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Ambition versus Historically Grounded Transition Feasibility: Structural Constraints in Carbon-Budget Pathways

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Abstract

Decarbonization is increasingly constrained by finite cumulative carbon budgets and by the speed of structural and technological change. This study evaluates the conditional structural viability of Reference, 1.5 °C, 2 °C, NDC, and Energy Justice pathways across ten world regions. Region-specific baseline trajectories for population, GDP, primary energy consumption, and CO₂ emissions are generated through an out-of-sample evaluated multi-model forecasting framework. Mitigation pathways are then constructed through iterative scaling under historically calibrated annual transition bounds and assessed using rolling Cobb–Douglas diagnostics, emissions-intensity decomposition, and technology-specific mitigation matching. The results show that the 1.5 °C-oriented pathway remains substantially above its adopted 276 GtCO₂ budget and retains unmet mitigation under all technology-deployment assumptions. The NDC pathway also remains technologically incomplete, whereas Energy Justice approaches high coverage under recent and medium-term deployment rates but retains residual implementation gaps. The modeled 2 °C pathway shows near-complete coverage of the gross positive region-year mitigation requirement across the three deployment assumptions; however, cumulative emissions remain slightly above the adopted 978 GtCO₂ budget. Gross technology-matching requirements are therefore distinguished from the net global cumulative emissions difference.

Keywords: Carbon budget, Decoupling, Dynamic Cobb-Douglas, Mitigation viability.

1. Introduction

Decarbonization can no longer be considered solely as a long-term climate-policy objective; it must also be assessed in terms of the structural viability of the transition required to achieve it. In 2024, global fossil fuel and industrial CO₂ emissions reached approximately 37.8 GtCO_{2eq}, while the global mean atmospheric CO₂ concentration measured at Mauna Loa was about 424.6 ppm.

Preliminary estimates indicate that global fossil CO₂ emissions increased further to approximately 38.1 GtCO₂ in 2025. Against this background, the IPCC AR6 assessed remaining carbon budgets from the beginning of 2020 of approximately 500 GtCO₂ for a 50% likelihood of limiting warming

to 1.5 °C and 1,150 GtCO₂ for a 67% likelihood of limiting warming to 2 °C. Both estimates are subject to an uncertainty of approximately ± 220 GtCO₂ associated primarily with future non-CO₂ forcing .

Using the AR6 remaining-budget estimates as the reference accounting framework, the budgets were translated to the 2026 model start by deducting beginning of 2020 of approximately 500 ± 220 GtCO₂ for 1.5 °C and 1150 ± 220 GtCO₂ for 2 °C like-for-like accounting basis. This yields operational 2026-2050 budgets of 276 and 978 GtCO₂ for the selected 1.5 °C and 2°C likelihood definitions, respectively . Because remaining carbon budgets depend on the accounting start date, warming likelihood, non-CO₂ forcing, and Earth-system uncertainty, updated January-2026 estimates are evaluated separately as a sensitivity benchmark rather than treated as directly interchangeable with the AR6-derived budgets.

The stringency of a mitigation pathway can be represented by the cumulative emissions reduction required relative to the Reference trajectory and, for temperature-oriented pathways, by the associated cumulative carbon budget. Whether that objective can be approached, however, also depends on the rates at which energy, technological, and economic systems can adjust. Strategies consistent with limiting warming to 1.5°C or 2°C require rapid, deep, and sustained reductions in emissions .

However, the speed of this transition is constrained by socio-technical inertia, path dependence, and capital-stock lock-in. Long-lived physical assets, slow technology diffusion, and persistent institutional arrangements can limit the rate at which energy systems adjust. Overcoming this structural inertia is hindered by the long operational lifetimes of physical assets, slow technology diffusion rates, and institutional path dependency. While adaptation is becoming more essential to address inevitable climate effects, the extent of forthcoming impacts is heavily influenced by the intensity and timing of immediate mitigation efforts.

Integrated assessment models such as MESSAGE-ix-GLOBIOM, IMAGE, GCAM and REMIND provide comprehensive representation of the interactions among economic activity, energy demand, technology deployment, land use and climate policy . These frameworks underpin much of the scenario literature associated with the Shared Socioeconomic Pathways and the IPCC assessment process . Their emissions trajectories generally emerge from changes in energy systems, technology costs, production structures, land use and policy assumptions rather than from direct adjustments to aggregate emission factors .

Recent studies have incorporated multidimensional feasibility constraints into mitigation scenarios, including institutional, technological, and regional implementation limits. The present study does not model these dimensions separately . Instead, it uses region-specific historical rates of aggregate change as empirical proxies for the pace of structural adjustment . Accordingly, feasibility is interpreted here in a conditional and historically grounded sense rather than as a direct measure of governance or institutional capacity. Therefore, this study assesses the conditional structural compatibility of mitigation pathways with historically observed rates of change and modeled technology-deployment constraints .

This distinction is especially important because energy infrastructure and industrial capital stocks exhibit substantial carbon lock-in and stock inertia . Physical assets like power plants, buildings, transport systems and industrial facilities often remain operational for several decades, while their replacement is constrained by investment cycles, supply chains, permitting, grid expansion, resource availability and institutional capacity . Assessing carbon-budget pathways consequently requires explicit consideration of the rates at which the structural determinants of emissions can change, together with the capacity of each country or region to invest in and deploy low-carbon energy technologies .

The Kaya identity distinguishes three principal channels of emissions change: the evolution of economic output per person, changes in the energy required to produce economic output and changes in the CO₂ emitted per unit of energy consumed. Although these identities do not establish causal relationships, they provide a transparent diagnostic framework to identify where the adjustment burden associated with a mitigation pathway is concentrated and whether the required rates of change remain within historically observed transition ranges .

Previous studies have extensively documented the roles of population, economic activity, energy intensity, and carbon intensity in emissions change . The contribution of this study is a regional and global framework that combines out-of-sample evaluated baseline projections, historically derived annual adjustment envelopes, recursive carbon-budget scaling, exact Kaya-based indicators, rolling structural diagnostics, equity-based allocation, and technology-deployment matching. The framework is designed to distinguish three outcomes that are often conflated: (i) numerical progress toward a carbon budget, (ii) compatibility of the required transition with historically observed adjustment rates, and (iii) the share of the mitigation requirement that can be represented by the modeled technology portfolio.

This integration makes it possible to distinguish three separate outcomes at regional and aggregate levels: numerical progress toward a carbon budget, the historically constrained structural adjustment required to sustain that pathway, and the share of the mitigation requirement that can be represented by historically observed technology deployment across ten regions: Africa, Central America, East Asia, Eurasia, Europe, the Middle East, North America, Oceania, South America, and South and Southeast Asia. Aggregate results are described as global only where the underlying country's coverage is complete; otherwise, coverage shares should be reported explicitly.

The simulated trajectories are first decomposed exactly through Kaya-based accounting indicators derived from population, economic output, primary energy consumption, and CO₂ emissions. Separately, the joint evolution of emissions, energy use, and economic output is examined through a region-specific rolling log-log regression. The rolling coefficients are used as scenario-consistent diagnostics of changing local associations and are not interpreted as an exact Kaya decomposition or as causal structural parameters .

The emissions gap between the Reference and mitigation pathways is subsequently matched to a portfolio including energy efficiency, solar, wind, hydropower, biomass, other renewables, nuclear energy, fuel switching from higher-carbon fossil fuels toward lower-carbon gaseous fuels, and carbon capture, utilization, and storage. Renewable displacement is accounted for separately and

is not included in the fuel-switching term . Future renewable generation is projected from historical regional deployment trends, with 2025 estimates aligned with the record-high projections of recent global assessments .

By benchmarking these trajectories against the IPCC AR6 Scenario database , this study provides an external reference for evaluating the plausibility of the modeled mitigation pathways. Unlike conventional scenario assessments that evaluate global or regional pathways mainly against emissions targets, this framework also tests how effectively each strategy can be accommodated by region-specific historical dynamics and technology-deployment patterns.

2. Methodology

This study evaluates the conditional structural viability of carbon-budget pathways through four linked stages: (i) region-specific multi-model baseline forecasting; (ii) bounded construction of carbon-budget, NDC, and equity-sensitive pathways; (iii) exact Kaya-indicator calculation combined with rolling log-log structural diagnostics; and (iv) integrated technology-based matching of the resulting mitigation requirements. The stages are applied consistently across the ten regional aggregates and the corresponding global totals.

First, internally consistent baseline trajectories for population, GDP, primary energy consumption, and CO₂ emissions are generated for ten regions: Africa, Central America, East Asia, Eurasia, Europe, the Middle East, North America, Oceania, South America, and South and Southeast Asia . Global trajectories are then calculated by aggregating the regional results, allowing the main findings to be summarized at the world level while preserving the regional detail used in the underlying analysis .

Second, carbon budget-constrained scenarios are constructed by iteratively adjusting regional emissions subject to annual bounds, while preserving coherence between emissions, energy use, and macroeconomic output. The resulting trajectories are evaluated through a structural decomposition into per-capita and intensity variables: per-capita CO₂ emissions ($\alpha = \text{CO}_2/\text{Pop}$), GDP per capita ($y = \text{GDP}/\text{Pop}$), energy intensity ($\varepsilon = \text{Energy}/\text{GDP}$), carbon intensity of energy ($k = \text{CO}_2/\text{Energy}$), carbon intensity output ($\eta = \text{CO}_2/\text{GDP}$), and energy use per capita ($e = \text{Energy}/\text{Pop}$), .

Historical series for population, GDP, and CO₂ emissions were compiled from World Bank indicators , reporting emissions excluding LULUCF (Fig. 1). Primary energy consumption was obtained from Our World in Data. All were harmonized and aggregated into ten regions according to *Supplementary Table 1*. To account for major structural breaks, Eurasia was curated from 1990 onward (post-Soviet transition). For the remaining regions, data were used from 1970 onward whenever available, however, for consistency across regions and variables, the figures report trajectories only from 1990 onward. Energy units were converted to ensure dimensional consistency, and all variables were checked for continuity, missingness, and outliers prior to modelling.

2.1. Baseline trajectory construction

To reduce dependence on exogenous socioeconomic scenario assumptions, annual trajectories from 2026 to 2050 were generated internally for four modeled state variables—GDP, population, primary energy consumption, and CO₂ emissions. These variables were subsequently combined to construct the standard Kaya indicators of affluence, energy intensity, carbon intensity of energy, and per-capita emissions. This approach ensures that the Reference pathway captures the structural inertia and path dependency inherent in regional historical data, rather than relying on idealized equilibrium paths. Rather than applying a single forecasting method, the analysis used a multi-model comparison framework designed to accommodate trend persistence, nonlinearity, and temporal dependence across regions.

The candidate pool comprised 35 forecasting specifications spanning classical statistical and trend-based methods, machine-learning and deep-learning models, and decomposition-based and hybrid approaches, including ARIMA, SVR, MLP, Prophet, recurrent Singular Spectrum Analysis (SSA), and several neural and hybrid architectures. All specifications were evaluated for each regional Kaya driver.

The year 2020 was retained in the chronological training sequence to preserve temporal continuity. Because the COVID-19 shock is structurally atypical, forecast performance is reported both with and without the 2020 observation in the validation metrics. The principal model ranking is based on the pre-specified validation protocol, while the alternative metric set is reported as a robustness check to demonstrate that model selection is not driven by selective exclusion of the pandemic year. Thus, the models were not trained on an artificially interrupted time series, while the reported MAE, RMSE, MAPE, and R^2 were prevented from being disproportionately influenced by the anomalous 2020 observation. Forecast performance was evaluated using the mean absolute error (MAE), root mean squared error (RMSE), mean absolute percentage error (MAPE), and coefficient of determination (R^2).

Forecast performance was assessed using rolling-origin validation over 2016–2023, with an expanding training window starting in 1970 (1990 for Eurasia) and a one-year-ahead horizon. Hyperparameters were tuned by time-series cross-validation without access to future observations. Models with positive out-of-sample (R^2) were ranked using an equal-weight normalized combination of MAE, RMSE, and MAPE, with the lowest-scoring model selected for each region-variable pair. Excluding 2020 was used only as a robustness check. The results of the best fitting model with their respective statistical errors are presented in *Supplementary Table 2*.

2.2.Scenarios construction

Five scenarios were constructed: Reference, 1.5°C, 2°C, NDC, and Energy Justice, as summarized in Table 1 and *Supplementary Table 3*. The Reference scenario corresponds to the internally generated baseline, representing a continuation of current socio-technical dynamics without additional cumulative carbon constraints. Global cumulative CO₂ budgets are imposed only in the 1.5°C, 2°C and Energy Justice scenarios. By contrast, the 2030-NDC Continuation scenario applies region-specific 2030 mitigation commitments using their corresponding base years. After 2030, emissions continue according to the implied 2025-2030 rate, subject to annual transition

bonds. This scenario is intended as a standardized continuation of the 2030 pledge architecture and should not be interpreted as a complete representation of the 2025-2035 NDC cycle.

Table 1. Definition and main constraints of the modelled scenarios.

Scenario	Constraints
Reference	Data-driven baseline reflecting structural inertia and path dependency. No additional regional or global climate policy restrictions are imposed.
1.5°C	Global cumulative CO ₂ budget of approximately 276 GtCO ₂ . The pathway is generated through iterative scaling subject to historically grounded feasibility corridors and scenario-specific transition multipliers. Regional reduction rates are model outputs rather than predetermined targets.
2°C	Global cumulative CO ₂ budget of approximately 978 GtCO ₂ over 2026-2050. The same iterative scaling and bounded-transition framework is applied, but with a less restrictive adjustment envelope than in the 1.5°C scenario.
NDC	Region-specific 2030 mitigation commitments are applied using corresponding base years. After 2030, emissions continue according to the implied 2025-2030 rate, subject to annual transition bounds. No global cumulative carbon budget is imposed. Used to evaluate the emissions gap between national pledges and temperature-aligned budgets.
Energy Justice	The Energy Justice pathway is treated as an illustrative equity-sensitive scenario rather than an isolated test of allocation justice. It combines a global cumulative CO ₂ budget of approximately 800 GtCO ₂ with differentiated regional effort based on historical responsibility, economic capacity, and current per-capita emissions. Accordingly, differences between this pathway and the other scenarios reflect both the selected global budget and the responsibility-capacity allocation rule; the 800 GtCO ₂ value is a scenario assumption rather than a quantity derived from the justice index itself.

The Energy Justice pathway distributes mitigation effort according to a responsibility–capacity framework combining historical responsibility, economic capacity, and current per-capita emissions. For region i , the Energy Justice Index (EJI) is defined as; $EJI_i = 0.40 R_i + 0.35 C_i + 0.25 P_i$, where R_i , C_i , and P_i represent min–max normalized historical responsibility, economic capacity, and current per-capita CO₂ emissions, respectively. Historical responsibility is measured as cumulative regional CO₂ emissions over 1990–2023, while economic capacity and current emissions are represented by GDP per capita and CO₂ emissions per capita in 2023. The resulting index is converted into a regional effort multiplier, $M_i = 0.50 + EJI_i$, yielding values between 0.50 and 1.50.

2.3.Economic-energy-emissions coherence via dynamic log-log calibration

To preserve internal consistency among economic activity (affluence), primary energy consumption and CO₂ emissions during scenario propagation, a region-specific rolling log-log model was estimated separately for each projection year. Exact Kaya indicators are calculated algebraically from the simulated GDP, population, primary energy, and CO₂ trajectories. The rolling log-log model is used separately as a regularized diagnostic of how the local association

among emissions, economic activity, energy use, and time evolves within each scenario; it does not constitute an exact or non-residual Kaya decomposition . For region (i) and projection year (t), the model is:

$$\ln(CO_{2(i,t)}) = \beta_{0(i,t)} + \beta_{GDP} \ln(GDP_{(i,t)}) + \beta_{Energy} \ln(Energy_{(i,t)}) + \beta_{Trend} Trend_{(i,t)} + \varepsilon_{(i,t)}$$

Where $CO_{2(i,t)}$ represents annual carbon dioxide emissions in the region (i) and the year (t), $GDP_{(i,t)}$ represents regional gross domestic product, $Energy_{(i,t)}$ represents primary energy consumption, and $Trend_{(i,t)}$ captures gradual structural changes, improvements in energy efficiency, and changes in the carbon intensity of the energy system. Because the model is estimated in logarithmic form, β_{GDP} and β_{Energy} describe local percentage-response associations within each rolling window. However, given ridge regularization, multicollinearity, coefficient bounds, and the use of recursively simulated observations, they are interpreted here as regularized diagnostic elasticities rather than causal or invariant structural elasticities.

Unlike a conventional Cobb–Douglas model estimated once over the complete historical period, the coefficients were re-estimated sequentially using a ten-year rolling window. To avoid perfect foresight bias and look-ahead bias common in cost-optimization IAMs, each regression used only information available up to year $t-1$. For instance, observations from 2016–2025 were used to calibrate the 2026 relationship. This moving-window approach allows the model to capture the socio-technical inertia and path dependency inherent in regional transitions, ensuring that scenario-driven adjustments remain consistent with historically grounded dynamics.

More generally, the estimation sample for year t was defined as:

$$W_{i,t} = \{t - 10, t - 9, \dots, t - 1\}$$

And the corresponding coefficient vector was estimated as:

$$\beta_{i,t} = \arg \min \left\{ \sum_s \in W_{i,t} [\ln(CO_{2(i,s)}) - \beta_{0(i,t)} - \beta_{GDP(i,t)} \ln(GDP_{i,s}) - \beta_{Energy(i,t)} \ln(Energy_{i,s}) - \beta_{Trend(i,t)} Trend_{i,s}]^2 + \lambda(\beta_{GDP(i,t)}^2 + \beta_{Energy(i,t)}^2 + \beta_{Trend(i,t)}^2) \right\}$$

A ridge penalty with $\lambda = 0.10$ was applied to the explanatory-variable coefficients to reduce numerical instability arising from the strong correlation between GDP, energy use, and time. The intercept was not penalized.

The estimated coefficients were then applied to the GDP and primary-energy values of year t to calculate the conditional Cobb–Douglas emissions level:

$$\widehat{CO_{2(i,t)}} = \exp(\beta_{0(i,t)} + \beta_{GDP} \ln(GDP_{(i,t)}) + \beta_{Energy} \ln(Energy_{(i,t)}) + \beta_{Trend} Trend_{(i,t)})$$

The recursive re-estimation procedure means that simulated observations progressively enter later rolling windows. Consequently, the resulting coefficient trajectories are interpreted strictly as ex-

post, scenario-consistent diagnostics of the constructed pathways. They do not provide independent causal evidence that the pathway itself generates decoupling, because part of the coefficient evolution reflects the scenario trajectories already imposed or generated by the model.

To prevent look-ahead bias, no observation from year t or any subsequent year was used to estimate the coefficients applied in year t . The ten-year rolling window is retained as the central specification to emphasize recent local dynamics, but the short sample and strong correlation among GDP, energy use, and time limit coefficient precision. Ridge regularization is therefore used for numerical stabilization, and the coefficient trajectories are interpreted qualitatively. Precise transition dates or causal conclusions are not inferred from individual zero crossings without supporting window-length sensitivity. As a final fallback, a regression based on all available historical observations through 2023 was estimated, as shown in Fig. 1, the rolling Cobb-Douglas methodology.

For numerical stability and economic plausibility, the estimated coefficients were constrained to predefined ranges: $-1.0 \leq \beta_{\text{GDP}} \leq 2.0$, $0.0 \leq \beta_{\text{Energy}} \leq 2.0$, and $-0.20 \leq \beta_{\text{Trend}} \leq 0.20$. These limits did not determine the coefficient values; they only prevented extreme estimates caused by small samples or multicollinearity. The model also reported the coefficient estimates before and after the application of these bounds, the coefficient of determination, the number of observations, the estimation window, and the condition number for each region, scenario, and projected year.

Population is treated as exogenous and enters only diagnostic metrics. In projection years, this calibration provides a coherence layer that prevents emissions pathways from becoming inconsistent with the joint evolution of GDP and energy under bounded adjustments.

The central analytical output of the paper is a dynamic decomposition of emissions into per-capita and intensity components. For each region and year, the following variables are computed from simulated trajectories: per-capita energy use (Rate), the energy intensity of economic output (ϵ), the carbon intensity of energy (k), the carbon intensity of economic activity (η), the economic output per capita (y), Energy-Use Intensity per Capita (e), and the per-capita CO₂ emissions (α).

Rolling Cobb–Douglas estimation framework

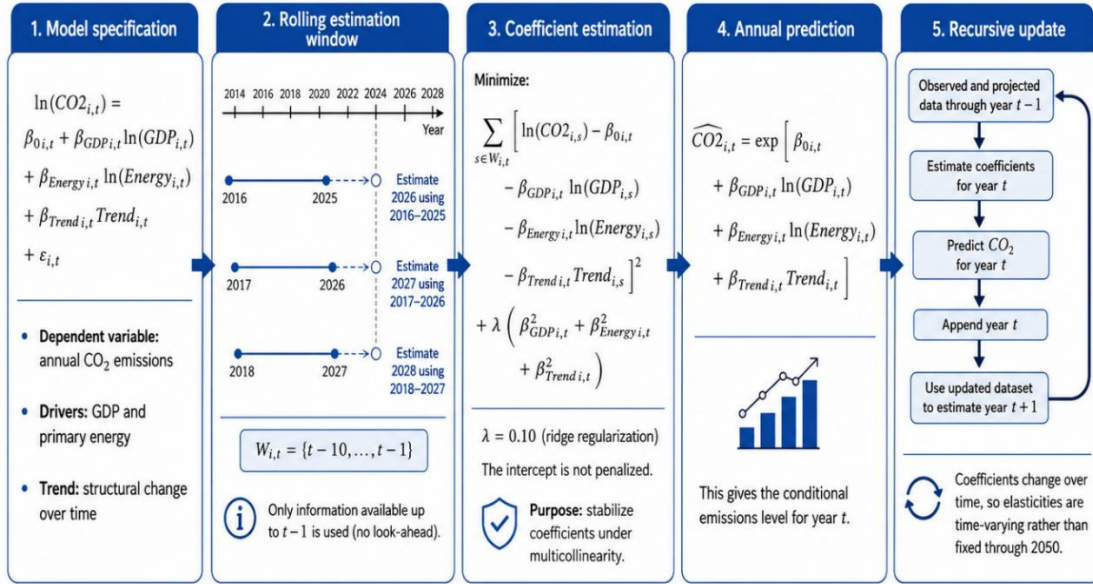


Fig. 1. Recursive rolling Cobb–Douglas framework for estimating regional CO₂ emissions.

2.4. Integrated technology-based mitigation assessment

To assess the technological viability of each scenario, the mitigation potential of renewable energy, nuclear energy, and carbon capture, utilization, and storage (CCUS) was evaluated using three alternative renewable deployment rates derived from the last 5 years, the last 10 years, and the full historical period. The technology-matching module is an accounting-based coverage assessment rather than a fully sector-resolved energy-system model. Renewable and nuclear potential is estimated from electricity-generation displacement, whereas the scenario emissions gap is economy-wide. Therefore, the resulting coverage ratios indicate how much of the modeled energy-related mitigation requirement can be represented by the selected technology portfolio under the stated assumptions; they should not be interpreted as proof that electricity-sector additions physically substitute for all transport, industrial-process, building, or non-electric fuel emissions.

CCUS trajectories were constructed from multiple project databases to address the implementation and institutional gaps identified in recent literature. Project-status weights are modeling assumptions used to discount nominal capacity according to project maturity; unless an empirical calibration is explicitly cited, they should not be interpreted as observed probabilities of project completion. Nominal project capture capacity was adjusted according to project status as: operational (1.0), under-construction (0.9), final investment decision (0.8), advanced development/planning (0.6), viability/planning/planned (0.35), announced or early development (0.15), cancelled or terminated/inactive/suspended/hold (0.0). The 85% utilization factor and the post-2030 capacity-addition rule are likewise scenario assumptions used to construct a central CCUS pathway and should be evaluated through sensitivity analysis where possible. Then, the weighted capacity of each project was calculated as:

$$\text{Weighted capacity} = \text{Nominal Capacity} \times \text{Status weight}$$

Regional operational capacity was obtained by cumulatively adding weighted project capacity according to the reported start year. Potential annual CO₂ capture was then estimated by applying a utilization factor of 85% from its nominal annual capacity. Project information through 2030 was used to calculate the mean annual regional capacity addition, which was subsequently applied from 2031 to 2050. The global CCUS pathway was calculated as the annual sum of the regional trajectories.

The technology-matching procedure then calculated the annual mitigation requirement for each region (r), scenario (s) and year (t) as:

$$\text{Required mitigation}_{r,s,t} = \max[\text{CO}_2\text{Reference}_{r,s,t} - \text{CO}_2\text{Scenario}_{r,s,t}, 0]$$

The zero term prevents negative mitigation values when scenario emissions are equal to or higher than Reference emissions. The calculated difference therefore represents the positive emissions-reduction gap that must be explained by the available technologies.

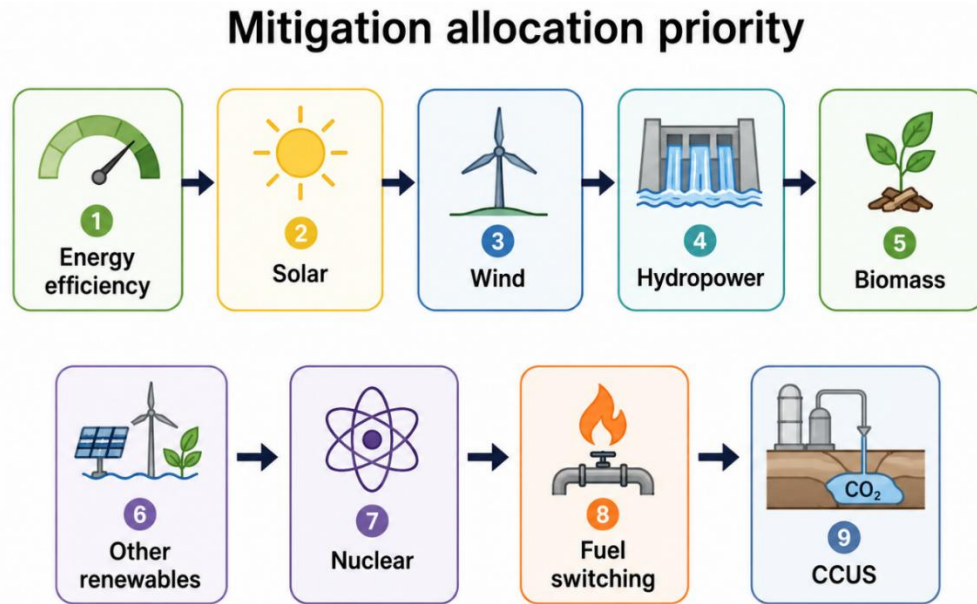
Renewable and nuclear energy mitigation potentials were estimated from projected additions to regional electricity generation relative to the 2025 baseline. For each region, technology, year, and historical trend window, only positive increases were considered. These additional generation volumes were multiplied by the average emission factor of the regional thermal power fleet to estimate potentially displaced CO₂ emissions by additional low-carbon electricity generation, expressed in MtCO₂/year, according to *Supplementary Table 4*.

Energy-efficiency mitigation was represented by a gradual reduction in energy intensity relative to the Reference pathway, increasing linearly from 2025 to scenario-specific targets in 2050. Fuel switching represented a gradual substitution of higher-carbon fuels by natural gas, while CCUS contributions were taken from the regional projections.

For each region, scenario, and year, the available technological potentials were allocated sequentially to the mitigation requirement, according to the order presented in Fig. 2. The contribution assigned to each technology was limited to the smaller of its available potential and the remaining mitigation gap:

$$\text{Allocated mitigations} = \min[\text{Available potential} - \text{Remaining mitigation gap}]$$

This procedure prevents the sum of technological contributions from exceeding the required emissions reduction and avoids double counting. The allocation sequence is an accounting convention used to prevent arithmetic over-allocation of the annual mitigation requirement. Total achieved mitigation and unmet mitigation are therefore treated as the primary coverage metrics. Technology-specific contribution shares are order-dependent and are interpreted only as illustrative attribution results unless robustness to alternative allocation orders is demonstrated.



Technologies are allocated sequentially until the required mitigation is met.

Fig. 2. Priority Order for Allocating the Required CO₂ Mitigation.

3. Results

The results are presented in a structured sequence. First, the statistical validity and internal coherence of the Reference pathway derived from Stage 1 are evaluated to ensure that baseline projections satisfy realism and plausibility criteria. Next, the effects of alternative carbon-budget and equity constraints on regional trajectories are examined through adjustments in energy intensity (ϵ), carbon intensity of energy (k), and overall emissions intensity (η). This progression enables viability to be assessed relative to a validated baseline rather than against unconstrained projections.

3.1. Historical and Projected

Fig. 3 presents the historical trajectories of per-capita CO₂ emissions from 1990 to 2023 and their projections from 2026 to 2050 under the Reference scenario. This scenario provides the baseline against which the alternative mitigation pathways are evaluated. The projected trajectories reflect the continuation of historically observed regional trends in CO₂ emissions from fossil-fuel combustion in power generation, heating, and other energy-related activities, excluding emissions from land use, land-use change, and forestry (LULUCF).

The results reveal substantial differences among regions. Per-capita emissions are projected to continue increasing in East Asia, Eurasia, South and Southeast Asia, and Central America. In Africa and the Middle East, the trajectories indicate a tendency toward stabilization, with only limited changes over the projection period. By contrast, North America, Oceania, Europe, and South America are projected to maintain declining trends in per-capita CO₂ emissions through 2050.

These divergent pathways highlight heterogeneous phases of regional energy-system development and decarbonization, with some regions still in a phase of growing energy demand and continued reliance on fossil fuels, and consistent with historical changes in energy consumption, efficiency, and the penetration of lower-carbon energy sources.

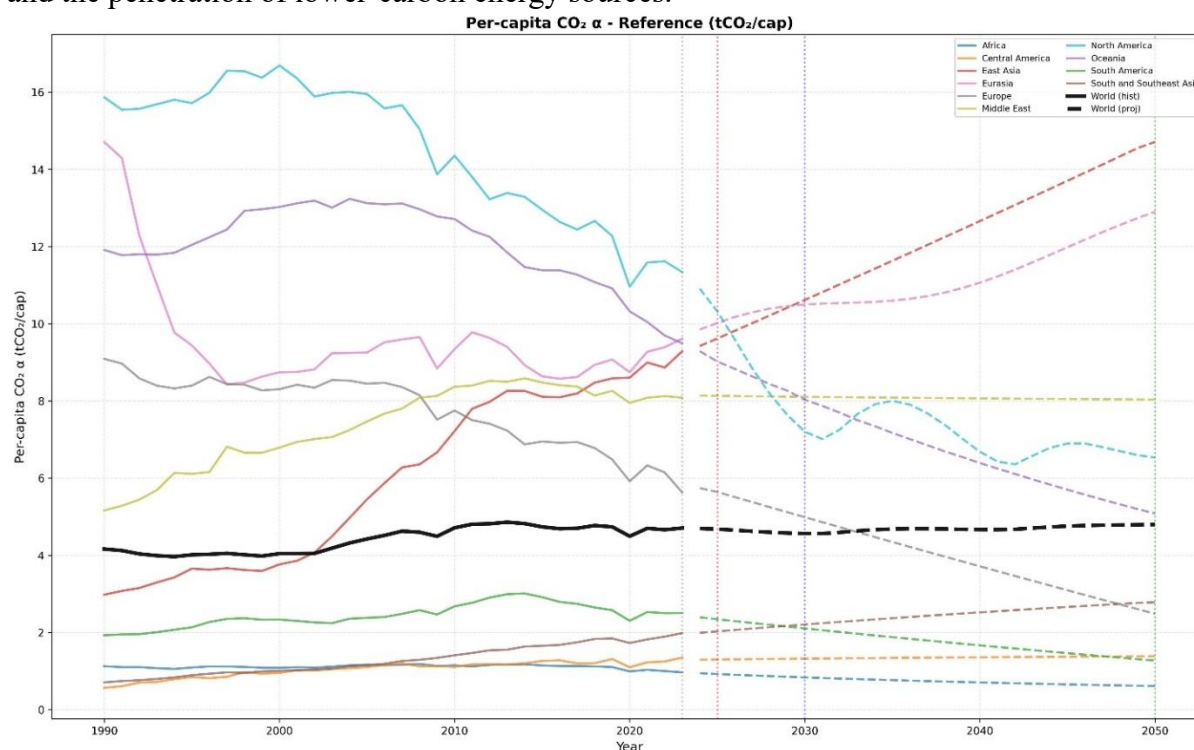


Fig. 3. Historical and Forecasted emission per capita (tCO₂/a,capita) by region from 1990 to 2050, Reference scenario excluding LULUCF.

Regionally, the Reference scenario reveals markedly divergent structural patterns in per-capita CO₂ emissions:

- **North America and Europe** maintain pronounced downward trajectories. Between 2026 and 2050, per-capita emissions in North America declined from approximately 9.59 to 6.53 tCO₂ per person and in Europe from 5.51 to 2.48 tCO₂ per person in Europe. Such reductions indicate that the decarbonization trends seen historically in their energy systems are ongoing.
- **Oceania and South America** also exhibit substantial declines. Per-capita emissions decrease from approximately 8.83 to 5.08 tCO₂ per person in Oceania and from 2.29 to 1.27 tCO₂ per person in South America. Nevertheless, Oceania remains among the regions with comparatively high per-capita emissions throughout much of the projection period.
- **East Asia** displays the strongest upward trajectory, with per-capita emissions increasing from approximately 9.82 tCO₂ per person in 2026 to 14.71 tCO₂ per person in 2050. Under the unconstrained Reference pathway, this region therefore becomes the largest per-capita emitter by the end of the projection period.

- **Eurasia** also maintains structurally high and increasing per-capita emissions, rising from approximately 10.18 to 12.90 tCO₂ per person. This trajectory indicates limited autonomous decarbonization under the Reference scenario and persistent dependence on carbon-intensive energy supply.
- **South and Southeast Asia** exhibits a steady increase from about 2.07 to 2.78 tCO₂ per person. Although per-capita emissions in this region are substantially lower than those in East Asia, Eurasia, North America, and the Middle East, the upward trend reflects the ongoing growth in energy demand and emissions based on the baseline assumptions.
- **Central America** exhibits a comparatively moderate increase, from approximately 1.31 to 1.38 tCO₂ per person. The small magnitude of this change suggests a generally stable trajectory with a slight upward trend rather than a rapid increase in emissions.
- **The Middle East** maintains persistently high but nearly stable per-capita emissions, decreasing only slightly from approximately 8.13 to 8.04 tCO₂ per person. This minor change suggests that, under the Reference pathway, there are no major autonomous reductions in the intensity of regional emissions.
- **Africa** continues to exhibit the lowest per-capita emissions among all regions. Its trajectory declines from approximately 0.90 tCO₂ per person in 2026 to 0.61 tCO₂ per person in 2050. It is important to point out that low values should not be seen as evidence of advanced decarbonization, but also as indicative of low energy consumption and access. Consequently, mitigation strategies in Africa must remain compatible with development-driven growth in energy services.

By 2050, the Reference scenario therefore projects continued regional divergence. East Asia, Eurasia, and South and Southeast Asia follow increasing trajectories, whereas North America, Europe, Oceania, South America, and Africa exhibit declining per-capita emissions. Central America increases only moderately, while the Middle East remains broadly stable at a high level. These results demonstrate that, without additional carbon-budget constraints, historically observed regional trends do not produce a uniform global transition toward lower per-capita emissions.

The declining per-capita emissions projected for North America and Europe may reflect a combination of historical structural changes, including improvements in energy efficiency, declining coal use, expansion of lower-carbon electricity sources, changes in the composition of economic activity, and reduced growth in energy demand. Although the declining contribution of energy-intensive industries may have influenced historical emissions trends, the present model does not explicitly isolate industrial contraction from other drivers. Therefore, the projected reductions should be interpreted as the continuation of aggregate regional decarbonization trends rather than as direct evidence of deindustrialization .

The increasing per-capita emissions projected for East Asia and South and Southeast Asia may reflect the continuation of historical growth in economic activity, industrial production, electricity consumption, urbanization, and energy-service demand. In these regions, rapid renewable-energy deployment has occurred alongside expanding total energy demand and persistent dependence on

fossil fuels, particularly coal. Consequently, additions of low-carbon generation may not be sufficient to produce absolute emissions reductions when electricity demand and fossil-based industrial energy use continue to increase .

3.2.Scenarios Comparison

Fig. 3 presents the regional trajectories of per-capita CO₂ emissions and the corresponding global trajectory, represented by the black line. The global series was calculated by aggregating regional emissions and populations, such that global per-capita emissions correspond to total emissions across all regions divided by their combined population. This population-weighted aggregation prevents small and large regions from contributing equally to the global average.

The same procedure was applied to each of the five scenarios—Reference, 1.5 °C, 2 °C, NDC, and Energy Justice—to obtain a comparable global per-capita emissions trajectory for each pathway, as shown in Fig. 4.

Because annual transition bounds are defined in Section 2.2 and Supplementary Table 3, the iterative scaling procedure does not force full convergence to the nominal carbon budget when the required annual change exceeds the historically observed adjustment envelope represented in the model. The resulting difference is interpreted as a conditional, historically grounded transition-compatibility indicator rather than a universal measure of physical or institutional feasibility. The resulting gap between simulated and nominal cumulative emissions is interpreted as a conditional structural-viability indicator within the assumptions of the framework. It measures the extent to which the target exceeds the historically observed adjustment envelope represented in the model.

The Reference scenario represents the continuation of current regional trends and results in the highest cumulative CO₂ emissions, reaching 1,037.1 GtCO₂ by 2050. The 2 °C scenario follows, with cumulative emissions of 987.2 GtCO₂. Lower cumulative emissions are obtained under the Energy Justice and NDC scenarios, which reach 795.5 and 781.0 GtCO₂, respectively. The 1.5 °C scenario produces the lowest cumulative emissions among the five pathways, totaling 688.1 GtCO₂ by 2050.

Although all mitigation scenarios reduce cumulative emissions relative to the Reference pathway, the results indicate that the modeled trajectories do not necessarily comply with their nominal carbon-budget targets. In particular, the 2 °C scenario slightly exceeds the adopted 978 GtCO₂ budget, while the 1.5 °C pathway remains substantially above the corresponding 276 GtCO₂ budget. Therefore, the scenario labels should be interpreted as mitigation pathways oriented toward these temperature goals rather than as pathways that fully achieve the associated carbon-budget constraints by 2050.

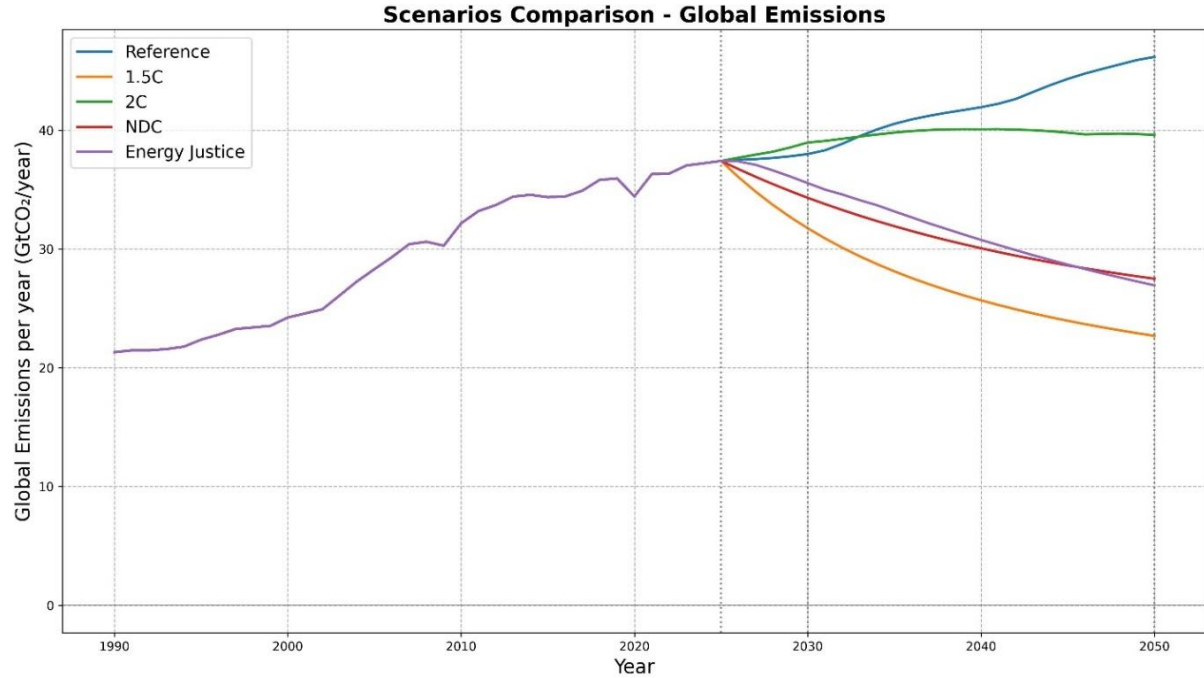


Fig. 4. World scenarios of GtCO₂ emissions per year.

To assess the external consistency of the five modeled pathways, their global trajectories were compared with scenarios from the IPCC AR6 Integrated Assessment Model database. The comparison included 928, of which 504 contained sufficient data for the complete matching procedure for comparison. The different IAM frameworks and model versions, include: GCAM, IMAGE, MESSAGEix-GLOBIOM, and REMIND-MAGPIE. These scenarios represent a broad range of socioeconomic assumptions, energy-system transformations, policy conditions, and climate-mitigation ambitions.

The comparison was based on a set of normalized structural indicators derived for both the pathways developed in this study and the IAM scenarios. These indicators included per-capita CO₂ emissions, energy use per capita, energy intensity of GDP, carbon intensity of energy, and carbon intensity of economic output. For each study pathway, the absolute percentage difference between the corresponding indicators and those of each IAM scenario was calculated over the common projection period. The indicator-specific differences were then combined into an overall matching score. The APPENDIX-A describes the comparison for each parameter (k , η , α , ε , Rate) among the curves obtained in this work and the 5 closest scenarios from the IAM scenarios as shown in Supplementary Figures 1 – 5.

Therefore, Table 2 presents the five closest IAM matches for the Reference, 1.5 °C, 2 °C, NDC, and Energy Justice pathways. The five IAM scenarios with the highest matching scores were retained for each pathway. An initial acceptance threshold of 10% was applied, with the comparison window expanded only when fewer than five eligible matches were identified.

Overall, this exercise is interpreted as external structural benchmarking rather than formal validation of the nominal temperature classification of the study pathways. Nearest-neighbor

similarity in the selected indicators does not guarantee consistency in cumulative emissions or warming outcome; accordingly, unrestricted matches can include IAM scenarios from different temperature classes. Where possible, class-restricted matches should be reported as an additional robustness test.

Table 2: Five closest IAM scenario matches for the pathways developed in this study among the 928 scenarios evaluated.

Scenario	Rank	IAM	Scenario Code	Scenario Category
Reference	1	IMAGE 3.2	SSP4-baseline	Reference_or_Baseline
	2	IMAGE 3.0.2	EMF33_Baseline	Reference_or_Baseline
	3	IMAGE 3.0.1	ADVANCE_NoPolicy	Unclassified
	4	IMAGE 3.0.1	SSP2-Baseline	Reference_or_Baseline
	5	IMAGE 3.0.1	CD-LINKS_NoPolicy	Unclassified
1.5°C	1	GCAM 5.3	R_MAC_85_n8	SSP585_like
	2	GCAM 5.3	R_MAC_75_n0	Unclassified
	3	GCAM 5.3	R_MAC_70_n0	SSP370_like
	4	GCAM 5.3	R_MAC_80_n8	Unclassified
	5	GCAM 5.3	R_MAC_90_n8	Unclassified
2°C	1	IMAGE 3.2	SSP2_SPA2_45I_D	SSP245_like
	2	REMIND-MAGPIE 1.5	SSP2-45	SSP245_like
	3	REMIND 1.7	ADVANCE_INDC	Unclassified
	4	REMIND-MAGPIE 1.7-3.0	CO_NDCplus	Unclassified
	5	IMAGE 3.2	SSP2_SPA2_34I_LIRE	Below_3C_or_intermediate
NDC	1	GCAM 5.3	R_MAC_90_n0	Unclassified
	2	GCAM 5.3	R_MAC_95_n0	Unclassified
	3	GCAM 5.3	R_MAC_99_n8	Unclassified
	4	GCAM 5.3	R_MAC_85_n0	SSP585_like
	5	GCAM 5.3	R_MAC_99_n0	Unclassified
Energy Justice	1	GCAM 5.3	R_MAC_95_n0	Unclassified
	2	GCAM 5.3	R_MAC_99_n0	Unclassified
	3	GCAM 5.3	R_MAC_90_n0	Unclassified
	4	GCAM 5.3	R_MAC_99_n8	Unclassified
	5	GCAM 5.3	R_MAC_85_n0	SSP585_like

3.3.Cobb-Douglas Coefficients

The global rolling Cobb–Douglas estimates reveal a progressive weakening and, in the more stringent scenarios, a reversal of the historical relationship between economic activity, energy use, and CO₂ emissions. At the beginning of the projection period, all scenarios share the same as the rolling window increasingly incorporates scenario-specific observations, the estimated relationships diverge.

3.3.1. Global rolling time-trend coefficient. The rolling time-trend coefficient captures the systematic evolution of CO₂ emissions that is not explained by contemporaneous

changes in GDP or primary energy consumption, as shown in Fig. 5. The coefficient is positive and consistent across scenarios at the beginning of the projection period, reflecting the persistence of historical emissions dynamics. It subsequently declines as scenario-specific observations are incorporated into the rolling apertures. The 1.5°C pathway shows the largest negative time coefficient, implying that a substantial downward structural pressure on emissions is required in addition to the effects directly attributable to GDP and total energy consumption.

The NDC and Energy Justice pathways also have negative time coefficients, indicating a gradual reduction of emissions due to sustained technological, regulatory and structural changes. The 2 °C pathway has a more gradual transition and stays at a point near zero or slightly positive for a long time indicating a less abrupt transformation. The time coefficient should not be interpreted as the effect of time itself. It is a proxy for neglected structural processes like changes in the technological composition of energy supply, electrification, energy efficiency, climate policy, restructuring of industry and changes in fuel carbon intensity.

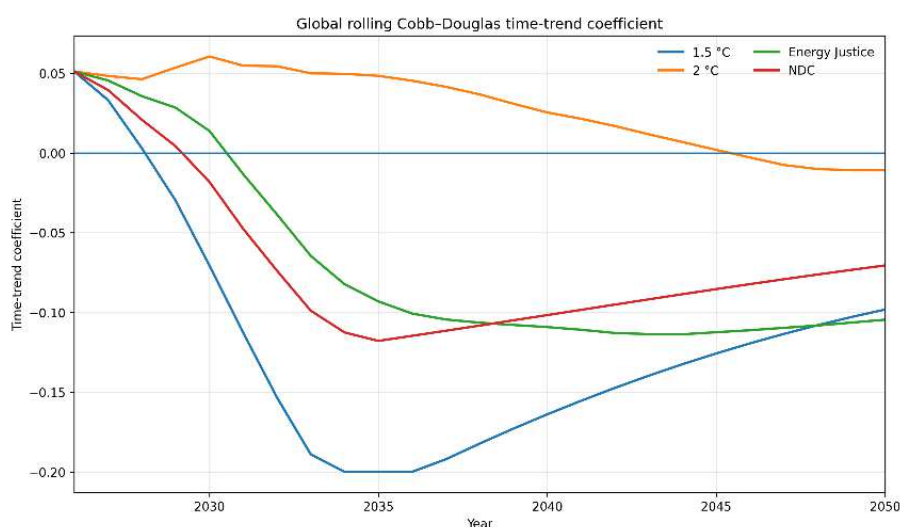


Fig. 5. Global rolling time-trend coefficient.

3.3.2. Global rolling energy elasticity. Rolling energy elasticity is a measure of the percentage response of CO₂ emissions to a percentage change in primary energy use, while maintaining the time trend and GDP constant within each estimation window. Initially, the coefficient is positive and consistent across all scenarios, suggesting that the historical energy mix continues to be associated with higher emissions with respect to increased energy consumption. The coefficient decreases in the mitigation scenarios and approaches zero over the projection, as shown in Fig. 6. In the mitigation scenarios, the coefficient decreases and approaches zero through the projection period, with the 1.5 °C, NDC and Energy Justice pathways being most affected.

This convergence towards zero reduces the historical association between total energy use and emissions. In practice, the scenarios are allowing the continued or increased delivery of energy services without a proportional increase in CO₂ emissions, due to the increasing share of renewable energy, nuclear power, fuel switching, efficiency gains, and carbon capture. The historical energy–emissions relationship is more closely maintained by the 2 °C scenario, which exhibits a slower decline. Values that are close to zero do not imply that energy consumption is irrelevant to emissions; rather, they suggest that the total energy use is less effective in explaining emissions when the carbon composition of the energy system undergoes a significant change.

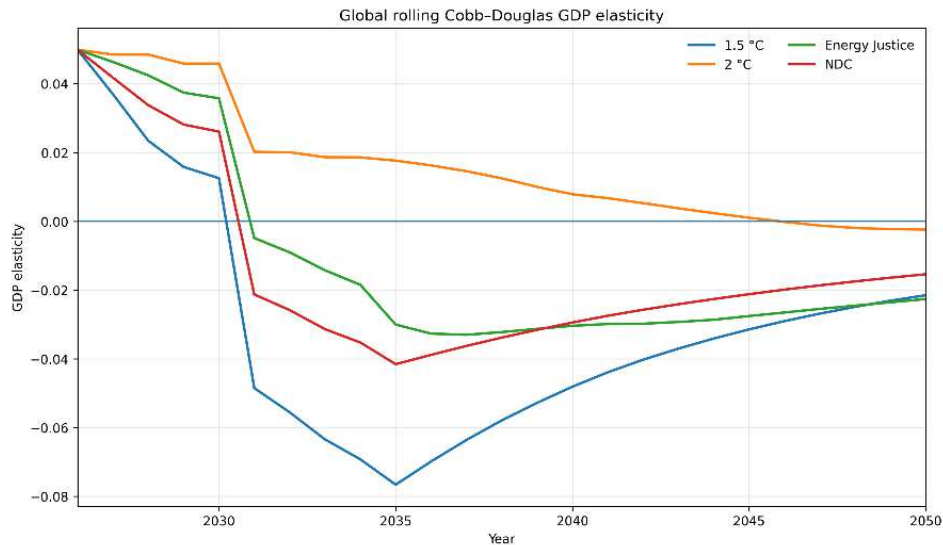


Fig. 6. Global rolling energy elasticity.

3.3.3. Global rolling GDP elasticity. As the ten-year estimation window gradually integrates the scenario-specific trajectories, the rolling GDP elasticity illustrates how the link between global economic activity and CO₂ emissions shifts. Because common historical observations continue to dominate their estimation windows, the scenarios exhibit similar and slightly positive elasticities at the start of the projection period. The GDP elasticity in the mitigation paths declines as the scenarios diverge, as depicted in Fig. 7.

The declining GDP coefficient in the more stringent pathways is a diagnostic property of the evolving simulated relationship between economic activity and emissions. Because scenario-generated observations progressively enter the rolling estimation window, negative coefficients should not be interpreted as independent evidence that economic growth causes emissions reductions. Rather, they indicate that the constructed pathway increasingly combines continued GDP growth with declining modeled emissions. Though at a slower pace, the NDC and Energy Justice pathways also head towards negative elasticities, suggesting progressive economic decoupling. The 2°C pathway, however, retains a small positive elasticity for a longer period, suggesting a more gradual divergence from the historical relationship between GDP

and emissions. The Reference pathway shows the highest continuity with the historical relationship.

Negative values show that the imposed mitigation trajectory requires the effects of technological change, energy-system decarbonization, and efficiency improvements to outweigh the emissions pressure associated with economic expansion; they should not be interpreted as proof that economic growth directly causes emissions reductions.

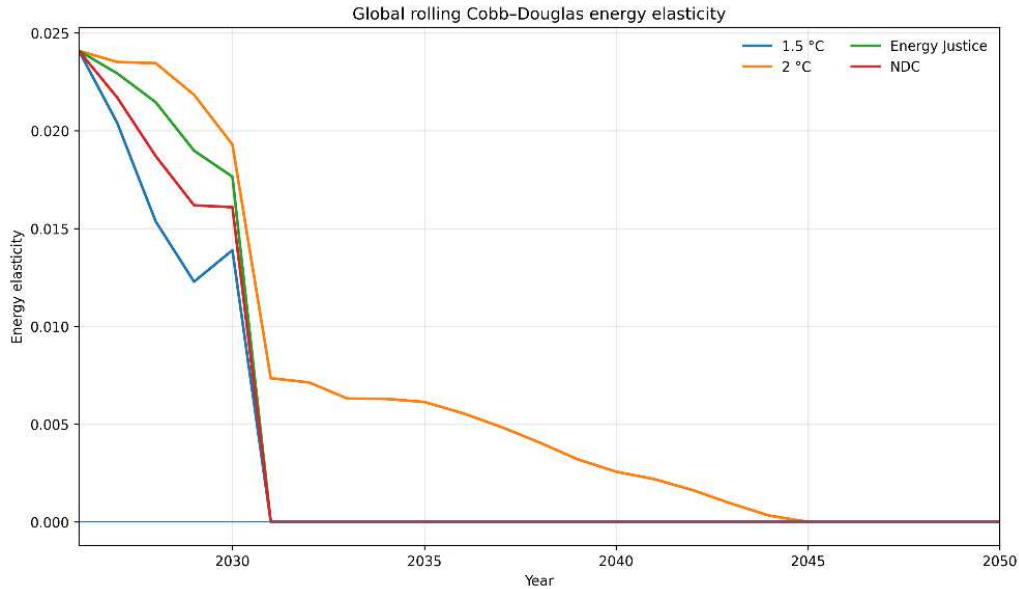


Fig. 7. Global rolling GDP elasticity.

3.4. Structural Drivers of Mitigation for each scenario

To assess the adequacy of the available mitigation pathways, three technology-deployment rates were considered. These rates were estimated from the trends observed over the last five years, the last ten years, and the complete 2000–2025 period. The three cases represent, respectively, the continuation of the most recent deployment dynamics, a medium-term historical trend, and a long-term historical trend. Table 3 presents the cumulative CO₂ abatement by technology between 2026 and 2050 under each deployment-rate assumption. The year-by-year mitigation trajectories of energy efficiency, renewable energy, nuclear power, and CCS under the 1.5 °C, 2 °C, NDC, and Energy Justice scenarios are presented in *Supplementary Figures 6–8*. More details about the renewable insertion rate are shown in APPENDIX-B and *Supplementary Fig. 9a, 9b, 9c and 9d*, while for the CCS is presented in APPENDIX-C and *Supplementary Fig. 10a – 10l*.

As shown in Table 3, the 1.5 °C pathway presented the largest absolute technological insufficiency across the three technology-deployment assumptions. The unmet mitigation reached 72.33 GtCO₂ under the last-five-year rate, 73.12 GtCO₂ under the last-ten-year rate, and 131.76 GtCO₂ under the 2000–2025 rate. The corresponding achieved mitigation amounted to 276.66, 275.89, and 217.21 GtCO₂, covering approximately 79.3%, 79.0%, and 62.2% of the cumulative mitigation requirement, respectively. Thus, neither recent nor long-term historical deployment rates were sufficient to reproduce the adopted 1.5 °C emissions pathway. Compliance with this trajectory

would require deployment rates above those observed historically, together with additional structural changes in final energy demand, industrial production, electrification, and the carbon intensity of the energy supply.

Table 3 summarizes the cumulative technology-matching results and should not be interpreted as additional evidence of Reference-pathway forecast validity . Baseline forecast performance is evaluated separately in Section 3.1 and Supplementary Table 2, where model accuracy is shown to vary across regions and variables

Table 3. Detailed cumulative abatement by technology (2026-2050) with different rates of technology insertion and for each scenario.

Scenarios	1.5°C (GtCO ₂)	2°C (GtCO ₂)	NDC (GtCO ₂)	Energy Justice (GtCO ₂)
Last 5 years rate				
Efficiency	106.66	57.63	52.44	92.52
Solar Power	68.82	22.96	47.84	48.43
Wind Power	61.79	0.14	42.74	47.04
Hydro Power	23.53	0.03	23.47	22.10
Biomass	2.17	0	7.05	1.28
Other	1.56	0	5.39	0.99
Nuclear	3.56	1.66	15.12	3.00
CCS	8.57	0.03	6.40	3.83
Unmet mitigation	72.33	0.04	56.78	23.67
Last 10 years rate				
Efficiency	108.95	60.95	53.47	92.84
Solar Power	55.39	18.74	38.45	38.10
Wind Power	47.46	1.14	33.26	37.43
Hydro Power	25.56	0.07	18.32	18.32
Biomass	6.37	0.02	6.03	5.61
Other	3.87	0.04	4.43	4.43
Nuclear	18.41	0.98	15.73	14.64
CCS	9.88	0.24	7.46	4.66
Unmet mitigation	73.12	0.33	80.09	26.84
All years rate (2000-2025)				
Efficiency	111.1	60.96	55.35	94.76
Solar Power	32.80	12.93	22.54	24.31
Wind Power	29.62	5.63	20.25	24.51
Hydro Power	14.95	0.73	10.57	11.14
Biomass	5.50	0.02	3.94	3.87
Other	4.17	0.02	2.96	3.06
Nuclear	5.88	0.27	4.75	4.66
CCS	13.19	0.44	8.76	5.93
Unmet mitigation	131.76	1.49	128.12	70.63

Table 4 presents the regional distribution of unmet mitigation under the last-five-year and last-ten-year deployment rates, while Supplementary Table 5 reports the corresponding results for the 2000–2025 rate. For the 1.5 °C pathway, the remaining gap was concentrated mainly in Eurasia and North America. Under the last-five-year rate, these regions accounted for 43.05 and 20.01 GtCO₂ of unmet mitigation, respectively, followed by the Middle East with 5.26 GtCO₂. A similar pattern was observed under the last-ten-year rate, whereas the 2000–2025 assumption produced a broader regional deficit, particularly in Eurasia, East Asia, North America, and the Middle East.

The 2 °C pathway is nearly fully covered with respect to the gross positive region-year mitigation requirement used by the technology-matching algorithm. Under the last-five-year deployment case, this gross positive requirement is approximately 82.5 GtCO₂, whereas the net cumulative difference between Reference and 2 °C emissions are approximately 49.9 GtCO₂. The difference reflects regional years in which 2 °C emissions exceed Reference emissions and are excluded by the max (Reference - Scenario, 0) operator. Accordingly, near-full coverage refers to the gross positive technology-matching requirement, not to the net global cumulative emissions difference. The residual gap was largely concentrated in the Middle East, especially under the longer historical windows.

The NDC pathway remained incomplete under all assumptions. The global unmet gap increased from 56.78 GtCO₂ under the last-five-year rate to 80.09 GtCO₂ under the last-ten-year rate and 128.12 GtCO₂ under the 2000–2025 rate. Regionally, the deficit was concentrated in North America, Eurasia, East Asia, and the Middle East. East Asia became particularly important under the longer windows, accounting for 36.24 GtCO₂ of unmet mitigation under the last-ten-year rate and 66.10 GtCO₂ under the 2000–2025 rate.

The Energy Justice pathway also remained below full coverage, with unmet mitigation of 23.67, 26.84, and 70.63 GtCO₂ across the three deployment assumptions. Under the last-five-year rate, the largest regional gaps occurred in North America, Eurasia, and the Middle East. Under the 2000–2025 rate, East Asia became the dominant source of unmet mitigation, with 38.41 GtCO₂.

Figures 11a–11j show the annual regional mitigation pathways under the last-five-year deployment rate. They complement the cumulative results in Tables 3 and 4 by showing how technology contributions, remaining emissions, and unmet mitigation evolve from 2026 to 2050. The figures confirm that the global shortfalls are driven by persistent regional gaps rather than by a uniform lack of mitigation potential across all regions.

Across all scenarios, energy efficiency provided the largest individual contribution, while solar and wind were the principal supply-side options. Hydropower, nuclear energy, biomass, other renewables, and CCS provided complementary mitigation. Overall, the combined evidence from Table 3, Table 4, Supplementary Table 5, and Figures 11a–11j shows that pathway feasibility depends strongly on both deployment speed and the regional distribution of mitigation potential.

Table 4. Regional unmet mitigation by scenario under the last-five-year, last-ten-year and all the period technology deployment rates.

Rate	Last 5 years				Last 10 years			
Units	(GtCO ₂)	(GtCO ₂)	(GtCO ₂)	(GtCO ₂)	(GtCO ₂)	(GtCO ₂)	(GtCO ₂)	(GtCO ₂)
Scenarios	1.5°C	2°C	NDC	Energy Justice	1.5°	2°C	NDC	Energy Justice
Africa	1.5	0	1.79	0	0.51	0.03	1.11	0
Central America	1.15	0.01	1.05	0.34	1.04	0	0.97	0.25
East Asia	0	0	12.61	0	1.65	0	36.24	4.45
Eurasia	43.05	0	13.84	8.79	42.76	0	13.64	8.55
Europe	1.3	0	0.69	0	2.97	0	2.04	0
Middle East	5.26	0.01	8.84	5.16	7.39	0.32	10.43	6.91
North America	20.01	0	16.25	9.21	16.54	0	13.93	6.51
Oceania	0	0	0	0	0	0	0	0
South America	0	0	0	0	0.20	0	0.02	0
South and Southeast Asia	0.06	0.01	1.72	0.17	0.06	0.01	1.71	0.16
World	72.33	0.04	56.78	23.67	73.12	0.33	80.09	26.84
Rate	Complete 2000–2025 period							
Units	(GtCO ₂)	(GtCO ₂)	(GtCO ₂)	(GtCO ₂)				
Scenarios	1.5°C	2°C	NDC	Energy Justice				
Africa	2.60	0	2.55	0.03				
Central America	0.93	0	0.90	0.17				
East Asia	38.77	0	66.10	38.41				
Eurasia	43.36	0	13.97	9.06				
Europe	6.56	0.03	5.21	0				
Middle East	9.72	1.43	12.16	8.85				
North America	20.47	0	16.53	9.57				
Oceania	0	0	0	0				
South America	4.44	0	2.53	0				
South and	4.90	0.06	8.16	4.53				

Southeast Asia					
World	131.76	1.49	128.12	70.63	

4. Conclusions

The results demonstrate that cumulative emissions are strongly influenced by scenario formulation and the transition constraints imposed. The 1.5°C-oriented pathway reaches 688.1 GtCO₂ over 2026–2050, remaining substantially above the adopted 276 GtCO₂ carbon budget, whereas the 2°C-oriented pathway reaches 987.2 GtCO₂, only slightly above its corresponding 978 GtCO₂ budget. These results indicate that the historically grounded transition constraints represented in the model are substantially more restrictive for the 1.5°C pathway than for the 2°C pathway. The NDC pathway produces lower cumulative emissions than the modeled 2°C pathway, but this should not be interpreted as evidence of greater mitigation ambition, since the two scenarios are constructed under different rules: the NDC pathway extends region-specific 2030 commitments, whereas the 2°C pathway is generated through cumulative-budget scaling subject to historically grounded transition bounds.

The Energy Justice scenario highlights the importance of differentiated regional mitigation efforts, assigning stronger decarbonization requirements to regions with greater historical responsibility and capacity. Nevertheless, the technology-deployment analysis shows substantial regional heterogeneity. Eurasia, East Asia, and the Middle East exhibit larger residual mitigation challenges, while other regions approach much higher levels of mitigation coverage under deployment rates consistent with the most recent five- and ten-year periods. These results indicate that maintaining recent rates of low-carbon technology deployment, together with continued improvements in energy efficiency and CCUS expansion, is critical for reducing regional implementation gaps.

The evolution of the GDP elasticity coefficient provides an additional indication of how rapidly the relationship between economic activity and CO₂ emissions must weaken across the modeled pathways. The rolling GDP coefficient declines more rapidly in the 1.5 °C, NDC, and Energy Justice pathways than in the 2 °C-oriented pathway, indicating a faster modeled weakening of the local GDP-emissions association. Because the estimated zero-crossing year is sensitive to the rolling window, regularization, and the progressive inclusion of simulated observations, the timing is interpreted qualitatively rather than as a precise estimate of additional structural-adjustment time.

The Kaya-based structural decomposition indicates that deeper emissions reductions depend primarily on rapid declines in the carbon intensity of energy, together with sustained improvements in energy intensity. The global rolling Cobb–Douglas estimates also show a progressive weakening of the historical relationship among economic activity, energy consumption, and CO₂ emissions under the more stringent pathways. In the 1.5 °C, NDC, and Energy Justice scenarios, the rolling GDP coefficients become negative while the energy coefficients approach zero. These patterns are interpreted as scenario-consistent diagnostics of a weakening modeled association among economic activity, energy use, and emissions, rather than as causal evidence of decoupling. The

primary structural interpretation is therefore based on the exact Kaya-derived intensity indicators, with the rolling coefficients used as complementary diagnostics.

These results indicate that the modeled pathways progressively depart from historically observed socio-technical relationships as mitigation requirements become more stringent. The estimated coefficients should therefore be interpreted as scenario-consistent structural diagnostics rather than causal elasticities, particularly because the later rolling regressions exhibit high condition numbers and declining statistical stability as the pathways move further from historical dynamics.

Finally, the technology-matching assessment shows that technology-based mitigation coverage is highly sensitive to the historical deployment window adopted. The 1.5°C-oriented pathway presents the largest technology-related shortfall, with unmet mitigation of 72.33 GtCO₂ under the last-five-year deployment rate, 73.12 GtCO₂ under the last-ten-year rate, and 131.76 GtCO₂ under the 2000–2025 period rate. These values correspond to coverage levels of approximately 79.3%, 79.0%, and 62.2%, respectively, indicating that none of the historically grounded deployment assumptions are sufficient to bridge the remaining mitigation gap under the modeled transition constraints.

Overall, the findings indicate that compatibility with climate-oriented pathways depends not only on cumulative emissions targets but also on the time, scale, and regional distribution of technological deployment within historically grounded transition bounds. Demand-side energy efficiency provides the largest and most stable contribution across the modeled portfolio. The persistence of substantial implementation gaps under the 1.5°C-oriented, NDC, and Energy Justice pathways indicates that maintaining historical transition and deployment patterns is insufficient to reproduce the required mitigation trajectories, highlighting the need for faster technological deployment, deeper structural change, and additional measures beyond those represented in the present framework.

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Author Contributions

Carlos E. Velasquez contributed to the conceptualization, methodology, data analysis, modeling, visualization, and preparation of the original manuscript. Douglas Silva de Oliveira, José Péricles

Freire, and Masoumeh Bararzadeh Ledari contributed to the interpretation of results, critical review, and revision of the manuscript. All authors reviewed and approved the final manuscript.

Competing Interests

The authors declare that they have no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

Data Availability

The data used in this study were obtained from publicly available sources, including the World Bank, Our World in Data, and the other databases cited in the manuscript. The processed data supporting the findings of this study are available from the corresponding author upon reasonable request.

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