 100-meter hub height, can still support hybrid solar-wind microgrids in selected northern districts. Waste-to-energy potential is estimated at around 200 MW, driven by urban waste streams in Raipur, Durg, Bhilai, and Korba.

Table 1: Current Installed Capacity in Chhattisgarh (2025, Approx.)

Energy Source	Installed Capacity (MW)	Share (%)
Thermal (Coal)	11500	82%
Hydro	1250	9%
Solar	900	6%
Biomass	300	2%
Wind	50	1%
Total	**14000**	**100%**

Table 2: Estimated Renewable Energy Potential in Chhattisgarh

Renewable Source	Potential (MW)	Utilization Feasibility (%)
Solar PV	24,000	60
Biomass	1,500	55
Small Hydro	300	50
Wind	800	40
Waste-to-Energy	200	70

Collectively, the statistical and resource assessment data demonstrate that Chhattisgarh has the renewable capacity to significantly alter its energy mix over the next decade. While the state continues to rely heavily on coal for industrial energy security, the vast renewable reserves particularly solar and biomass present a realistic pathway to reduce carbon emissions, diversify generation sources, and transition toward a low-carbon energy future [20]. These quantified potentials form the basis for scenario modeling in the subsequent sections, enabling an evidence-driven evaluation of Chhattisgarh's sustainable energy transition.

Table 3: Scenario Comparison Summary

Parameter	BAU 2035	MT 2035	AGT 2035
Renewable Share (%)	24	41	63
Installed Solar (MW)	3500	7000	10000
CO_2 Emission Reduction (%)	8	30	55
Levelized Cost of Energy (₹/kWh)	4.8	4.2	3.7
Energy Storage Capacity (GWh)	0.2	0.7	1.5

5. Scenario Modeling and Results

The scenario modeling for Chhattisgarh's energy transition was carried out to evaluate the potential impacts of different renewable deployment strategies on the overall energy mix, carbon emissions, and long-term sustainability. Three scenarios Business-as-Usual (BAU), Moderate Transition (MT), and Aggressive Green Transition (AGT) were developed to capture the range of possible outcomes depending on policy direction, financial investments, and technological availability. Each scenario incorporates projected energy demand for 2035 (estimated at 95 to 105 TWh), renewable resource availability, cost trends, grid readiness, and potential industrial decarbonization measures [21]. The modeling framework combines statistical projections with optimization outputs to quantify how renewable integration shapes Chhattisgarh's future energy landscape. In the *Business-as-Usual (BAU)* scenario, the state continues its current pattern of high coal dependency with limited renewable expansion. Although solar and biomass capacities increase modestly due to natural market growth, coal remains the dominant source accounting for well over 70% of electricity generation by 2035. As a result, renewable penetration rises only marginally from 18% in 2024 to around 24% in 2035. Emission reductions are minimal, estimated at only 8 to 10%, primarily due to efficiency improvements in existing thermal plants rather than structural changes in the energy mix. This scenario highlights that without policy interventions, environmental pressures and industrial pollution levels will continue to escalate [22]. The *Moderate Transition (MT)* scenario envisions a more balanced and strategically guided approach to renewable adoption. Here, solar capacity expands to approximately 7,000 MW, biomass increases to around 700 MW, and small hydro receives moderate investment. This diversification, along with partial grid modernization, enables renewables to supply around 41% of the state's electricity by 2035. As a result, CO_2 emissions decline by 30 to 32%, reflecting a meaningful though not transformative environmental improvement. The MT scenario demonstrates that even moderate policy action, such as renewable purchase obligations, financial incentives, and improved land acquisition processes, can significantly reshape the energy landscape and reduce carbon intensity [23].

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The *Aggressive Green Transition (AGT)* scenario represents the most ambitious and environmentally beneficial pathway. It assumes large-scale deployment of solar power exceeding 10000 MW, expansion of biomass-based generation to nearly 1200 MW, and upgrades to the existing hydropower network to add around 200 MW of additional capacity. Critical to this scenario is the integration of approximately 1.5 GWh of battery storage, enabling effective management of renewable intermittency and ensuring supply reliability for energy-intensive industries. Together, these measures elevate the renewable share of the energy mix to 60 to 65% by 2035. The AGT scenario delivers the highest environmental benefits, achieving a projected reduction of 48 to 55% in carbon emissions [24]. Moreover, the enhanced share of decentralized systems such as agricultural biomass plants and distributed solar strengthens rural development and reduces transmission losses. Finally, the results clearly demonstrate that Chhattisgarh's renewable energy potential, especially in solar and biomass, can drive substantial carbon reduction and reshape the state's energy economy [25]. The AGT scenario emerges as the most sustainable option, though the MT scenario also provides significant improvements with comparatively lower investment needs. These findings underscore the critical role of policy frameworks, financial instruments, and grid modernization in enabling a successful low-carbon transition. The modeling outcomes form the basis for strategic recommendations presented in the subsequent discussion and conclusion sections [26].

6. Discussion

The scenario analysis clearly illustrates that Chhattisgarh's transition to a low-carbon energy system is both technically feasible and environmentally essential [27]. The state's rich solar irradiance, extensive agricultural biomass availability, and moderate small hydropower resources provide a strong foundation for renewable energy expansion. The results highlight a sharp contrast between the Business-as-Usual (BAU) pathway and the two transition-oriented scenarios. Under BAU, reliance on coal remains high, and renewable energy penetration increases only marginally, resulting in minimal reductions in greenhouse gas emissions [28]. This indicates that without proactive policy interventions, the state will continue to face escalating environmental pressures, including air pollution, land degradation from mining activities, and rising health concerns in industrial regions such as Korba and Raigarh. The BAU scenario underscores that economic growth driven by traditional energy sources is unsustainable and incompatible with India's long-term climate commitments [29]. In contrast, the Moderate Transition (MT) scenario demonstrates that even incremental progress supported by moderate policy measures, improved land acquisition mechanisms, and streamlined approval processes can significantly alter the energy landscape [30]. The increase in solar capacity to around 7,000 MW and the expansion of biomass-based power generation lead to a 41% renewable share by 2035, accompanied by a substantial 30 to 32% reduction in carbon emissions. This scenario shows that with targeted interventions, existing infrastructure can be complemented rather than completely overhauled, allowing a smoother transition for industries, communities, and the power sector [31].

The Aggressive Green Transition (AGT) scenario represents the highest-impact pathway, offering the strongest potential for long-term sustainability. Large-scale integration of solar, biomass, upgraded hydropower, and battery storage not only elevates renewable penetration to over 60% but also significantly improves grid stability. The addition of 1.5 GWh of storage ensures that industrial consumers who rely heavily on uninterrupted, high-quality power can shift toward renewable energy without compromising productivity [32]. The AGT scenario also supports decentralized energy solutions, enabling rural communities to benefit from biomass plants, micro-hydel systems, and distributed solar rooftops. This decentralized model aligns with global best practices for just transitions, providing economic opportunities while reducing transmission losses and strengthening local energy resilience [33]. The discussion reveals that the key enablers of Chhattisgarh's renewable transition include robust policy frameworks, financial incentives, grid modernization, and technological advancements such as battery storage and hybrid solar-biomass systems [34]. Investments in digital grid infrastructure, smart metering, and flexible energy scheduling will be essential to manage intermittent renewable generation. Furthermore, the state must prioritize environmental regulations, industrial emission controls, and sustainable land-use planning to ensure that renewable energy development does not conflict with ecological conservation or community welfare [35]. The findings confirm that Chhattisgarh's energy transition requires a coordinated and forward-looking approach that integrates technological feasibility, economic considerations, and socio-environmental priorities [36]. The modeled scenarios provide clear evidence that a renewable-based future is not only possible but economically and environmentally advantageous, offering a strategic pathway for the state to contribute meaningfully to India's national climate objectives [37].

7. Conclusion

This study demonstrates that Chhattisgarh possesses substantial renewable energy potential and is well-positioned to transition toward a low-carbon and sustainable energy mix over the next decade. Through an integrated modeling approach combining statistical analysis, resource assessment, and scenario simulations, it becomes clear that renewable energy particularly solar and biomass offers a practical and economically viable solution for reducing the state's overwhelming dependence on coal. Currently, coal accounts for nearly 82% of the state's electricity generation, contributing to high carbon emissions, environmental degradation, and air quality challenges in industrial corridors such as Korba, Raigarh, and Bhilai. However, the modeling results show that meaningful progress is achievable through targeted policy interventions, technological adoption, and strategic investment in renewable infrastructure. Among the three analyzed scenarios, the Aggressive Green Transition (AGT) scenario provides the most transformative pathway. By expanding solar capacity to over 10000 MW, enhancing biomass generation to approximately 1200 MW, upgrading hydropower facilities, and integrating 1.5 GWh of battery storage, the state could achieve a renewable share of 60 to 65% by 2035. This shift would reduce carbon emissions by nearly 48 to 55%, marking a significant step toward environmental sustainability and aligning with India's national commitment to achieving net-zero emissions by 2070. The Moderate Transition (MT) scenario also presents substantial benefits, demonstrating that even incremental progress through moderate policy support can elevate renewable penetration to 41% and reduce emissions by 30 to 32%. In contrast, the Business-as-Usual (BAU) scenario underscores the environmental and health risks of continuing on the current pathway, offering only marginal improvements in emissions and energy diversification. The findings emphasize that Chhattisgarh's energy transition will depend heavily on enabling factors such as grid modernization, affordable financing mechanisms, land-use planning, industrial decarbonization policies, and community-centered renewable projects. With its abundant solar irradiance, robust agricultural base, and increasingly favorable technological landscape, the state holds the capability to emerge as a renewable energy leader in central India. By adopting a long-term, integrated policy vision and leveraging its natural resources responsibly, Chhattisgarh can achieve a sustainable, resilient, and low-carbon energy future that supports both economic growth and environmental stewardship.

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