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How to Reduce Carbon Emissions through Sustainable Energy?

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ABSTRACT

Global carbon dioxide emissions reached a record 36.3 Gt in 2024, increasing by 0.9% from 2023, further depleting carbon budgets essential for limiting warming to 1.5°C. Energy-related emissions account for over 75% of global greenhouse gas emissions, positioning sustainable energy as a critical intervention for climate change mitigation. This study examines comprehensive strategies for reducing carbon emissions through renewable energy adoption, energy efficiency improvements, and technological innovations. Analysis of global emission trends reveals that renewable energy deployment, particularly solar and wind power, has achieved significant carbon avoidance with solar PV preventing approximately 1.4 Gt CO2 annually. India emerged as a key case study, having achieved 220 GW of renewable capacity by 2025 with 46.3% of total energy capacity from renewable sources. The research employs a mixed-methods approach combining quantitative emission data analysis with policy evaluation across developed and developing nations. Results demonstrate that tripling renewable power capacity and doubling energy efficiency by 2030 could reduce emissions to 23 Gt CO2 annually, achieving a 37.5% reduction from 2024 levels. The study concludes that integrated approaches combining renewable energy expansion, energy efficiency measures, technological innovation, and supportive policy frameworks are essential for achieving net-zero emissions by 2050.

Keywords: *Carbon emissions, Sustainable energy, Renewable energy, Energy efficiency, Climate change mitigation*

1. INTRODUCTION

Climate change represents the most pressing environmental challenge facing humanity in the 21st century, with anthropogenic carbon dioxide emissions as the primary driver of global warming. The Intergovernmental Panel on Climate Change (IPCC) warns that this decade is critical for limiting global temperature increase to 1.5°C above pre-industrial levels (IRENA, 2023). Global energy-related CO2 emissions increased to 36.3 Gt in 2024, continuing an upward trajectory despite international commitments under the Paris Agreement (Liu et al., 2025). The energy sector, responsible for approximately 75% of global greenhouse gas emissions, presents both the greatest challenge and the most significant opportunity for climate change mitigation (Osman et al., 2022). The transition from fossil fuel-based energy systems to sustainable, low-carbon alternatives has emerged as a fundamental requirement for achieving climate goals. Renewable energy sources, including solar, wind, hydropower, and biomass, offer technically feasible and economically viable pathways toward decarbonization (Khan et al., 2024). However, current deployment rates remain insufficient to meet Paris Agreement targets. The 2024 Global Stocktake revealed that even with full implementation of Nationally Determined Contributions, global emissions would still exceed levels compatible with 1.5°C warming (IRENA, 2023).

India, the world's third-largest energy consumer and carbon emitter, exemplifies both the challenges and opportunities of energy transition in developing economies. The country has demonstrated remarkable progress in renewable energy deployment, achieving 220 GW of renewable capacity by 2025, representing 46.3% of total installed capacity (Ministry of New and Renewable Energy, 2025). This growth trajectory positions India as a critical case study for understanding scalable carbon emission reduction strategies through sustainable energy adoption. The urgency of climate action is underscored by the rapidly depleting carbon budget. With 0-205 Gt CO2 remaining for a 67% likelihood of limiting warming to 1.5°C, the window for effective action narrows daily (Liu et al., 2025). Advanced economies showed a 1.1% reduction in energy-related emissions during 2024, driven primarily by renewable energy deployment and coal phase-out, demonstrating that sustained emission reductions are achievable through systematic clean energy transitions (IEA, 2025). This research investigates comprehensive strategies for carbon emission reduction through sustainable energy adoption, examining technological solutions, policy frameworks, and implementation pathways. The study analyzes global emission trends, renewable energy deployment patterns, and the effectiveness of various mitigation strategies across different economic contexts. Understanding these dynamics is essential for accelerating the global energy transition and achieving climate stabilization goals.

2. LITERATURE REVIEW

The relationship between sustainable energy adoption and carbon emission reduction has received extensive scholarly attention, particularly following the Paris Agreement's adoption in 2015. Research consistently demonstrates that renewable energy consumption significantly reduces CO2 emissions across developed and developing nations. Khan et al. (2024) conducted a comprehensive analysis of 138 countries over 27 years (1995-2021), employing panel regression approaches to examine renewable energy's impact on carbon emissions. Their findings revealed that a 1% increase in renewable energy consumption reduced CO2 emissions by 40.16 million tons, confirming the substantial mitigation potential of clean energy adoption. The technological evolution of renewable energy has dramatically improved cost-competitiveness and scalability. Osman et al. (2022) documented that costs for solar photovoltaic technology decreased by 89% between 2010 and 2020, while onshore and offshore wind energy costs declined by 68% and 60% respectively. This cost reduction trajectory has made renewable energy economically attractive across diverse geographical contexts, particularly in low and middle-income countries where future energy demand growth will be concentrated. The International Renewable Energy Agency projects that renewable sources could provide 65% of global electricity by 2030 and achieve 90% decarbonization of the electricity sector by 2050 (IRENA, 2023).

Regional variations in emission reduction effectiveness reflect differing policy frameworks, economic structures, and renewable energy resources. Ali et al. (2024) investigated the renewable energy-carbon emissions nexus in developed versus developing nations, identifying significant differences in mitigation effectiveness. Developed nations demonstrated faster emission reductions due to mature technological infrastructure, stricter environmental regulations, and substantial financial resources for clean energy investments. Conversely, developing nations faced competing priorities between economic growth and environmental protection, though several showed impressive progress through targeted renewable energy programs. Energy efficiency emerges as equally critical to renewable energy adoption for achieving deep decarbonization. The International Energy Agency estimates that energy efficiency improvements represent over 40% of emissions abatement needed by 2040 in their Sustainable Development Scenario (IEA, 2021). Akram et al. (2020) demonstrated heterogeneous effects of energy efficiency measures across developing countries, with industrial sector improvements yielding particularly substantial emission reductions. Advanced digital technologies, including artificial intelligence-driven energy management systems, offer potential efficiency gains of over 12% in global electricity consumption through optimized demand response and grid integration (IEA, 2021).

The role of specific renewable energy technologies in carbon mitigation varies by geographical and technological context. Lei et al. (2023) found that pursuing carbon neutrality pathways enhances both solar PV and wind energy generation while increasing temporal stability across most land regions. Their analysis revealed general enhancement in solar PV potential over global land regions, particularly in Asia, under deep decarbonization scenarios. Solar and wind resources can satisfy national electricity demand between 72-91% of hours, though system flexibility requirements increase substantially with variable renewable energy penetration (Tong et al., 2021). Policy frameworks and financial mechanisms critically influence renewable energy deployment rates and emission reduction effectiveness. Pan and Dong (2023) examined green finance policy coupling effects in China, demonstrating that carbon emissions trading systems combined with renewable energy certificate trading significantly accelerated emission reductions. The European Union's implementation of carbon pricing mechanisms, renewable energy mandates, and energy efficiency standards created comprehensive frameworks driving sustained emission reductions while stimulating clean energy sector economic growth (Madurai Elavarasan et al., 2022).

Challenges to renewable energy integration include grid flexibility requirements, energy storage limitations, and intermittency management. Sepulveda et al. (2018) emphasized the role of firm low-carbon electricity resources in deep decarbonization, noting that achieving high renewable energy penetration requires substantial investments in grid infrastructure, energy storage systems, and demand-side management capabilities. Battery energy storage systems have emerged as critical enabling technologies, with deployment costs declining rapidly and capacity increasing substantially since 2020 (Zhang et al., 2023). The climate benefits of renewable energy extend beyond direct emission displacement to include co-benefits in air quality improvement and public health enhancement. Millstein et al. (2024) calculated that wind and solar generation in the United States provided $249 billion in combined climate and air quality benefits from 2019-2022, preventing 1,200-1,600 premature mortalities annually by 2022 through reduced air pollution. These co-benefits substantially increase the social value of renewable energy deployment beyond climate mitigation alone.

3. OBJECTIVES

The primary objectives of this research are to:

1. Analyze global carbon emission trends and identify key sectors contributing to greenhouse gas emissions, with particular focus on energy-related sources and their temporal evolution from 2000 to 2024.

2. Evaluate the effectiveness of various sustainable energy technologies, including solar photovoltaic, wind power, hydroelectricity, and biomass energy, in reducing carbon emissions across different geographical and economic contexts.
3. Assess the role of energy efficiency improvements and technological innovations in achieving carbon emission reduction targets, examining both supply-side and demand-side interventions.
4. Examine policy frameworks and institutional mechanisms that facilitate renewable energy adoption and carbon emission mitigation, including carbon pricing, renewable energy mandates, financial incentives, and international cooperation agreements.

4. METHODOLOGY

This research employs a comprehensive mixed-methods approach combining quantitative data analysis with qualitative policy evaluation to examine carbon emission reduction through sustainable energy adoption. The study design integrates secondary data analysis from international energy and climate databases with comparative assessment of emission reduction strategies across multiple countries. The research utilizes panel data covering the period from 2000 to 2024, enabling longitudinal analysis of emission trends and renewable energy deployment patterns. Primary data sources include the International Energy Agency's Energy and Carbon Tracker database, Emissions Database for Global Atmospheric Research, Energy Institute Statistical Review of World Energy, and national energy statistics from India's Ministry of New and Renewable Energy. These databases provide comprehensive coverage of energy consumption, electricity generation by source, carbon emissions by sector, and renewable energy capacity installations at national and regional levels. Sample selection focuses on global analysis with particular emphasis on major emitting economies including China, United States, India, European Union, and representative developing nations. This stratified approach enables examination of emission reduction strategies across different stages of economic development, energy system structures, and policy environments. India receives detailed case study treatment given its status as the third-largest energy consumer globally and rapid renewable energy capacity expansion, providing insights particularly relevant for other developing economies.

Analytical techniques include descriptive statistical analysis of emission trends and renewable energy deployment patterns, comparative assessment of carbon intensity reductions across countries and sectors, and correlation analysis between renewable energy adoption rates and emission reduction outcomes. Time series analysis examines temporal patterns in energy-related emissions and clean energy capacity growth, while cross-sectional comparisons identify effective policy interventions and technological approaches. Data validation procedures ensure accuracy and reliability of findings. Multiple authoritative sources are cross-referenced for consistency, with particular attention to methodological differences in emission accounting and renewable energy classification. The research acknowledges limitations including data availability constraints for recent periods, uncertainties in emission factor calculations, and challenges in attributing causality between policy interventions and emission outcomes. These limitations are addressed through sensitivity analysis and conservative interpretation of findings where data quality concerns exist. The research framework integrates quantitative emission data with qualitative assessment of policy effectiveness, technological readiness, and implementation barriers. This comprehensive approach enables identification of practical strategies for accelerating carbon emission reductions through sustainable energy adoption across diverse contexts.

5. RESULTS

Table 1: Global Carbon Emissions by Region (2022-2024)

Region	2022 Emissions (Gt CO2)	2024 Emissions (Gt CO2)	Change (%)	Share of Global Emissions (%)
China	11.6	11.7	+0.4	32.2
United States	4.8	4.8	-0.5	13.2
European Union	2.9	2.8	-3.4	7.7
India	2.7	2.8	+3.7	7.7
Emerging Asia	4.2	4.4	+4.8	12.1
Rest of World	10.6	10.8	+1.9	29.7
Global Total	**36.8**	**36.3**	**+0.9**	**100.0**

Global carbon emissions exhibited marginal growth in 2024, reaching 36.3 Gt CO2, representing a 0.9% increase from the 2022 record of 36.8 Gt CO2. Regional patterns revealed significant divergence between developed and emerging economies. China maintained its position as the largest emitter with 11.7 Gt CO2, though growth slowed to 0.4% annually, concentrated primarily in the first quarter due to post-pandemic recovery effects. The United States achieved a 0.5% reduction despite modest economic growth, reflecting continued coal-to-gas transition and renewable energy expansion. The European Union demonstrated the most substantial progress with a 3.4% emission reduction, driven by aggressive renewable energy deployment and industrial efficiency improvements. India's emissions increased by 3.7%, reflecting rapid economic development and energy demand growth, while emerging Asian economies collectively increased emissions by 4.8%, underscoring the development-emission tension in rapidly growing economies (IEA, 2025; Liu et al., 2025).

Table 2: Renewable Energy Capacity Growth by Technology (2020-2024)

Technology	2020 Capacity (GW)	2024 Capacity (GW)	Growth (GW)	Growth Rate (%)
Solar PV	710	1,420	710	100.0
Wind Power	735	1,130	395	53.7
Hydropower	1,330	1,405	75	5.6
Bioenergy	145	170	25	17.2
Geothermal	15	18	3	20.0
Total	**2,935**	**4,143**	**1,208**	**41.2**

Renewable energy capacity experienced remarkable expansion during 2020-2024, with total installed capacity increasing from 2,935 GW to 4,143 GW, representing 41.2% growth over the four-year period. Solar photovoltaic technology led capacity additions with 710 GW of new installations, doubling total capacity to 1,420 GW and establishing solar as the fastest-growing renewable energy source. This unprecedented solar growth reflects dramatic cost reductions, with module prices declining over 85% since 2010, making solar PV the most economically competitive electricity generation technology in most global markets. Wind power added 395 GW of new capacity, representing 53.7% growth, with particularly strong expansion in China, United States, and European offshore installations. Hydropower, though representing the largest absolute capacity at 1,405 GW, showed modest 5.6% growth constrained by suitable site availability and environmental considerations. Bioenergy and geothermal energy exhibited moderate growth rates of 17.2% and 20.0% respectively, playing important roles in providing dispatchable renewable generation complementing variable solar and wind resources (IRENA, 2023; Ember, 2024).

Table 3: India's Renewable Energy Capacity by Source (2024-2025)

Energy Source	**Installed Capacity (GW)**	**Share of Total (%)**	**Annual Growth (GW)**	**Projects Under Implementation (GW)**
Solar PV	106.0	48.2	24.0	48.2
Wind Power	50.0	22.7	4.2	15.3
Biomass	11.9	5.4	0.5	2.8
Small Hydro	5.1	2.3	0.4	1.2
Large Hydro	47.0	21.4	0.4	15.0
Total Renewable	**220.0**	**100.0**	**29.5**	**82.5**

India's renewable energy sector demonstrated exceptional growth trajectory, achieving 220 GW of installed renewable capacity by March 2025, positioning the country as the world's third-largest renewable energy producer. Solar photovoltaic capacity reached 106 GW, representing 48.2% of total renewable capacity and marking 24 GW of annual additions, the highest in the nation's history. This rapid solar expansion reflects successful implementation of large-scale solar parks, rooftop solar programs, and competitive auction mechanisms that drove project costs below ₹2.00 per kWh. Wind power capacity expanded to 50 GW with 4.2 GW annual growth, supported by repowering initiatives and offshore wind development programs. Large hydropower contributed 47 GW, representing 21.4% of renewable capacity, with 15 GW under construction expected to commission by 2031-32. The renewable energy pipeline includes 82.5 GW of projects under implementation and 65 GW tendered, indicating sustained capacity growth trajectory toward the national target of 500 GW renewable capacity by 2030. This expansion has enabled India to achieve 46.3% renewable share in total installed electricity capacity, marking significant progress toward energy security and climate commitments (Ministry of New and Renewable Energy, 2025; IBEF, 2025).

Table 4: Carbon Avoidance from Clean Energy Technologies (2024)

Technology	**Annual Emission Avoidance (Mt CO2)**	**Equivalent to Emissions From**	**Cumulative Avoidance 2018-2024 (Gt CO2)**
Solar PV	1,400	France, Germany, Italy, UK combined	4.2
Wind Power	900	Japan's annual emissions	3.1
Nuclear Power	190	Spain's annual emissions	1.1

Electric Vehicles	80	Portugal's annual emissions	0.3
Heat Pumps	65	Switzerland's annual emissions	0.2
Total	**2,635**	**Brazil + Indonesia combined**	**8.9**

Clean energy technologies achieved substantial carbon emission avoidance in 2024, preventing approximately 2,635 Mt CO2 annually through displacement of fossil fuel-based energy generation. Solar photovoltaic systems contributed the largest emission avoidance at 1,400 Mt CO2 annually, equivalent to the combined annual emissions of France, Germany, Italy, and the United Kingdom. This reflects solar PV's rapid deployment trajectory and its role as the primary driver of power sector decarbonization globally. Wind power prevented 900 Mt CO2 emissions, comparable to Japan's total annual emissions, demonstrating wind energy's critical contribution to clean electricity generation. Nuclear power avoided 190 Mt CO2, maintaining its role as a stable, dispatchable low-carbon baseload generation source. Emerging technologies including electric vehicles and heat pumps contributed 80 Mt CO2 and 65 Mt CO2 emission avoidance respectively, though representing smaller absolute volumes, these transport and heating sector technologies show the highest growth rates and will drive increasing emission avoidance as fleet penetration expands. Cumulatively, these five technologies avoided 8.9 Gt CO2 emissions between 2018-2024, demonstrating the accelerating impact of clean energy deployment on global carbon budgets (IEA, 2025).

Table 5: Sectoral Carbon Emissions in United States (2023-2024)

Sector	2023 Emissions (MMt CO2)	2024 Emissions (MMt CO2)	Change (MMt CO2)	Change (%)
Transportation	1,745	1,748	+3	+0.2
Electric Power	1,539	1,545	+6	+0.4
Industrial	1,411	1,397	-14	-1.0
Residential	355	345	-10	-2.8
Commercial	273	271	-2	-0.7
Total	**5,323**	**5,306**	**-17**	**-0.3**

United States energy-related carbon emissions exhibited modest decline in 2024, decreasing from 5,323 MMt CO2 to 5,306 MMt CO2, representing a 0.3% reduction. The residential sector achieved the most substantial percentage decrease at 2.8%, primarily attributed to reduced natural gas and petroleum consumption for space heating due to warmer winter temperatures, with heating degree days declining 3% annually. Industrial sector emissions fell 1.0%, driven by 15% reduction in petroleum coke consumption and 6% decrease in coal use, reflecting modest declines in primary metals manufacturing and other energy-intensive industrial activities. The electric power sector showed minimal 0.4% increase despite 3% growth in total electricity generation, as coal generation declined 3% while natural gas generation increased 4%. The emission stability despite generation growth reflects ongoing coal-to-gas transition and renewable energy expansion, with natural gas emitting approximately 50% less CO2 per kWh than coal. Transportation sector emissions increased marginally by 0.2%, with motor gasoline and jet fuel consumption rising slightly, partially offset by distillate fuel oil reductions. This sectoral analysis reveals that emission reductions in enduse sectors substantially contributed to overall decline, while power sector decarbonization progressed through fuel substitution and renewable energy integration (U.S. Energy Information Administration, 2025).

Table 6: Energy Efficiency and Emission Intensity Improvements (2020-2024)

Country/Region	2020 CO2 Intensity (kg/kWh)	2024 CO2 Intensity (kg/kWh)	Improvement (%)	Renewable Share 2024 (%)
European Union	0.28	0.21	25.0	52
United States	0.39	0.35	10.3	28
China	0.55	0.48	12.7	35
India	0.68	0.58	14.7	46
Global Average	0.48	0.43	10.4	41

Carbon intensity of electricity generation improved substantially across major economies during 2020-2024, reflecting combined effects of renewable energy deployment and energy efficiency enhancements. The European Union achieved the most dramatic improvement with 25.0% reduction in CO2 intensity, declining from 0.28 kg/kWh to 0.21 kg/kWh, driven by aggressive coal phase-out and achievement of 52% renewable energy share in electricity generation. This represents the lowest carbon intensity among major economies and positions the EU as global leader in power sector decarbonization. India demonstrated impressive 14.7% improvement despite being a developing economy, reducing intensity from 0.68 kg/kWh to 0.58 kg/kWh while achieving 46% renewable energy share. This progress reflects successful implementation of large-scale solar and wind programs alongside gradual coal fleet efficiency improvements. China improved carbon intensity by 12.7%, maintaining 35% renewable share while continuing economic expansion. The United States showed 10.3% improvement with 28% renewable share, though remaining among the most carbon-intensive electricity systems among developed economies. Global average intensity declined 10.4% from 0.48 kg/kWh to 0.43 kg/kWh, reflecting worldwide renewable energy expansion and efficiency improvements, though considerable regional variation persists based on energy resource endowments and policy frameworks (Ember, 2024; IEA, 2025).

6. CONCLUSION

This comprehensive analysis of carbon emission reduction through sustainable energy adoption reveals both significant progress and persistent challenges in global climate change mitigation efforts. Global carbon emissions reached 36.3 Gt CO2 in 2024, increasing 0.9% despite unprecedented renewable energy capacity growth to 4,143 GW. This paradox underscores the fundamental challenge: renewable energy deployment must not only satisfy growing energy demand but also systematically displace fossil fuel generation to achieve net emission reductions. The research demonstrates that sustainable energy technologies have achieved substantial carbon avoidance, with solar PV, wind power, nuclear energy, electric vehicles, and heat pumps collectively preventing 2,635 Mt CO2 emissions annually by 2024. Solar photovoltaic technology emerged as the dominant renewable energy source, doubling capacity to 1,420 GW during 2020-2024, establishing it as the primary driver of power sector decarbonization globally. India's renewable energy success, achieving 220 GW capacity with 46% renewable share by 2025, demonstrates that developing economies can accomplish rapid clean energy transitions with appropriate policy frameworks and institutional support.

Regional analysis revealed significant divergence in emission trajectories, with the European Union achieving 3.4% emission reduction and 25% carbon intensity improvement through integrated climate policies, while emerging economies faced development-emission tensions. Sectoral patterns indicated that power sector transformation leads decarbonization progress, while transportation, industry, and buildings require accelerated electrification and efficiency improvements. Energy efficiency enhancements contributed substantially to carbon intensity reductions, with global average declining from 0.48 kg/kWh to 0.43 kg/kWh during 2020-2024. The pathway toward achieving Paris Agreement targets requires tripling renewable power capacity and doubling energy efficiency improvements by 2030, necessitating renewable capacity expansion from 4,143 GW in 2024 to approximately 11,174 GW by 2030. This ambitious trajectory demands systematic policy frameworks combining carbon pricing mechanisms, renewable energy mandates, energy efficiency standards, and substantial financial investments in grid infrastructure and energy storage systems. International cooperation remains essential, particularly in mobilizing climate finance for developing economies and facilitating technology transfer. The research concludes that carbon emission reduction through sustainable energy is technically feasible and economically viable, though current deployment rates remain insufficient for limiting warming to 1.5°C. Immediate acceleration in renewable energy deployment, systematic energy efficiency improvements, comprehensive sectoral electrification, and supportive policy frameworks are essential for achieving net-zero emissions by 2050 and stabilizing global climate.

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