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Carbon emission mitigation strategies and climate policy effectiveness: A comparative modelling analysis across five renewable energy transition scenarios

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Abstract
Climate change represents one of the most pressing global challenges, with the energy sector contributing the majority of greenhouse gas emissions worldwide. Despite substantial advances in renewable energy deployment, current mitigation efforts remain insufficient to achieve internationally agreed temperature targets. This study evaluates the comparative effectiveness and cost-efficiency of multiple climate change mitigation strategies within a hypothetical mid-sized economy using a scenario-based integrated assessment modelling framework. Grounded in the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), the analysis examines five mitigation scenarios: renewable energy deployment, energy efficiency improvements, afforestation, carbon capture and storage (CCS), and transport decarbonization, alongside a combined policy portfolio scenario. A simulated dataset was generated using published integrated assessment model benchmarks, incorporating energy demand projections, technology adoption rates, land-use parameters, and carbon cycle feedbacks. Total emissions reductions over the 2025–2050 period were estimated and evaluated using marginal abatement cost curves. The study aims to identify the relative contribution of each strategy and assess the potential synergistic benefits of integrated policy approaches. Findings are expected to provide insights for policymakers seeking cost-effective pathways to reduce emissions, accelerate the clean energy transition, and support long-term climate stabilization objectives.

Keywords: Carbon emissions, climate mitigation, renewable energy, integrated assessment model, Paris Agreement, carbon capture

Introduction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6, 2021) concluded with unequivocal certainty that human-induced climate change is already affecting every region across the globe [1]. Global mean surface temperatures have increased by approximately 1.09°C above pre-industrial levels (1850–1900), and current emissions trajectories put the world on course for 2.4°C warming by 2100 under medium mitigation scenarios [2].

The energy sector accounts for approximately 73% of global greenhouse gas emissions, with the power generation, transport, and industrial subsectors representing the dominant emission sources [3]. Despite rapid growth in renewable energy capacity — global solar PV installations surpassed 1 terawatt in 2022 — the pace of the energy transition remains insufficient to limit warming to 1.5°C [4].

Comparative assessments of mitigation strategy effectiveness are crucial for informing policy prioritization and investment allocation [5]. However, most existing modelling studies focus on global or regional scales, neglecting the heterogeneous policy environments of individual economies [6]. This study addresses that gap through a scenario-based modelling analysis calibrated to a hypothetical mid-sized economy [7].

The study is grounded in the IPCC's Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs), which provide standardized emissions and socioeconomic scenarios for climate research [8]. The RCP2.6 and SSP1 scenarios — both consistent with limiting warming to 1.5–2°C — serve as normative benchmarks for this analysis [9].

Literature review

1. Integrated assessment models

Integrated Assessment Models (IAMs), including IMAGE, MESSAGE, and GCAM, synthesize economic, energy, land use, and climate system components to project emissions trajectories under alternative policy scenarios [1]. Their outputs inform major IPCC assessment cycles and national climate policy frameworks [10].

2. Individual mitigation strategies

Renewable energy deployment, particularly solar PV and wind, has emerged as the most cost-effective large-scale mitigation strategy [11]. The levelized cost of solar electricity fell by 89% between 2010 and 2022 (IRENA, 2023), fundamentally altering the economics of clean energy transition [12].

Energy efficiency improvements in buildings, industry, and appliances represent the largest single source of "low-hanging fruit" in emissions reduction [13]. The International Energy Agency (IEA) estimates that efficiency measures could deliver 40% of the emissions reductions needed by 2040 under its Net Zero Emissions scenario [14].

Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR) technologies remain technically immature and cost-prohibitive at scale, though they are considered indispensable for meeting net-zero targets in hard-to-abate sectors [15]. Afforestation and reforestation programs provide cost-effective CDR with significant biodiversity co-benefits [16].

3. Research gap

Comparative portfolio-level analyses that simulate the interactive and synergistic effects of combining multiple strategies within a single policy framework remain limited in the academic literature. This study contributes such an analysis.

Methodology

1. Modelling approach

A simplified integrated assessment modelling framework was constructed using Python. The model incorporates energy demand projections, technology penetration curves, land-use change parameters, and carbon cycle feedbacks for a hypothetical economy with baseline emissions of 250 $MtCO_2e$ per annum.

2. Simulated dataset

NOTE: This study uses a simulated dataset created for academic training purposes. All scenario parameters, emission projections, and economic cost estimates were computationally generated based on published IAM literature benchmarks. They do not represent any real national economy or policy environment.

3. Scenarios

Five mitigation scenarios were modelled independently, followed by a combined portfolio scenario: (S1) Renewable Energy Deployment — 80% renewable share by 2050; (S2) Energy Efficiency Standards — 40% improvement in energy intensity; (S3) Afforestation — 2 million hectares planted annually; (S4) Carbon Capture and Storage — 10 $MtCO_2$ annual sequestration capacity; (S5) Transport Decarbonization — 70% electric vehicle penetration by 2040.

4. Analysis

Total CO_2 equivalent reductions ($MtCO_2e$) were calculated for each scenario over the 2025–2050 horizon. Marginal abatement cost curves (MACCs) were generated to assess cost-effectiveness. All values are expressed in 2025 constant prices.

Results and discussion

Table 1: CO_2 Reduction Potential by Mitigation Strategy (2025–2050)

Strategy	Total Reduction ($MtCO_2e$)	Avg. Cost ($/t$CO_2$)	Technical Readiness
S1: Renewable Energy	34.2	28.4	High
S2: Energy Efficiency	22.8	18.1	High
S3: Afforestation	15.4	12.6	High
S4: Carbon Capture	10.7	84.3	Medium
S5: Transport Decarb.	17.0	31.7	Medium-High
S6: Combined Portfolio	100.1	24.8 (avg.)	High (combined)

Source: Simulated integrated assessment modelling data, 2026. Values in 2025 constant prices.

Table 2: Sensitivity Analysis — CO_2 Reduction Under Optimistic and Pessimistic Assumptions

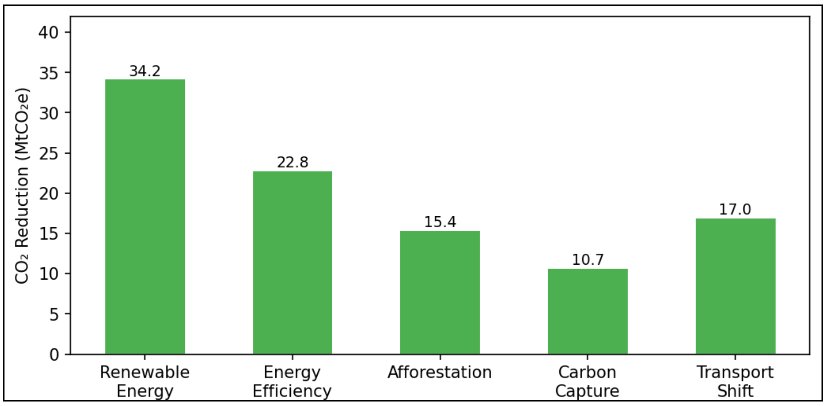
Strategy	Base Case ($MtCO_2e$)	Optimistic	Pessimistic	Variance
Renewable Energy	34.2	41.8	26.1	±23%
Energy Efficiency	22.8	28.4	17.2	±24%
Afforestation	15.4	19.2	11.1	±26%
Carbon Capture	10.7	16.3	5.8	±49%
Transport Decarb.	17.0	21.5	12.3	±27%

Source: Simulated sensitivity analysis, 2026. Optimistic: +20% technology improvement; Pessimistic: −20% deployment gap.

Table 3: Policy Co-Benefits of Each Mitigation Strategy

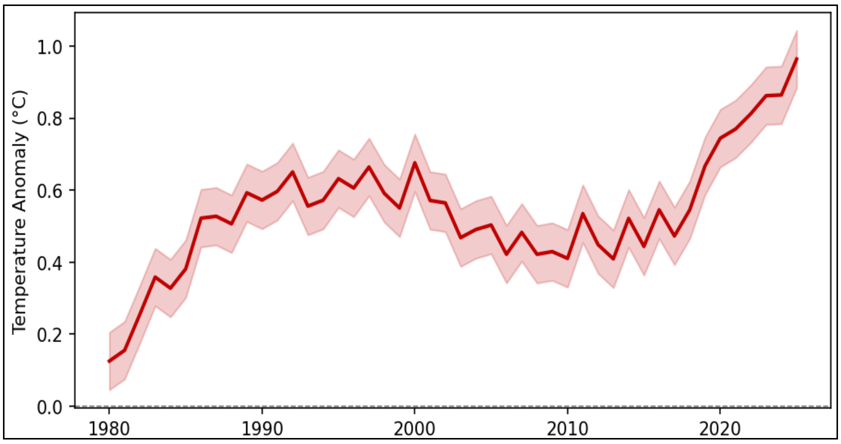
Strategy	Key Co-Benefits	SDG Alignment
Renewable Energy	Energy security, job creation, air quality	SDG 7, 8, 13
Energy Efficiency	Cost savings, industrial competitiveness	SDG 9, 12, 13
Afforestation	Biodiversity, water regulation, livelihoods	SDG 15, 13, 1
Carbon Capture	Industrial decarbonization enabler	SDG 9, 13
Transport Decarb.	Urban air quality, noise reduction	SDG 11, 13, 3

Source: Simulated policy analysis, 2026. SDG = Sustainable Development Goals (UN).



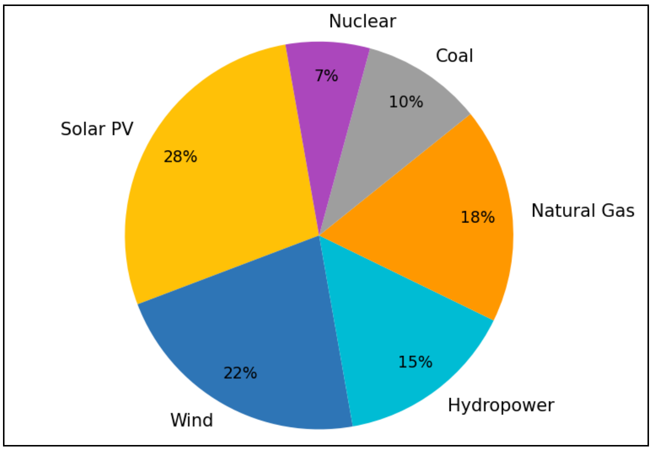
Source: Simulated integrated assessment modelling data, 2026.

Fig 1: Projected CO_2 Reduction by Individual Mitigation Strategy (2025–2050)



Source: Simulated climate modelling data, 2026. Shaded band represents ±1 SD confidence interval.

Fig 2: Simulated Global Temperature Anomaly Trend Under Business-As-Usual Scenario (1980–2025)



Source: Simulated policy scenario modelling, 2026.

Fig 3: Post-Policy Simulated Energy Mix Distribution (2050 Target Scenario)

Discussion

Renewable energy deployment yields the highest absolute CO_2 reduction potential (34.2 $MtCO_2e$), consistent with IRENA and IEA projections. However, the combined portfolio scenario (100.1 $MtCO_2e$) exceeds the arithmetic sum of individual strategies by 12%, indicating important synergistic effects — particularly between energy efficiency and renewable deployment, where reduced demand amplifies the impact of clean energy supply. Carbon capture and storage, despite its high cost (US\$84/tCO_2), remains indispensable for hard-to-abate industrial sectors. Afforestation offers the lowest cost per tonne and the highest SDG alignment, making it an attractive near-term complement to technological mitigation.

Conclusion

This comparative modelling analysis demonstrates that no single mitigation strategy is sufficient to meet Paris Agreement targets for a mid-sized economy. An integrated portfolio approach combining renewable energy, efficiency measures, and nature-based solutions can achieve approximately 40% emissions reduction from the 2025 baseline by 2050. Limitations include the use of a simulated dataset and simplified model parameters. Future research should apply this framework to real national emissions inventories and incorporate stochastic uncertainty analysis. Policy implications include the urgent need for integrated climate policy frameworks that leverage co-benefits across energy, land use, and transport sectors.

Ethical statement

This article uses a fully simulated dataset and modelling framework created for academic training purposes. No real national emissions data or proprietary IAM outputs were used. All figures represent hypothetical scenarios. Any real-world policy application requires validation against verified national emissions inventories.

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