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LETTER

Equitable cooperation deepens the solution space for high ambition pathways

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Abstract

Integrated assessment model scenarios informing global climate ambition typically treat fairness and cooperation as external to the modelling process, reinforcing a perceived tension between fair effort-sharing and the urgent collective action needed to minimise exceedance of 1.5 °C. Here we introduce a generalisable framework that embeds principle-based fair-share considerations directly into the scenario generation process. This framework produces scenario variants that reconfigure transition pathways while preserving global peak and end of century climate outcomes. We explore this space across allocation approaches, transfer limits, and cooperation mechanisms, and propose a new lowest-feasible transfer scenario variant to bound it. We examine the integrated system shifts this new variant implies, and contrast it with the common exploration of fairness through ex-post assessments and unlimited financial transfers. We observe that the renewables deployment and electrification trajectories remain largely unchanged across all fair-share variants, while restricting transfers to lowest-feasible volumes accelerates global fossil decline. This effect prevails even when interregional cooperation is focussed on financing carbon dioxide removal with geological storage, where higher-responsibility regions' fair-share obligations remain met primarily through domestic gross emissions reductions. Against a globally cost-effective 2 °C (>67%) scenario that reduces discounted consumption by approximately 0.8% relative to the no-new-policy reference scenario, integrating fair-share considerations raises this to at most 1.3% when transfers are restricted to lowest-feasible volumes. Notably, this aggregate is distributionally progressive, where lower-responsibility regions gain relative to the cost-effective source scenario. This deepened solution space persists even under a stringent 1.5 °C goal, though with differentiation increasingly settled through finance, and reveals dynamics that emerge only when scenario generation itself accounts for differentiated responsibilities and capabilities. Ultimately, we find that a 'gross emissions reductions first' strategy among higher-responsibility regions generates system-wide benefits, releasing pressure on lower-responsibility regions to collectively meet climate goals.

1. Introduction

The 'remaining carbon budget' concept has served as a crucial scientific and political compass informing climate ambition in line with the temperature goal of the Paris Agreement [1–4]. Collective failure to respect the 1.5 °C limit, however, means that adherence to this budget entails a temporary exceedance and return, or overshoot [5–7]. This requires methods for ambition setting that reconcile

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the disproportionate harms anticipated for those least responsible [8–11] with the need to show urgent collective ambition in line with international law and norms [12–14]. In this evolving policy context, it is essential to distinguish physical exceedance of the global remaining carbon budget, from regional 'carbon debt,' a normative concept that is defined as the excess of a region's cumulative emissions beyond a principle-based fair share that must be addressed through deeper domestic emissions reductions, drawdown and/or financial transfers enabling higher effort elsewhere [15–21]. Minimising overshoot magnitude and duration is thus both a scientific imperative and also a matter of justice as it concerns not only global outcomes but also the regional processes through which these are achieved, as emphasized in contemporary multilateral climate deliberations [22, 23]. Addressing this requires a collective demonstration of highest possible ambition [24] and fair and innovative forms of international cooperation [25], alongside parallel progress on adaptation and loss and damage finance [26].

Assessments using contemporary integrated assessment models (IAMs) inform these deliberations by generating scenarios consistent with some of the Paris Agreement's core tenets, e.g. Articles 2.1(a) (the long-term temperature goal) and Article 4.1 (the mitigation goal to achieve net-zero GHGs). However, most scenario experiments continue to treat principle-based considerations of fairness and cooperation as external to model frameworks [27]. In doing so they also often leave implicit the inherently normative distributional judgement in equalising marginal mitigation effort across regions. This reflects a common perception that equity and ambition are separate and in tension. Methodologically, either ex post fair shares are calculated that neglect their integrated energy system and economic implications [19, 28] or regionally differentiated energy systems are modelled that are disconnected from principle-based fairness considerations relevant to contemporary multilateral climate policy debates [29–31].

We address this gap constructively and in the spirit of prior scenario logic advances [32], establishing a generalisable framework to endogenise principle-based fair-share considerations within existing modelling processes. This framework makes the distributive judgement embedded in least-cost scenario generation [33] explicit and configurable, deepening the scenario evidence base. We illustrate this by operationalising Paris Agreement's recognition of 'common but differentiated responsibilities and respective capabilities' (which allows for a range of distributive interpretations [34, 35]), through six different allocation approaches reflecting two different principle families and three responsibility start years. We implement this within the MESSAGEix-GLOBIOM-GAINS IAM to define fair-share scenario variants across a set of existing globally cost-effective mitigation pathways. The framework itself is agnostic to the allocation chosen and the scenarios to which it is applied, enabling extension to a wider set of approaches in future work rather than treating those shown here as uniquely privileged. The variants we do show demonstrate a broad range of pathways to meet collective ambition while minimising regional carbon debt accrual and addressing corresponding overshoot responsibility.

2. A framework for modelling equitable cooperation variants

Our scenario variant framework preserves collective climate ambition in any existing mitigation scenario (what we term the 'source' scenario) while imposing configurable regional fairness objectives and cooperation mechanisms (see figure 1). We partition source scenario emissions into 'covered' and 'excluded' emissions categories, reflecting necessary scientific and normative judgements in principle-based fair-share assessments. Covered emissions in our illustrations comprise regional Kyoto gases excluding land-use, land-use change and forestry (LULUCF), international shipping, and aviation, which can be modified in other applications of the framework. Excluded emissions (in our case from LULUCF, international shipping, and aviation) follow the source scenario carbon price trajectory to prevent cross-sectoral leakage, with mathematical formulations provided in the supplementary information (SI—Detailed methods). We explore the solution space across equal cumulative per capita (ECPC) and a capability-adjusted cumulative per capita (CAPC) allocations in our main text, examining responsibility start years of 1990, 2015 and 2025 to capture how the choice of principle and interpretation shift regional fair shares and highlighting the depth this creates (see SI—Detailed methods). Allocations are computed once over the full accounting horizon using SSP-consistent full century population trajectories. Regions whose cumulative emissions exceed their allocation must address this through some combination of domestic gross emission reductions, domestic carbon dioxide removal (CDR), and interregional cooperation of various forms.

Equitable cooperation is modelled through a frictionless cap-and-trade mechanism that allows regions to transfer covered emissions allocations, with an endogenous cooperation price emerging from the global commodity balance this creates. Regions exceeding their allocation purchase allowances from regions with remaining allocation at this endogenous price. When the permitted volume of transfers is constrained, regions must also mitigate at home, reallocating physical mitigation effort and inducing the energy investment shifts we

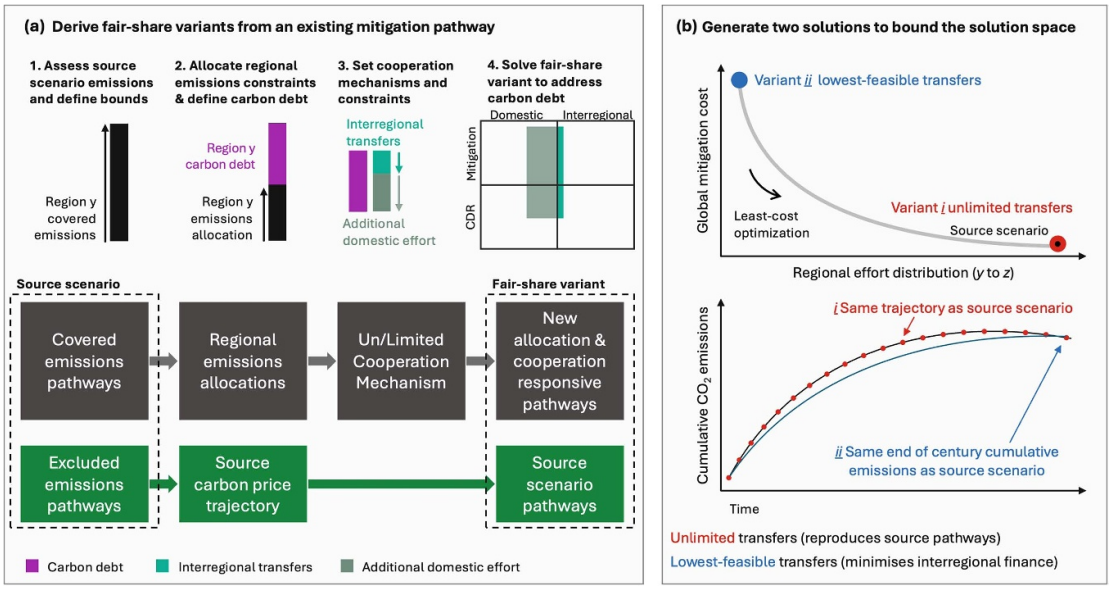

Figure 1. Deriving fair-share variants from existing mitigation scenarios. (a) Conceptual operationalisation of carbon debt for a representative higher-responsibility region (Region y). The region's fair-share allocation (short black bar) serves as the binding constraint. The difference between this allocation and the source scenario emissions (tall black bar) defines the full-century carbon debt (purple bar), which must be addressed through additional domestic mitigation, domestic carbon dioxide removal (CDR), or interregional cooperation. (b) Modular scenario logic within the integrated assessment model (IAM) framework. Emissions are partitioned into 'covered' categories (subject to fairness constraints) and 'excluded' categories (following source scenario prices to prevent carbon leakage). (c) Solution space bounded by two corner solutions, showing how effort shifts between higher-responsibility (y) and lower-responsibility (z) regions under global cost-effective optimisation. (Top) Global mitigation cost curve illustrating the solution space between 'Unlimited transfers' (red) and 'Lowest-feasible transfers' (blue) variants. (Bottom) Stylised cumulative CO_2 emissions showing both variants should reproduce the same end-of-century endpoint as the source scenario.

report below. We define bounds of this new solution space through two corner solutions: an 'unlimited transfers' variant permitting unconstrained interregional financial transfers, reproducing source scenario emissions pathways while quantifying interregional financial obligations; and a 'lowest-feasible transfers' variant identifying the minimum interregional finance enabling model feasibility, starting from a policy floor and increasing iteratively until the model converges. The policy floor (approximately 100 billion USD per year) reflects the collective climate finance commitment established at the 15th Conference of Parties in Copenhagen [36] and extended through 2025 and is taken as a conservative representation of already committed interregional finance flows. The New Collective Quantified Goal (300 billion USD per year by 2035) [37] implies this floor is conservative going forward. This variant forces higher-responsibility regions toward greater domestic mitigation, altering regional carbon prices and energy investment patterns relative to the source scenario. The space between these variants describes a continuum of feasible configurations that differ in how effort is distributed but converge on the same aggregate climate outcome. Full mathematical formulations, including fair-share allocations, objective function modifications, cooperation constraint implementation, and iterative solution procedure, are provided in the Detailed methods and Model implementation sections of our SI.

We demonstrate this framework using the MESSAGEix-GLOBIOM-GAINS IAM, a global energy–economy–environment systems model with a 12-region spatial representation (see SI—Model implementation). The model version used here incorporates statistical data through 2025 and includes updated population and GDP projections aligned with the latest Shared Socioeconomic Pathway updates. Macro-economic responses are captured through iterative coupling with MACRO, a growth model that maximises the intertemporal utility of consumption of a representative producer-consumer in each region, yielding optimal savings, investment, and consumption responses to energy-system costs. We generate globally cost-effective source scenarios under two remaining carbon budgets from 2020, allowing overshoot: 800 Gt CO_2 (consistent with limiting warming to approximately 2 °C with 67% likelihood) and 500 Gt CO_2 (consistent with 1.5 °C with 50% likelihood). This is modelled under the Shared Socioeconomic Pathway SSP2 'Middle of the Road' narrative, and we include a comparison using SSP1 'Sustainability' narrative in the Extended results section of our SI.

Figure 1 visualises the framework, whose application in this paper yields four key insights that we discuss in further detail below, each represented by one of the figures that follow. First, both transfer corner solutions reproduce the end-of-century net cumulative CO_2 emissions of the source scenario,

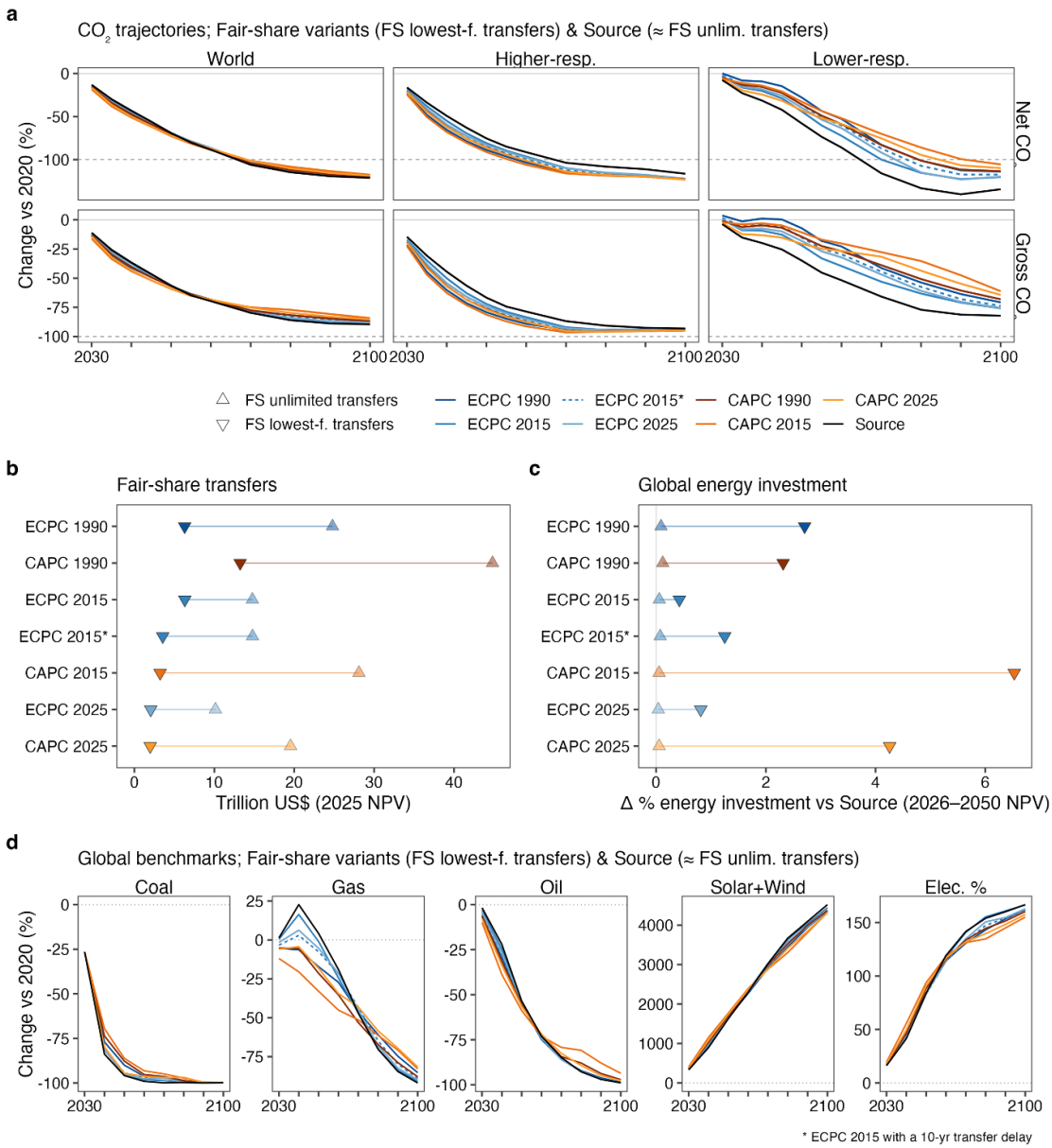

Figure 2. Physical transition and transfers across fair-share allocations under an approximate 2 °C budget (>67%, SSP2). Fair-share variants are shown across six allocation approaches (ECPC and CAPC, each with 1990, 2015, and 2025 responsibility start dates), alongside the globally cost-effective source scenario, and the ECPC 2015* timing variant in which cooperation onset is delayed by ten years. Upward-pointing triangles indicate unlimited transfers and downward-pointing triangles indicate lowest-feasible transfers. (a) Net and gross CO_2 emissions as a percentage change relative to 2020 levels for the World and for higher- and lower-responsibility region groups; at the World level both transfer corners closely reproduce the net trajectory of the source scenario, while at the group level the lowest-feasible corner departs from it. (b) Cumulative interregional fair-share financial transfers (NPV 2026-2100, trillion USD, 5% discount rate). (c) Change in global cumulative near-term energy-supply investment relative to the source scenario (%, 2026–2050 NPV). (d) Global benchmark trajectories for coal, gas, oil, renewables (solar & wind), and the electrification share; all global benchmarks, including renewables, are shown as percentage change relative to 2020.

demonstrating that fairness and ambition are not inherently in tension, rather the corners bound a solution space of configurations that differ in how effort is distributed while key near-term global benchmarks remain largely unchanged (figure 2). Second, within this solution space, interregional financial transfers and domestic mitigation effort are substitutable policy levers to a degree, beyond which model feasibility constraints bite. These variants yield marginal consumption losses globally and progressive redistribution at the regional level, where model feasibility constraints mean that extending historical responsibility eventually scales financial flows rather than the physical transition, and delaying cooperation raises total costs (figure 3). Third, the mechanism through which interregional cooperation is channelled matters acutely. Restricting this to financing novel CDR increases costs and requires higher-responsibility regions to accelerate near-term gross emissions reductions globally (figure 4). Fourth, even under a stringent 1.5 °C budget, the deepened solution space persists, with constrained transfers

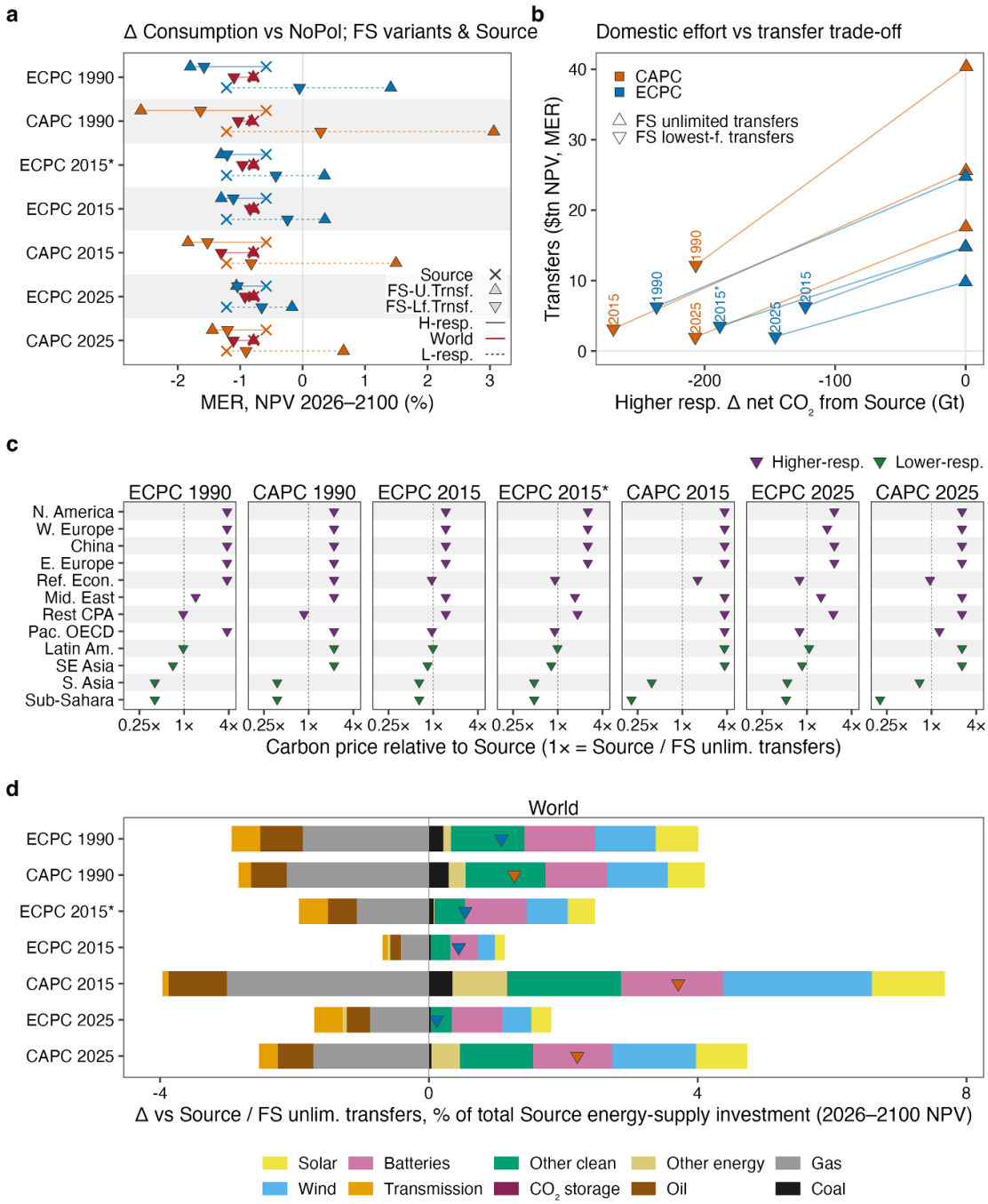

Figure 3. The economics of equitable cooperation. Analysis of the SSP2 2 °C (>67%) fair-share variants across the six allocation approaches and the ECPC 2015* 10 year cooperation delay variant. Upward-pointing triangles indicate unlimited transfers and downward-pointing triangles indicate lowest-feasible transfers; the source scenario is shown as crosses. (a) World (red) and regional cumulative change in consumption relative to a no-new-policy reference scenario (NPV, 2026–2100, market exchange rates, 5% discount rate). Lower-responsibility regions see relative consumption gains under the fair-share variants, while higher-responsibility regions see relative consumption reductions. (b) Trade-off between higher-responsibility domestic effort (change in net CO_2 emissions relative to the source scenario) and interregional transfers. (c) Change in regional carbon price relative to the source scenario. (d) World energy-supply investment reallocation by technology (change relative to the source scenario, which is identical to change relative to the unlimited transfer FS variant), highlighting that shifts are driven by renewables and their derivatives (solar, wind, storage). Note that each segment is expressed as a share of total source-scenario energy supply investment. The Transmission series refers to transmission and distribution infrastructure.

driving a 'gross emissions reductions first' response among higher-responsibility regions that releases pressure on lower-responsibility regions, however the flexibility to shift energy systems is reduced, with fair-share deficits met increasingly through transfers (figure 5).

3. Exploring a deeper solution space

Having introduced the conceptual framework, we now apply it across progressively stringent conditions to map the deepened solution space it reveals. We first examine how the framework reshapes regional

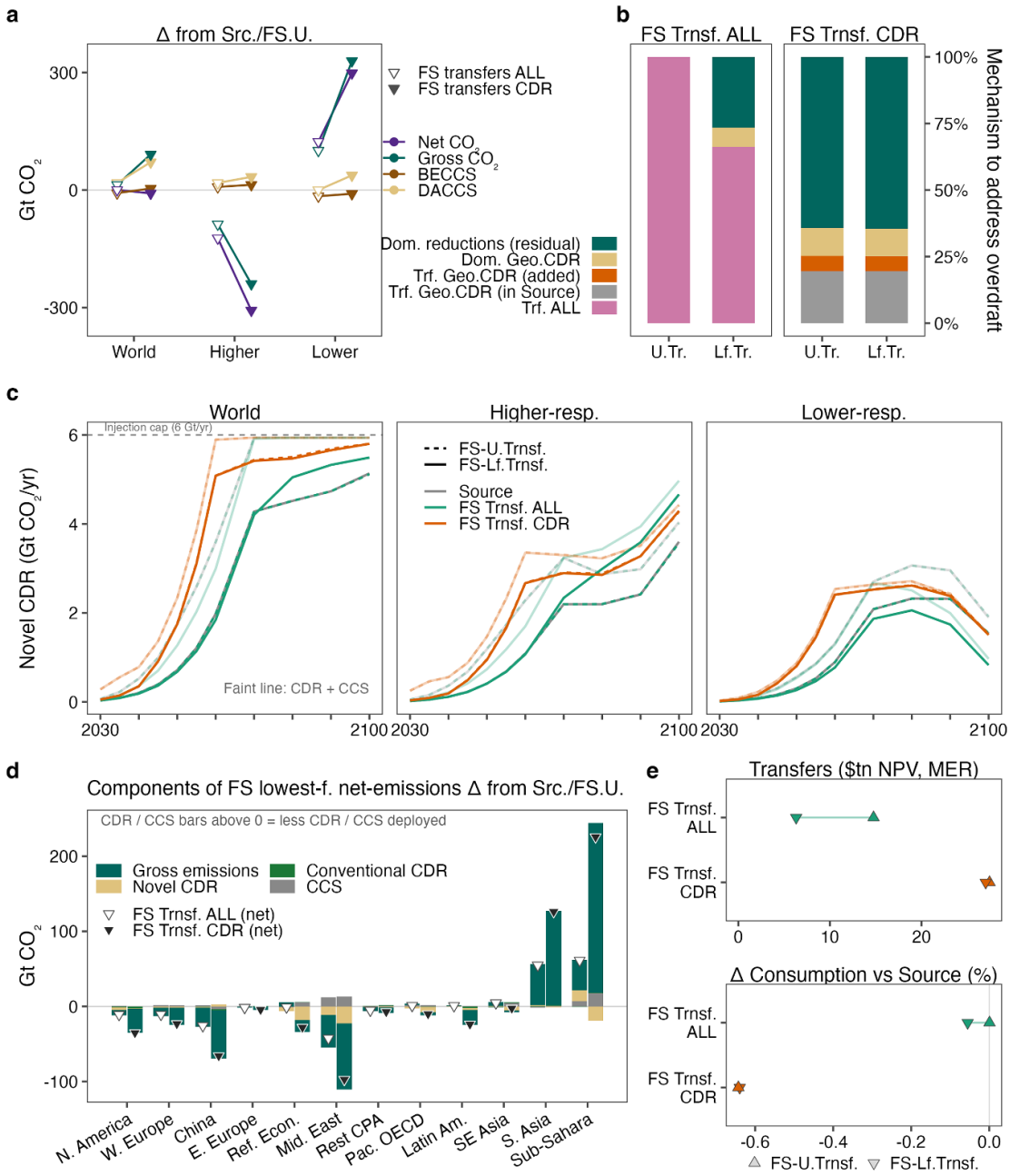

Figure 4. Restricting cooperation to novel carbon dioxide removal. Analysis of cooperation restricted to novel CDR compared with the SSP2 2 °C fair-share variants (ECPC 2015) and the source scenario. Upward-pointing triangles indicate unlimited transfers and downward-pointing triangles indicate lowest-feasible transfers. (a) Cumulative change in net CO_2 emissions and its components (gross emissions, BECCS, DACCS) relative to the source scenario and the unlimited-transfers fair-share variant, for the World and for higher- and lower-responsibility region groups, as cooperation shifts to novel CDR only. (b) How the higher-responsibility overdraft (carbon debt) is resolved (domestic gross reductions, domestic CDR, interregional transfers), shown as shares by instrument scope and transfer level. (c) Annual novel-CDR deployment against the 6 Gt CO_2 per year injection cap for the World and region groups. (d) Change in net emissions decomposed into four levers (gross reductions, novel CDR, conventional CDR, and fossil and industrial CCS) under all-mitigation and CDR-only cooperation. (e) Interregional transfers and global consumption cost relative to the source scenario.

efforts and financial obligations for an approximate 2 °C (>67% likelihood) end of century temperature goal under a middle-of-the-road SSP2 socioeconomic narrative (figure 2). Throughout this work, and acknowledging that group membership may shift a little by principle, the higher-responsibility group we show comprises North America, Western Europe, China, Eastern Europe, the Reforming Economies, the Middle East, Rest of Centrally Planned Asia, and Pacific OECD, and the lower-responsibility group comprises Latin America, Southeast Asia, South Asia, and Sub-Saharan Africa. All scenario variants shift how effort is distributed across these regions rather than how much is achieved globally.

The unlimited transfers variant reproduces source scenario emission pathways, while under lowest-feasible transfers higher-responsibility regions reduce gross emissions substantially faster than the

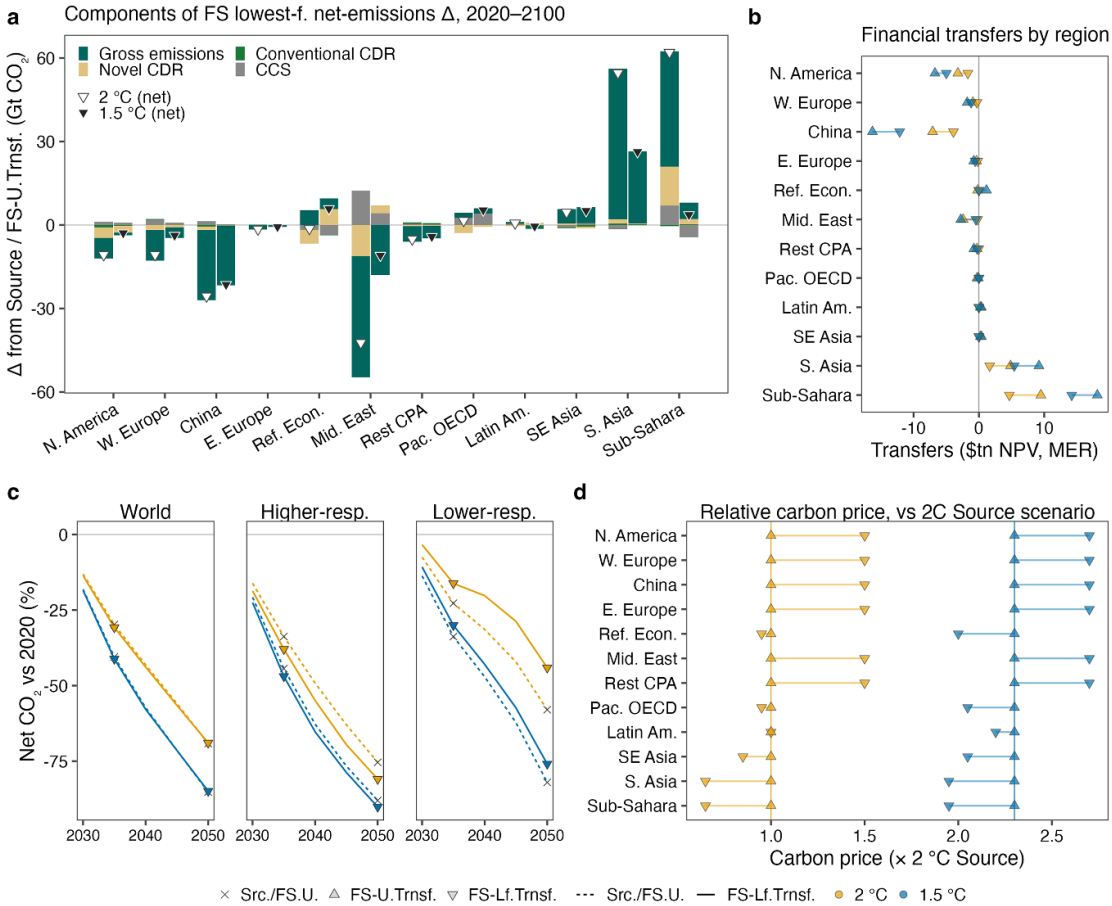

Figure 5. Returning to 1.5 °C under equitable cooperation (SSP2, ECPC 2015). The figure compares the approximate 2 °C and 1.5 °C budgets under the ECPC 2015 reference case. Upward-pointing triangles indicate unlimited transfers and downward-pointing triangles indicate lowest-feasible transfers, with symbol shading reinforcing the distinction, and crosses indicate the source scenario. (a) Per-region change in mitigation levers (the difference between lowest-feasible and unlimited transfers), shown as paired bars for the two budgets. (b) Per-region interregional financial transfers, showing unlimited and lowest-feasible transfer levels for each budget; tightening to 1.5 °C raises the total transfer volumes. (c) Net CO_2 emissions as a percentage change relative to 2020 levels to 2050 for the World and for higher- and lower-responsibility region groups, comparing the source scenario with lowest-feasible transfers. The unlimited-transfers corner reproduces the source pathway and is therefore plotted jointly with it as the dashed source line. (d) Regional carbon price shifts relative to the 2 °C source scenario.

source scenario and lower-responsibility regions draw on their remaining allocations, leaving the world trajectory essentially unchanged. Under the ECPC 2015 case, higher-responsibility regions reach approximately 55% below 2020 net CO_2 levels by 2040 under lowest-feasible transfers, compared with 49% in the source scenario, while lower-responsibility regions ease from 31% to 20% below 2020 levels, and the World benchmark shifts by roughly one percentage point while still preserving cumulative global outcomes by the end of the century (figure 2(a)). Benchmark global renewables deployment and electrification are largely indistinguishable across variants, whereas the total fossil phase-out accelerates when transfers are constrained, with global fossil primary energy in 2040 falling 3%–21% below the unlimited-transfers variant depending on the allocation approach, and with deeper cuts in gas use outweighing a marginally slower coal exit, due to faster near-term gross emissions reductions among higher-responsibility regions (SI table 5). Financially, the unlimited transfers variant quantifies cumulative interregional transfer obligations ranging from 10.1–44.8 trillion USD NPV (cumulative, 2026–2100, 5% discount rate) across the approaches we consider here. This reflects the upper bound in each case implied by an unconstrained and entirely financial operationalisation of effort-sharing, providing an analogue to common ex-post fair-share finance quantifications.

The lowest-feasible transfer variant reduces transfers to less than half in each case, reflecting shifts in mitigation effort to higher-responsibility regions. This represents a novel solution made possible by our framework, which together with the unlimited transfer variant bounds the new solution space where energy systems, financial transfers, and regional emissions trajectories all adjust endogenously to satisfy both the global climate constraint and regional fairness objectives. The range between these corners thus describes a continuum of feasible pathways, from large-scale financial flows to sharply accelerated

domestic transformation, that all respect global climate ambition in the source scenario from which they branch. The constrained transfer variant notably also represents a potential opportunity, where lower-responsibility regions may pursue additional technically feasible mitigation effort to reduce global temperatures further, helping minimise the disproportionate climate impacts to which these regions are often most vulnerable.

Importantly, the depth of this solution space is narrative dependent. Moving to the SSP1 "Sustainability" narrative, with faster decarbonisation potential and shifting demographic assumptions (see SI—Extended results), compresses the range between the corner solutions to the point where higher-responsibility regions could in principle meet their fair-share allocations without inter-regional cooperation, leaving the 100 billion USD per year policy floor as the binding constraint. In essence, this comparison quantifies the intuition that a sustainable development trajectory ought to make integrating fairness considerations easier. We turn next to the economics of this solution space.

4. The economics of equitable cooperation

Interregional transfers are redistributive financial flows. Under unlimited transfers (assuming all cooperation channels are available), they leave global consumption unchanged relative to the source scenario, because the physical system is unchanged. A global cost does arise, however, when mitigation efforts shift, such as when transfers are constrained, as reflected in the deviation in consumption from the global cost-effective allocations (figure 3). We report consumption rather than GDP here as the latter includes investment and energy-system expenditure that fair-share variants reallocate, so a region investing more to decarbonise faster can show higher output while households consume less. Under the ECPC 2015 fair-share variants, for example, we see that global consumption is unchanged under unlimited transfers and falls by less than 0.1% under lowest-feasible transfers relative to the source scenario. These magnitudes hold in general across all allocation approaches considered, where fair-shares variants with lowest-feasible transfers simply consumption losses of 0.1%–0.5% relative to the source scenario (0.8–1.3% relative to the no-new-policy reference scenario), with the upper bound reached under the CAPC 2015 allocation (SI table 4).

With the important caveat that we externalise climate damages and associated net welfare considerations here [38], we find that these shifts are distributionally progressive, where lower-responsibility regions see a reversal of economic outcomes across fair-share variants, relative to the globally cost-effective source scenario. The direction of these shifts follows intuition where fairness considerations endogenously reallocate effort from lower-responsibility to higher-responsibility regions. Notably, these consumption shifts are larger under lowest-feasible than unlimited transfer variants because resolving carbon debts through unconstrained finance leaves the underlying energy system largely unchanged, whereas constrained transfers forces integrated system shifts that generate economic spillovers for all regions (see SI—Extended results for comparison of results at purchasing-power parity).

As also noted in the earlier sections, substantive system shifts occur in the lowest-feasible transfer variants (and when cooperation mechanisms are constrained) where permitted (or expected) financial transfers do not resolve regional fair-share obligations. Here we show that under such a scenario and over the near term, greater volumes of capital flow out of fossil energy production and into renewable energy generation globally. This occurs because, when transfers are constrained, higher-responsibility regions can no longer purely finance mitigation abroad and must cut domestic emissions sooner. Between the two corners under the ECPC 2015 case, approximately 8.5 trillion USD NPV of additional transfers substitutes for approximately 170 Gt CO_2 of domestic higher-responsibility mitigation (figure 3(b)). The cost-effective domestic response is thus accelerated near-term renewables and storage deployment rather than late-century CDR. These reallocations are visible in regional carbon prices (figure 3(c)). Under lowest-feasible transfers in the ECPC 2015 case, carbon prices in higher-responsibility regions rise to approximately 1.5 times the uniform source scenario price, while prices in regions holding remaining allocation fall to between 0.65 and 1.0 times this level. This price difference reflects the effect of the transfer constraint on each region; under unlimited transfers a single global price is re-established and the difference disappears.

Finally, we note that delaying cooperation comes at a cost. We model a ten year delay in cooperation onset (under an ECPC 2015* variant). As shown in the earlier figure 2, under lowest-feasible transfers, cumulative near-term energy investment rises from 0.4% above the source scenario to approximately 1.2% under the delay variant (figures 2, 2026–2050 NPV), roughly tripling the near-term investment increment, with the greater shift from fossil to renewable investment is also visible over the full century (figure 3). Deferring cooperation therefore increases mitigation investment needs and transitional stress on the global energy system as higher-responsibility regions take on more of the global mitigation effort domestically to reduce accrued carbon

debt. We next turn to restrictions in cooperation mechanisms.

5. Restricting cooperation to novel CDR

The preceding analysis assumes a full range of cooperation mechanisms (excluding LULUCF), but in practice, international cooperation may be channelled through specific instruments (figure 4). We explore this by restricting interregional cooperation to financing novel CDR, specifically BECCS and DACCS, thereby excluding the broader suite of cooperation options available. Under this restriction, variants diverge from the source scenario even when transfer volumes are unconstrained. Figure 4 quantifies this shift at the global level, showing that gross emissions rise while net cumulative emissions are preserved by the end of the century, relative to the fair-share variants in which cooperation spans all mitigation options (excluding LULUCF). Under the CDR-only mechanism the transfer volume is nearly invariant to the permitted transfer level ($27.4 versus $27.0 trillion NPV), because the transferred CDR volume (approximately 125 Gt CO_2 in both corner solutions) is also governed by technical and geological rather than solely economic constraints (figure 4(c)). Expressed per tonne of mitigation transferred, cooperation restricted to novel CDR costs approximately 220 USD per tCO_2, roughly an order of magnitude above the 20–30 USD per tonne when cooperation spans all mitigation options (excluding LULUCF) (SI table 3). Roughly two-thirds of the higher-responsibility region overdraft (in the source scenario) is still met by avoiding it through domestic gross emissions reductions, with domestic novel CDR covering a further tenth (figure 4(b)). Global consumption losses rise from marginal to just over 0.6% relative to the source scenario (figure 4(e)). The majority share of transfers finance geological removals expected to be deployed in lower-responsibility regions in the source scenario (figure 4(b)), though we do see an acceleration of the global scale-up of geological sequestration, reaching the 6 Gt CO_2 per year around mid-century, ahead of the source scenario (figure 4(c)).

These aggregate responses comprise heterogeneous regional shifts driven by resource endowments and energy system structures. In higher-responsibility regions, the inability to finance non-CDR mitigation abroad leads to concurrent but distinct adjustments. All deepen domestic gross emissions reductions relative to the all-mitigation variant, particularly North America, Western Europe and China, while the Middle East and the Reforming Economies simultaneously scale up domestic sequestration (figure 4(d)). In lower-responsibility regions, CDR-specific finance produces responses shaped by local cost structures and constraints. Sub-Saharan Africa sees DACCS expansion at the expense of industrial CCS, leveraging geological storage potential as a regional resource for export, though concurrently generating higher net cumulative regional emissions offset by greater domestic effort in higher-responsibility regions. South Asia in contrast develops no additional removal-export capacity, reflecting its modelled novel CDR constraints, and instead only adjusts by drawing further on its remaining allocation, with net cumulative emissions beyond the all-mitigation variant (figure 4(d)).

These regionally differentiated responses confirm that restricting cooperation mechanisms produces integrated mitigation portfolio shifts that cannot be anticipated from ex-post analysis alone. We see that equitable cooperation solutions diverge from simple novel CDR reallocation as commonly assumed in fair-share studies conducted outside model frameworks. The global mitigation cost distortions induced by such a constraint evidently compel higher-responsibility regions to implement more stringent domestic action, comprising a range of context-dependent mitigation options, while incentivising some (not all) lower-responsibility regions to establish specialised, export-oriented carbon removal capacity where resource potentials permit. We finally turn to equitable cooperation under a 1.5 °C future.

6. Returning to 1.5 °C

The results above establish a deepened solution space comprising substitutable combinations of interregional cooperation and domestic action. We now examine whether this persists under a more stringent climate goal, applying the framework to an SSP2 narrative source scenario which limits warming in 2100 to 1.5 °C with approximately 50% likelihood, and considering a reference ECPC 2015 fair-share variant set (figure 5).

Our results show that tightening the budget increasingly exhausts surplus mitigation capacity across all regions, narrowing the scope for reallocating physical effort under fair-share constraints. Cumulative net emissions reallocated toward lower-responsibility regions between the corner solutions falls from approximately 120 Gt CO_2 under the 2 °C budget to approximately 35 Gt CO_2 under 1.5 °C (figure 5(a)), while total transfers roughly double at the unlimited corner (14.8–29.2 trillion USD NPV) and triple at the lowest-feasible corner (6.3–19.6 trillion USD NPV) (figure 5(b), SI table 2). Fair-share differentiation is thus increasingly settled through finance rather than through physical system shifts. Notably, whereas lowest-feasible transfers permit lower-responsibility regions to reduce net CO_2 by 2050 approximately 14%-points less than the source scenario under the 2 °C budget, this narrows to approximately 6%-points under 1.5 °C, leaving

these regions cutting emissions to roughly 76% below 2020 levels by 2050 even at lowest-feasible transfers, while global benchmarks remain essentially invariant across the corners (approximately 41% below 2020 levels by 2035 and 85% by 2050; figure 5(c)). The decomposition shows that domestic action continues to be achieved cost-effectively through immediate gross emissions reductions rather than through scaling novel CDR to address excess emissions in the second half of the century (figure 5(a)). Tightening the budget also scales the uniform carbon price to approximately 2.3 times the 2 °C source level, with the relative spread of regional prices around this level reducing under lowest-feasible transfers (figure 5(d)).

These results demonstrate that even under the most stringent carbon budgets, the pathway to collectively meeting 1.5 °C ambition is not singular. A tighter but persistent feasible solution space exists in which near-term gross emissions reductions among higher-responsibility regions, interregional financial transfers, and commensurate effort among lower-responsibility regions can be combined in multiple configurations, though with domestic mitigation capacity largely exhausted, the weight of differentiation shifts from the physical system toward finance.

7. Discussion

Our results demonstrate that endogenising principle-based fair-share considerations within IAM reveals energy system and economic dynamics that are not captured by ex-post fair-share analyses. This is a broader finding than the specific equity operationalisations we examine, demonstrating rather that the solution space available to policymakers is considerably deeper and faces important integrated feasibility considerations than captured by globally cost-effective pathways and ex-post distributional assessments.

Our framework reproduces the classical equity-efficiency [28, 30] result as its unlimited-transfer corner, with unrestricted transfers, equity and efficiency separate and the cost-effective pathway unaffected. Our main contribution concerns what happens when that idealisation fails. When expected transfers fall below these levels, meeting regional fairness considerations requires shifts in energy systems. This distinguishes our results from the existing literature describing; ex-post fair-share quantifications [19, 21, 39], fair financial obligations [28] or reallocation of CDR obligations [40, 41] without integrated energy-economy feedback, and the formative differentiated-effort literature [30] that explores the theoretical basis but does not directly link principle-based regional fair-shares with modelled regional efforts. For example, where ex-post assessments report fair-share finance as a fixed obligation, our corner solutions show that the required volume can move with shifts in physical effort while remaining consistent with aggregate climate outcomes. This structural reallocation between transfers and domestic effort defines the deeper solution space.

The aggregate nature of 'equitable cooperation' and of 'transfers' within our framework requires careful interpretation. We combine distinct cooperation channels, including climate finance for historical responsibility and cooperative mechanisms for cost-effective future mitigation, into a single financial flow, thereby abstracting from the complex institutional architectures necessary for implementation. In practice, these financial flows would operate through specific governance structures under the Paris Agreement, ranging from cooperative approaches under Article 6.2 to the centralized crediting mechanism under Article 6.4 (with its mandated cancellations for overall mitigation in global emissions and Adaptation Fund contributions), non-market approaches (Article 6.8), and direct financial support under Articles 9 and 10 of the Paris Agreement [42]. Our framework does not distinguish among these mechanisms or their specific modalities or uptake patterns. Consequently, our results should not be misconstrued as prescribing specific carbon market designs or endorsing Article 6 mechanisms to compensate for nationally determined contribution (NDC) shortfalls. Rather, they provide a model-based quantification of aggregate potential of interregional cooperation, encompassing both market and non-market approaches, to enable global collective climate action at scale.

With these caveats in mind, fair-share variants reveal a spectrum of opportunity from large scale financial transfers to rapidly accelerating domestic action. Across this spectrum the global welfare cost is small and distributionally progressive, with lower-responsibility regions gaining relative to the cost-effective source scenario. A key and consistent feature of the latter end of the spectrum is the shift toward near-term gross emissions reductions when permitted transfer levels are constrained. This 'gross emissions reductions first' strategy generates system-wide benefits, releasing pressure on lower-responsibility regions to collectively meet climate goals. The dynamics we observe shift under more optimistic sustainable development futures, where faster and cheaper decarbonisation across all regions reduces the carbon debt requiring interregional cooperation, making fairness considerations easier to reconcile with high ambition. The choice of cooperation mechanisms also matters, though perhaps counterintuitively, highlighting the importance of integrated model quantifications in examining these trade-offs. Restricting cooperation to novel CDR, for example, forces higher-responsibility regions to pivot toward earlier and deeper domestic gross emissions reductions while incentivising some others to leverage geological storage capacity as a regional resource, with

heterogeneous responses shaped by local cost structures and resource endowments. Above all, our results demonstrate that the window for regional differentiation remains open even in 1.5 °C-consistent scenarios where the remaining carbon budget is effectively exhausted before the first model timestep. The composition of this differentiation nevertheless shifts as budgets tighten, with domestic mitigation capacity at the limit, differentiation is expressed less through reallocated physical effort and more through interregional finance, raising the practical weight of interregional cooperation and collective finance commitments in any equitable operationalisation of 1.5 °C ambition. Importantly, none of these dynamics are visible within ex-post fair-share assessments of cost-effective source scenarios; they emerge only when the scenario generation process itself accounts for differentiated regional responsibilities and capabilities.

By embedding fairness objectives in the scenario generation process, as constraints imposed at scenario design stage and satisfied through endogenous modelled cooperation mechanisms, our framework extension produces internally consistent scenario variants that are distinct from, yet as 'feasible' as, their cost-effective source scenarios. These variants are self-consistent model solutions that explore pathways previously absent from scenario ensembles. This matters for policy deliberations as it demonstrates that the contemporary scenario evidence base can and should be deepened to explore the full range of feasible futures available to decision-makers. Ultimately, this unifies the urgent scientific basis for ambition with the equally pressing normative basis for fairness and should encourage future scenario assessments to routinely explore such variants, particularly lowest-feasible transfers, alongside globally cost-effective pathways.

Several limitations motivate future work. All fair-share variants presume functional multilateral governance and regional adherence to allocated budgets, requirements that may be difficult to imagine in the current geopolitical context, though this caveat applies equally to any scenario describing global pathways consistent with returning to 1.5 °C. The operationalization of fairness objectives relies on specific value judgements. The allocation approaches examined here, remain a subset of the many valid interpretations of CBDR&RC, and their application is predicated on emissions allocation rather than explicit development objectives or broader justice considerations, which could be explored in future work within this framework. Relatedly, we externalise climate damages, where the reported consumption outcomes capture mitigation costs and interregional transfers only, whereas damage falls disproportionately on the same lower-responsibility regions that gain under cooperation, so a damage assessment of the welfare outcomes is a possible extension requiring work beyond the scope of this study. Furthermore, achieving 1.5 °C regardless of fair-share considerations requires large-scale CDR in the second half of the century. While all scenarios examined here remain within prescribed geological carbon storage limits, the required scale up and injection rates remain an avenue for further exploration. Finally, the boundaries drawn between 'covered' and 'excluded' emissions, specifically the exclusion of international shipping and aviation and LULUCF emissions from the fair-share logic in our illustrative examples, represent strong normative choices that will influence regional obligations.

By offering a generalisable, modular approach for producing and exploring scenario variants in a structured manner, we help move beyond the paralysis of the 'fairness versus efficiency' debate and contribute to the robust evidence base required for the next generation of NDCs to the Paris Agreement. This approach reframes the implementation challenge from debating whether fairness is compatible with ambition to navigating within an expanded solution space where equitable cooperation functions as a structural element of climate action. As the world approaches the critical juncture of emerging 1.5 °C exceedance and the second Global Stocktake to the Paris Agreement, this work makes clear that fairness need not be a constraint on ambition but can instead be a defining feature of its feasibility.

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Data availability statement

The code, figures and model reporting data that reproduce this analysis are archived on Zenodo at https://doi.org/10.5281/zenodo.22686495 (GitHub: https://github.com/setupelz/repl_2026_faircoop), and the interactive explorer of the scenarios is at https://setupelz.com/faircoop/.

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