Separate sectoral decarbonization policies accelerate climate action but could jeopardize key sustainability targets

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Abstract

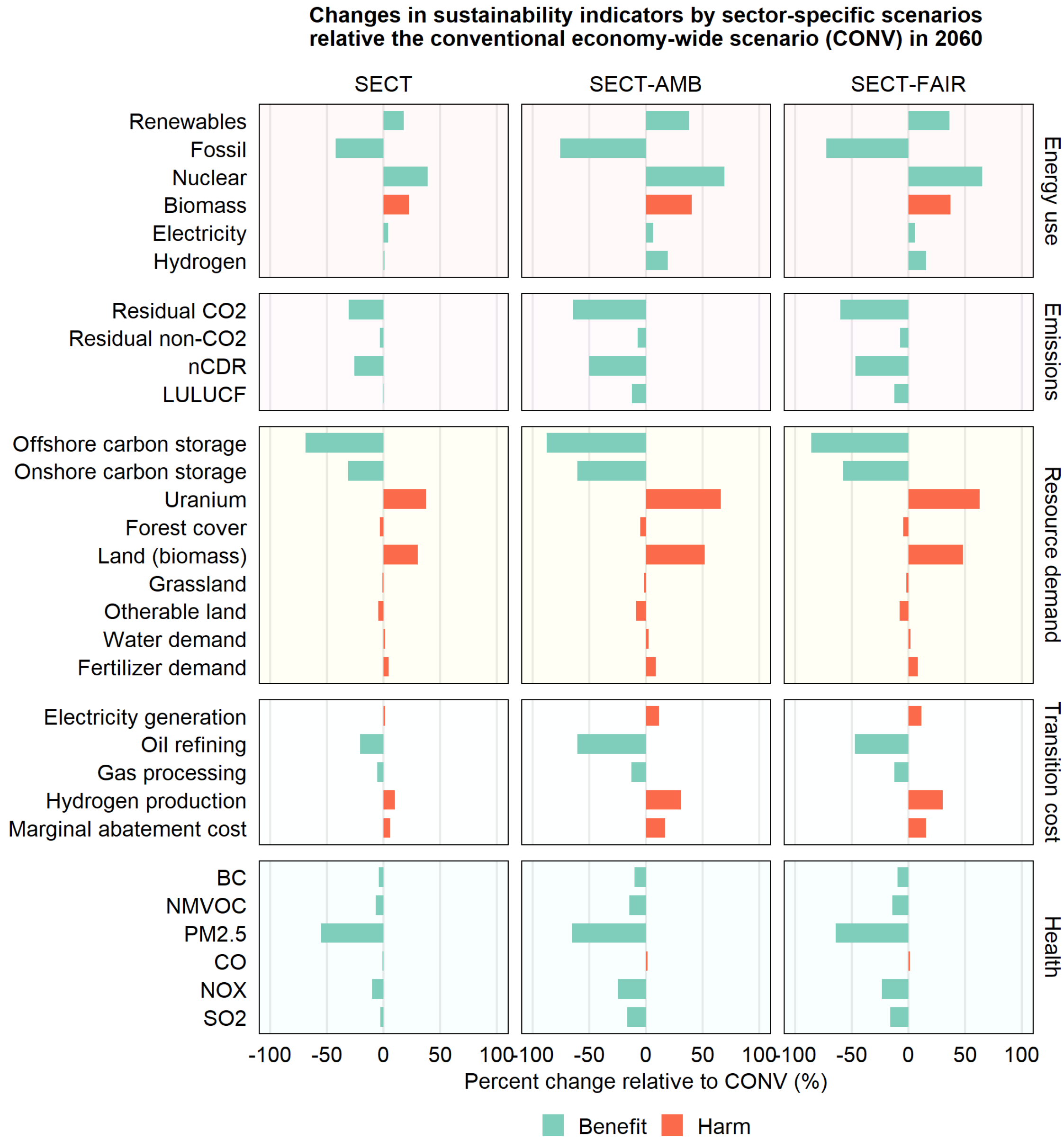
The Paris Agreement grants countries flexibility in designing their pathways to net-zero emissions, yet most have focused on economy-wide, cost-effective approaches without clearly defining the role of sectoral emission reductions and/or carbon dioxide removal (CDR). These blanket strategies prioritize low-cost sectors, leaving significant residual emissions and relying on uncertain, largely unproven CDR technologies to bridge the gap—an inherently risky approach.

In this study, we introduce a new framework that incorporates the explicit role of sector decarbonization. We examine three variations of sector-specific policies: selective (SECT), universal (SECT-AMB), and equity-informed (SECT-FAIR), and compare them with a conventional economy-wide carbon pricing scenario (CONV), all aligned with limiting warming to 1.5°C.

Our findings reveal that by 2060, sector-specific policies could reduce residual GHG emissions by 6–12 $GtCO_2$/year and lower gross CDR requirements as well by 6–12 $GtCO_2$/year compared to CONV. They also achieve slightly lower peak warming (by 0.006–0.01°C) and cut air pollution (PM2.5) by over 50%. However, these gains are accompanied by trade-offs, including higher transition costs, increased demand for biomass, water, uranium, and fertilizer, and potential risks to biodiversity from forest loss and land-use shifts.

To maximize the climate benefits of sector-specific policies with no or limited sustainability impacts, it is crucial to carefully design and implement these policies with a focus on minimizing resource demands, protecting biodiversity, and addressing potential trade-offs, while also ensuring that they complement, rather than hinder, efforts to achieve net-zero emissions and climate stability.

Graphical abstract



Introduction

As global carbon dioxide (CO_2) emissions continue to rise, the remaining carbon budget (RCB) continues to diminish rapidly [1,2]. Based on current emissions, the remaining carbon budget (RCB) to limit global warming to 1.5°C (likelihood of 33-67%) could be entirely exhausted within the next 4-7 years [1,3]. Immediate and substantial net emission reductions, through a combination of aggressive decarbonization and complementary carbon dioxide removal (CDR) [2], are urgently needed to accelerate progress toward global net-zero targets and halt further temperature increases.

In response to this urgency, more than 70 percent of countries have some commitment to achieve domestic net-zero emissions within this century [4]. However, many of these commitments fall short in clearly quantifying the respective contributions of sectoral emission reductions and removals [5,6]. This ambiguity stems from a preference for economy-wide carbon pricing approaches, which are typically more cost-effective and politically appealing than defining detailed sector-by-sector targets [7–12]. The flexibility allowed under the Paris Agreement, along with the many ways in which the RCB can be managed [13], creates room for countries with strong fossil fuel interests to delay immediate emission reductions and instead rely on the future deployment of CDR technologies [14], once they become economically viable.

However, such delays come at a cost. Each year of postponed emission reduction increases the burden on future CDR to deliver larger net negative emissions to meet the same climate target. For instance, the Sixth Assessment Report of the International Panel on Climate Change (IPCC AR6) scenarios show that 1.5°C pathways which involve rapid near-term emissions reductions with limited or no temperature overshoot require a median cumulative net negative of 220 $GtCO_2$ from the year of net zero to 2100. In contrast, 1.5°C pathways with delayed reductions and higher overshoot require a median of 360 $GtCO_2$ of net negative emissions over the same period. Greater reliance on future CDR not only assumes successful scale-up of technologies that remain unproven[2,15–17] but also increases the risk of overshooting safe CO_2 levels in the atmosphere if those technologies fail to deliver. Moreover, large-scale CDR deployment raises sustainability concerns, including land-use competition, increased energy demand, and threats to food and water security [18–23].

These concerns have led to urgent calls for the formulation of pathways that limit the reliance on and requirement for CDR. Studies such as those by Fuhrman et al. [24], Grubler et al. [25], and Edelenbosch et al. [26], have taken initial steps in addressing these calls, demonstrating that sector-specific targets and reductions in sector energy consumption can reduce CDR requirements and lower peak and end-of-century warming. However, these studies assume common sector-specific policies globally, which is convenient for simplicity in policy design and modeling. When such generalized policies are applied universally, they could lead to a rapid and disruptive energy transition process with significant unjust transitions for low-income countries [27]. In this context, key questions arise: Should sector-specific policies be limited to only rich and historically large emitters while the rest of the world follow cost-effective economy-wide pathways? Alternatively, due to the rapidly declining remaining carbon budget, should all countries be mandated to pursue sector-specific policies with equal level of stringency? Or, for reasons of equity and just transition, should some countries bare heavier sector-specific decarbonization burdens than others?

To address these gaps, this study evaluates how differentiated sector-specific approaches compare with conventional economy-wide policies regarding CDR reliance, climate outcomes, and sustainability impacts. We analyze three sector-specific scenarios against a standard economy-wide benchmark (CONV), all aligned with limiting warming to 1.5°C. The first scenario, "SECT," applies sector-specific decarbonization to historically significant emitters, while other countries follow economy-wide cost-effective targets. The second scenario, "SECT-AMB," extends sector-specific policies to all countries, recognizing the urgent need for collective action. Finally, the "SECT-FAIR" scenario takes equity principles into account, imposing stricter sector-specific obligations on historically large emitters while allowing lower emitters more flexibility (see Table 1 for scenario details). Together, these scenarios clarify how the design of climate policies, universal versus selective, uniform versus differentiated, and cost-effective versus equity-informed, shapes emission trajectories, sectoral transitions, and reliance on CDR. This framework provides key insights into how policy choices influence ambition, cost, equity, and feasibility, offering actionable guidance for developing effective and fair climate policies.

Our approach differs from traditional economy-wide integrated assessment model (IAM) scenarios by setting explicit emission reduction targets within the energy and industrial processes sectors. While most previous scenarios from IAMs rely on a backcasting approach [28], which identifies pathways to meet predefined climate targets through a single economy-wide carbon price [7–12], our we focus on sector-specific policies in this study. This method directly targets emissions reductions in high-impact sectors without relying on the least-cost pathways of economy-wide strategies, which can delay action in critical sectors (See Figure 1). We find that compared to economy-wide targets, sector-specific policies could reduce residual GHG emissions by 6–12 $GtCO_2$/year and lower CDR requirements as well by 6–12 $GtCO_2$/year by 2060, resulting in slightly lower peak warming (0.006–0.01°C) and a 50% reduction in PM2.5 air pollution. However, these benefits come with trade-offs, including higher transition costs, increased demand for biomass, water, uranium, and fertilizer, and potential risks to biodiversity.

Here, we reveal the importance of sector-specific policies in achieving rapid decarbonization while reducing reliance on uncertain climate mitigation technologies such as CDR, offering a more direct path to meeting 1.5°C climate targets. For policymakers, these findings highlight the need to balance emissions reductions with sustainability considerations, ensuring that sectoral strategies are carefully designed to minimize resource demands and protect biodiversity while achieving climate goals.

Methods

The objectives of this study are achieved using a modified version of Global Change Analysis Model (GCAM-TJU), one of the most widely used integrated assessment models. GCAM operates by converting primary energy resources into secondary energy carriers through various energy transformation sectors. Market shares among competing technologies within these sectors are allocated based on either relative cost or absolute cost logits, influenced by technology costs, efficiency, and fuel prices [29]. Key inputs determining the cost of a technology include non-energy costs—covering capital, construction, operation, and maintenance expenses—and the efficiency of energy transformation, where more efficient technologies use less fuel per unit of output. Fuel prices, another critical parameter, are determined endogenously within each modeling period, reflecting changes in supply, demand, and resource depletion [30,31]. GCAM achieves market equilibrium by simulating decision-making processes of representative agents across multiple sectors (e.g., regional electricity, refining, land use). These agents base their resource allocation on costs, prices, and other relevant factors, interacting through markets for physical goods (like electricity and agricultural commodities) and services (such as emissions permits). The model iteratively adjusts prices to balance supply and demand across all commodities, including fossil fuels and emissions permits, thus ensuring market equilibrium in each period [32]. Emission calculations within GCAM are performed by associating CO_2 emissions with the fuel consumption of each technology, based on global average emission coefficients (e.g., CO_2 per gigajoule) for coal, oil, and natural gas. Additionally, emissions from agriculture and land use changes are calculated based on the extent of these changes, the carbon density of ecosystems, and regional growth profiles [33]. Hector v.2.5.0 is the default climate model within the version of GCAM used in this study. The global historical trends of surface temperature, atmospheric CO_2, and radiative forcing are reproduced by Hector [33]. Additional details of the model's land, water, and fertilizer modules are described in detail in the Supplementary Information.

Updates to GCAM in current study

In this study, we adopt a distinct modeling approach to evaluate sector-specific CO_2 emission reductions. Our primary objective is to model explicit emission reduction targets across all energy and industrial processes. To achieve this, we utilize our modified version of GCAM 6.0, known as GCAM-TJU 6.0, which incorporates the functionality to impose direct emission reduction targets on specific sectors. In the standard version of GCAM, CO_2 emissions from energy, industry, and other sources are aggregated under a single "CO2" tag. This structure enables cost-effective mitigation across the economy but does not allow for differentiated sectoral targets. As a result, emission reductions are concentrated in the sectors where it is cheapest to act, often leaving significant residual emissions in harder-to-abate areas. Our modification addresses this limitation by separating energy and industrial process emissions from the common CO_2 tag. We assign unique tags to these sectors, allowing the model to independently apply and track explicit reduction targets in each sector within a single model run. This represents a major improvement over previous modeling efforts, which typically required manual, iterative adjustments to simulate fuel or technology shifts, or applied a uniform carbon price across all sectors. That approach often led to an underestimation of emissions in key sectors. Our framework offers a more direct and transparent way to evaluate the outcomes of sector-specific climate policies.

With the exception of these updates, all other technological, energy, materials and cost assumptions are same as those present in the standard version of the model, and are available in detail in a public GitHub repository [31].

Modeling sector decarbonization pathways for CONV, SECT, SECT-AMB, and SECT-FAIR

CONV represents a conventional economy-wide approach designed to limit global warming to 1.5°C, where a uniform carbon price is applied across all sectors of the economy. This means that each country faces the same carbon price, regardless of sector. In this scenario, global net greenhouse gas (GHG) emissions reach zero by 2060. According to the scenarios assessed in the IPCC AR6 [2], pathways consistent with a 1.5°C target reach net-zero GHG emissions from 2050 onwards (within the 5th to 95th percentiles). Non-CO_2 GHG emissions are converted to CO_2 equivalents using 100-year global warming potentials (GWPs). Importantly, emissions from land-use change are not included in the emission constraint. However, emissions from land use are subject to a carbon tax at a fraction of the carbon price imposed on fossil fuel and industry emissions. This tax gradually increases from about 10% to 100% between 2025 and 2100, incentivizing both emission reductions and carbon storage through land-use changes such as afforestation and reforestation [34].

In our scenarios, the amount of CDR deployment is determined endogenously within the model. Since it is often more cost-effective to delay emission cuts and offset emissions later through CDR, the presence of these technologies under uniform carbon pricing pathways can inadvertently slow down emission reduction efforts [35], leading to pathways where the role of CDR, especially before mid-century, becomes exaggerated [10] (Fig. 1). This is particularly concerning given that these technologies have yet to be proven at scale [15]. Consequently, there have been urgent calls within the scientific community to detach CDR and decarbonization targets as a means of ensuring that negative emissions can be scaled up without undermining significant emission reduction efforts [36,37]. We examine three variations of sectoral implementation: selective (SECT), universal (SECT-AMB), and equity-informed (SECT-FAIR), and compare them with a conventional economy-wide carbon pricing approach (CONV), all aimed at limiting global warming to 1.5°C.

The selective sector-specific scenario (SECT) introduces explicit emission reduction targets for energy and industrial sectors, but only in countries with above-average historical fossil fuel and industrial emissions from 1830 to 2023. Historical emissions data, collected from Jones et al. [38], were mapped to GCAM's 32 regions, and cumulative emissions up to 2023 were calculated for each region. Countries or regions above the global average of 59.19 $GtCO_2$ were classified as major emitters, including the US (431 $GtCO_2$), China (274 $GtCO_2$), EU-27 (479 $GtCO_2$), India (62 $GtCO_2$), Japan (68 $GtCO_2$), Middle East (65 $GtCO_2$), and Russia (121 $GtCO_2$). These major emitters are required to reduce their energy and industrial CO_2 emissions by 85% by 2050 and 113% by 2100 relative to 2020 levels, while the rest of the world continues under the economy-wide carbon price. The benchmark pathway chosen is based on IPCC AR6 C1 and C2 scenarios for the variable "Emissions|CO2|Energy and Industrial Processes" (50^{th} percentile).

Building on SECT, the universal and ambitious sector-specific scenario (SECT-AMB) applies the same sectoral targets as in SECT but this time globally. Each country and region is required to reduce its energy and industrial CO_2 emissions by 85% by 2050 and 113% by 2100 relative to 2020 levels. In this scenario, we recognize the rapidly diminishing carbon budget and call for a collective global effort to achieve the net-zero target irrespective of historical responsibilities. While this scenario distributes the burden more evenly across all nations, the burden on historically large emitters is somewhat reduced compared to SECT, due to the universal nature of the effort.

Acknowledging the need for all countries to contribute to future sustainability, the SECT-FAIR scenario incorporates equity and just transition principles. It extends SECT-AMB by adjusting the level of stringency for those with lower historical emissions. Under SECT-FAIR, historically large emitters follow the same stringent mitigation pathway as in SECT-AMB, but other countries adopt a less aggressive trajectory. These countries reduce their energy and industrial CO_2 emissions by 74% by 2050 and 98% by 2100 relative to 2020 levels, consistent with the 75th percentile of IPCC benchmarks for 1.5°C-compatible pathways. Table 1 provides a general description for these four scenarios.

To fully test the climate and sustainability impacts, co-benefits, and trade-offs without external interference, we did not impose any limits on biomass consumption or geological carbon storage in any of the scenarios. This approach ensures that the observed differences between the scenarios are driven primarily by the availability of uniform versus multiple carbon pricing mechanisms, rather than constraints on resource use. This design allows us to explicitly isolate the effects of sector-specific policies without external interference from other components within the model.

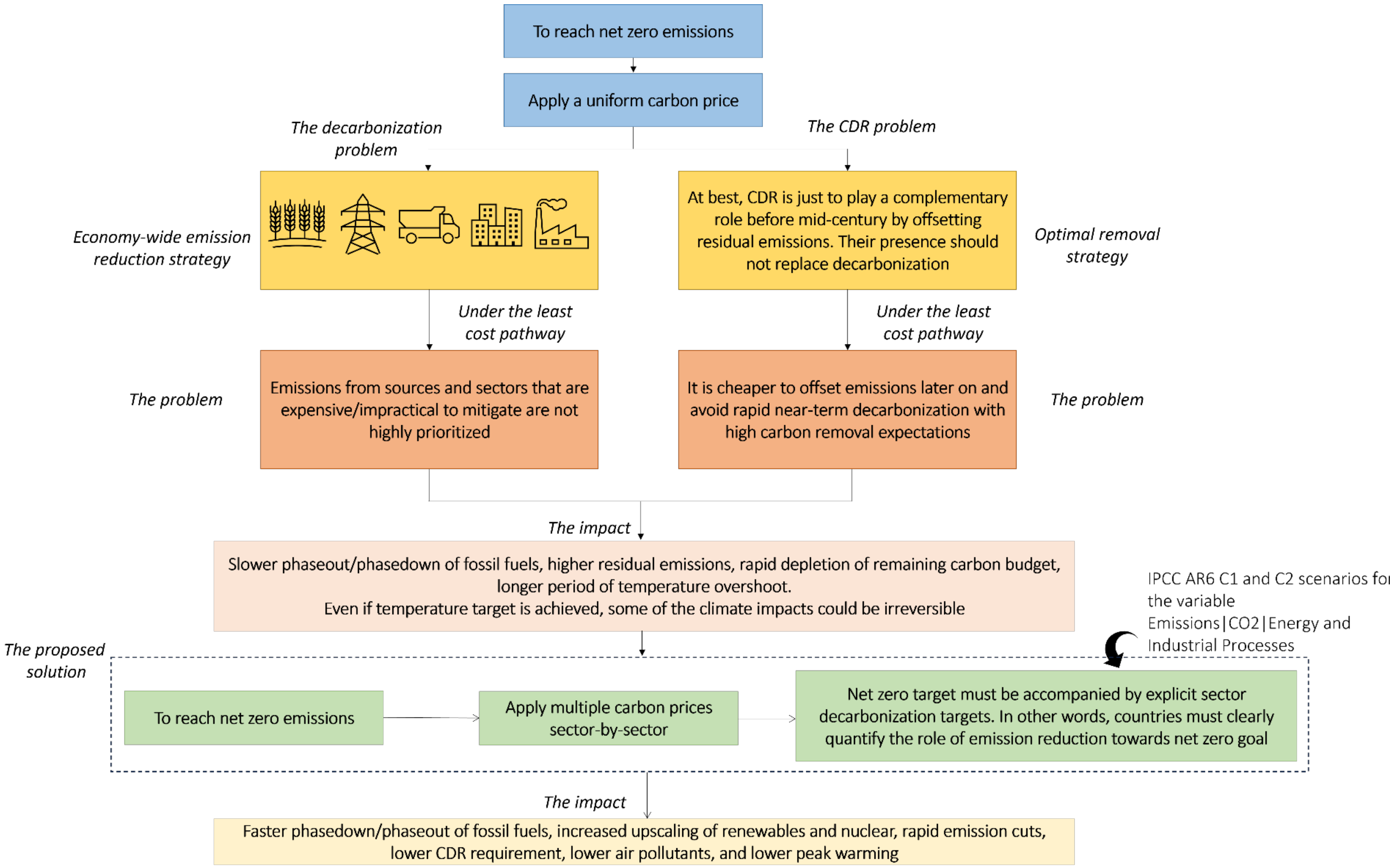


Fig. 1 Conceptual framework depicting economy-wide uniform carbon pricing strategies towards net zero and the negative impacts associated with such policy designs. Sector-specific targets that accompany the broad net zero target has the potential to significantly remedy this problem

Table 1 Scenarios' description.

Scenario	Eligibility criteria for mandating sectoral policies	Benchmark pathway for sectoral emission reduction	Description of benchmark pathways consistent with 50th and 75th percentiles	Pathway(s) for eligible regions
Conventional (CONV): Global 1.5C under one uniform carbon price pathway where total net zero GHG is expected by 2060	None	None	None	None
Sectoral (SECT): Follows CONV but with explicit targets for energy and industrial sectors towards the broad global net zero goal.	Limited solely to countries with historical cumulative fossil fuel CO2 emissions from 1830-2023 higher than the global average (see Method for eligible regions)	**SECT and SECT-AMB:** IPCC AR6 C1 and C2 scenarios for the variable "Emissions|CO2|Energy and Industrial Processes" (50th percentile).	For 50th percentile, relative to 2020 levels, each region must reduce its energy and industrial sectors' CO2 emissions by 85% and 113% by 2050 and 2100, respectively	**SECT:** Each eligible country and region must set sector specific targets towards the broad global net zero goal.
Sector-ambitious (SECT-AMB): Same as SECT	All GCAM countries and regions are eligible			**SECT-AMB:** Same as SECT. However, all countries and regions are mandated to explicitly pursue sectoral emission reduction targets towards the broad global net zero goal. The level of level of sector mitigation stringency is same for all countries.
Sector-fair (SECT-FAIR): Same as SECT	Follows SECT-AMB but with equitable consideration of sectoral emission targets	IPCC AR6 C1 and C2 scenarios for the variable "Emissions|CO2|Energy and Industrial Processes" (50th percentile for major emitters and 75th percentile for rest of the world)	For 50th percentile, relative to 2020 levels, each region must reduce its energy and industrial sectors' CO2 emissions by 85% and 113% by 2050 and 2100, respectively.	**SECT-FAIR:** Same as SECT-AMB but takes equity and just transitions into account, ensuring that historically-large emitting countries take on more stringent sector decarbonization pathways (50th percentile), while providing lower historical emitters the opportunity to pursue relatively less stringent sector decarbonization targets (75th percentile) without compromising the broader net zero goal.

			For 75th percentile, relative to 2020 levels, each eligible region must reduce its energy and industrial sectors' CO2 emissions by 74% and 98% by 2050 and 2100, respectively	

Note: *Under the economy-wide scenario (CONV), a uniform carbon price applies equally across all countries and sectors in pursuit of the net-zero target. In contrast, under our sector-specific scenarios, each country or region adopts its own unique energy and industrial process carbon price, distinct from the carbon price on other non-energy/industrial sectors of the economy. To simplify our analysis, we applied this region-specific differentiated carbon price uniformly across all energy and industrial sectors within each region. However, the emission reduction benefits identified here could potentially be even greater if each individual sector within a region were assigned its own tailored carbon price. Such detailed sector-level differentiation, though valuable, lies beyond the scope of this study. Here, we primarily aim to highlight the importance and effectiveness of implementing region-based sector-specific policies within broader net-zero goals as against global economy-wide cost-effective approach.*

Results

Our results indicate slower emission reductions when relying solely on economy-wide strategies (CONV) in pursuit of net-zero targets. This slower pace occurs because economy-wide policies use a single, uniform carbon price applied equally across all sectors to meet climate objectives. Driven by cost-effectiveness, this approach mainly targets sectors where emissions reductions are cheapest, leaving substantial emissions largely untouched in sectors that are more expensive or considered "hard-to-abate." The underlying assumption is that cheaper CDR options will become available in the future to offset these residual emissions, thus delaying immediate and essential action.

In contrast, sector-specific policies introduce distinct carbon prices explicitly tailored for each region's sectoral emission reductions, separate from the general economy-wide price. This tailored pricing compels immediate and deeper reductions across all sectors, even those traditionally viewed as difficult or expensive to decarbonize. Consequently, adopting sector-specific policies accelerates emission reductions, significantly lowering cumulative emissions and reducing future dependence on uncertain CDR technologies.

Compared to CONV, the SECT-AMB scenario prevents approximately 125 $GtCO_2$ of gross fossil fuel and industry (FFI) CO_2 emissions globally between 2025 and 2060 (Fig. 2). To put this figure into perspective, this avoided emissions for the next 35 years is equivalent to twice India's cumulative historical emissions over the last 190+ years. Additionally, it surpasses the combined historical emissions of Australia, Brazil, Pakistan, South Africa, South Korea, Argentina, and Colombia from 1830 to 2023. (Also see Supplementary Figure S1 and Supplementary Figure S2 for results on SECT and SECT-FAIR).

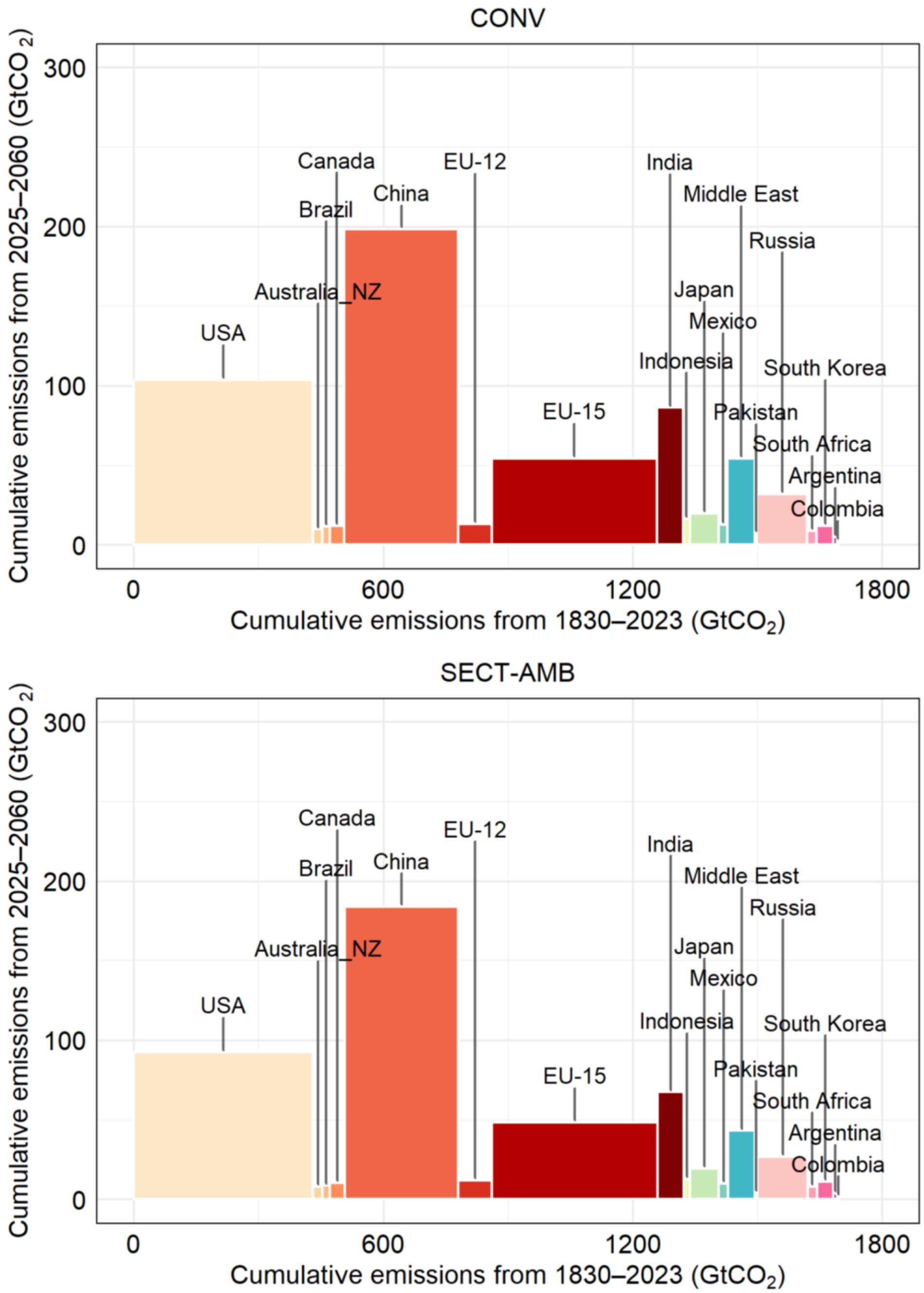


Fig. 2 Impact of sector-specific and economy-wide pathways on gross emission reduction. The results show cumulative emissions from 2025-2060 on the y-axis and historical cumulative emissions since 1830-2023 in the x-axis. The upper panel represents results for CONV scenario and that of SECT-AMB is in the lower panel

At a global level, applying sector-based policies universally accelerates emission reductions more effectively than uniform economy-wide approaches. Also, if sector-specific targets are limited only to historically large emitters (the SECT scenario), global emissions decline more slowly than in scenarios where every country explicitly adopts sector-specific commitments (SECT-AMB and SECT-FAIR). Yet, at the country level, interesting differences emerge (Fig. 3). Under the SECT scenario, major emitters bear greater responsibility, explicitly targeting emissions reductions in their most polluting sectors. Under the same climate target, this selective or equity-informed sector-specific approach indirectly eases decarbonization pressures on other countries compared to the conventional economy-wide (CONV) scenario.

For example, aggressive decarbonization efforts by major emitters under SECT allow African and Latin American countries to collectively emit approximately 600 million tonnes more residual emissions in 2060 than they would under CONV (Fig. 3a). Furthermore, extending sector-specific policies globally rather than limiting them solely to major emitters further distributes the decarbonization effort more evenly. The USA, for instance, would face cumulative emissions of about 116 $GtCO_2$ between 2020 and 2060 under the SECT scenario. However, if all countries embraced sector-specific emission targets (SECT-AMB), the USA could avoid the additional burden of mitigating around 2 $GtCO_2$ (Fig. 3b).

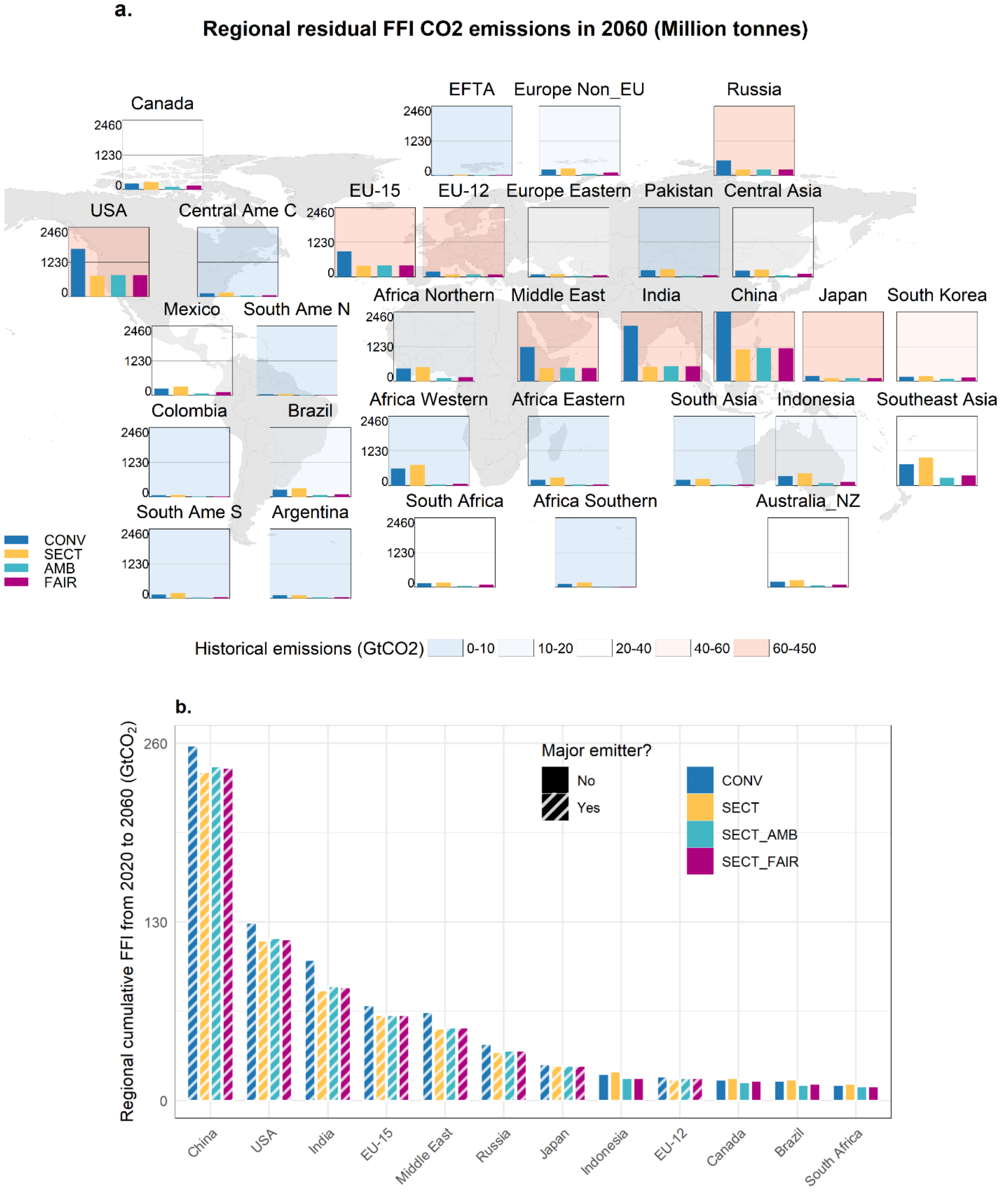


Fig. 3 Impact of sector-specific and economy-wide pathways on regional residual and cumulative emissions. (a) Regional residual FFI CO2 emissions in 2060 (b) Cumulative FFI CO2 emissions from 2020-2060 for selected regions. Historical emissions data, collected from Jones et al. [38]*, were mapped to GCAM's 32 regions, and cumulative emissions up to 2023 were*

calculated for each region. For our study, countries or regions above the global average of 59.19 $GtCO_2$ have been classified as major emitters, including the US, China, EU-27, India, Japan, Middle East, and Russia.

All our scenarios are consistent with limiting global warming to 1.5°C. However, based on their projected gross CO_2 emissions (without considering their negative emissions), both CONV and SECT-AMB would exceed the RCB. According to the IPCC AR6 (50th percentile for all C1 and C2 scenarios), this budget is approximately 500 $GtCO_2$ from 2020 onwards [2]. Crucially, because of faster emission reductions under SECT-AMB, this exceedance is significantly smaller, with 47 $GtCO_2$ less than under CONV by 2050 (Fig. 4a).

Since all scenarios overshoot the RCB, temperatures are projected to temporarily rise above the 1.5°C target. By the time global net zero CO_2 is achieved (around the 2050s) and net zero GHG emissions (around the 2060s), peak warming is expected to surpass 1.7°C in all our scenarios. Nevertheless, due to quicker near-term emission cuts, sector-specific scenarios show a lower peak temperature, approximately 0.006–0.01°C less than CONV at the point of net zero GHG (Fig. 4b).

The implications of this difference are substantial. The delayed action and greater overshoot in the CONV scenario necessitate significantly higher carbon dioxide removal in the long run. By the time net zero GHG emissions are required, CONV will demand about 27 $GtCO_2$/yr of gross negative emissions to counterbalance residual emissions. In contrast, SECT-AMB would require less than 15 $GtCO_2$/yr to reach the same net-zero target by the same deadline, highlighting the advantage of proactive, sector-specific action in reducing reliance on extensive, uncertain CDR technologies (Fig. 4c).

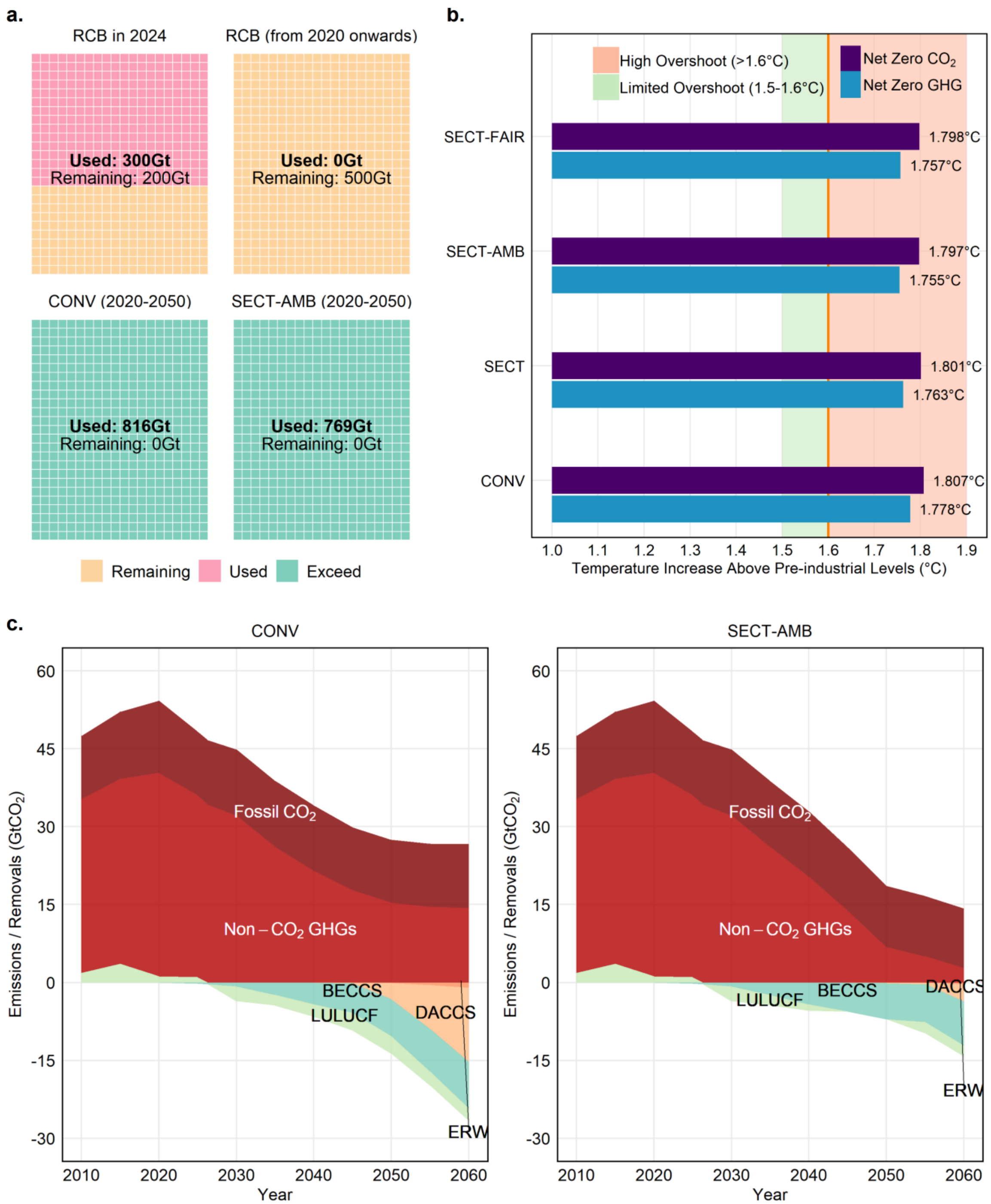


Fig. 4 Climate impacts of sector-specific and economy-wide pathways. (a) Represents the remaining carbon budget of 500 $GtCO_2$ from 2020 onwards (IPCC AR6 50th percentile for 1.5C) [2]. *There are 500 tiles within each square, and a single tile represents 1 $GtCO_2$. As of 2024, the world has already used 300 out of the remaining 500 $GtCO_2$* [39]. *(b)Temperature increase above pre-industrial levels at both net zero GHG and CO2 for all four scenarios. (c) Positive and negative emissions under*

CONV and the most ambitious sector-specific scenario. (Also see Supplementary Figure S3 and Supplementary Figure S4 for results on SECT and SECT-FAIR).

As reliance on future CDR increases under the economy-wide CONV scenario, the volume of emissions left unabated also grows substantially (Fig. 5a). For instance, the cumulative reliance on technological CDR in the USA from 2020 to 2060 decreases significantly, from 55 GtCO_2 under CONV to just 22 GtCO_2 under SECT-AMB, which forces a much faster rate of emissions reduction to meet the same net emissions target. Brazil further illustrates this shift vividly: under CONV, Brazil stands out prominently, deploying nearly 20 GtCO_2 of negative emissions technologies with about 14 GtCO_2 of cumulative gross emissions. However, transitioning to SECT-AMB significantly reduces Brazil's reliance on CDR (from 20 GtCO_2 down to 4 GtCO_2) with a rapid cut in cumulative emissions from 14 GtCO_2 to 11 GtCO_2.

Fig. 5a also highlights another crucial metric, which is the ratio of CDR to residual emissions in the year global net-zero GHG emissions are achieved. A ratio of exactly 1 signifies net-zero CO_2 emissions, values below 1 indicate more emissions remaining than can be removed (net-positive CO_2 emissions), and ratios above 1 indicate removal of more CO_2 than remains emitted (net-negative CO_2 emissions) [40]. Under the CONV scenario, many countries end up with ratios below 1, shifting additional burdens onto other nations to achieve higher ratios and collectively reach global net-zero around mid-century. In contrast, under SECT-AMB, this responsibility is more evenly distributed. Only South Korea and South Africa (from our selected countries in the figure) achieve ratios below 1 in SECT-AMB, compared to seven countries under CONV. Consequently, countries like the USA and Brazil experience increased pressure under CONV, having to achieve significantly higher ratios (3.2 and 8.5, respectively) compared to relatively manageable ratios (2.5 and 7.7) under SECT-AMB (Also see Supplementary Figure S5 and Supplementary Figure S6 for results on SECT and SECT-FAIR).

These disparities in emission reduction burdens are also clearly reflected in the timing of domestic net-zero CO_2 targets (Fig. 5b). Under CONV, several countries, including India, the Middle East, and the EU-12, do not achieve domestic net-zero CO_2 before 2060 due to delays in near-term emission cuts and reliance on the expectation of cheaper future CDR technologies. This delay shifts the burden onto other countries, such as the USA and Canada, which must reach net zero by 2050 and 2042 respectively, five and ten years earlier than under SECT-AMB. This is because under the SECT-AMB scenario, most countries prioritize immediate emissions reductions rather than relying heavily on future CDR, resulting in widespread achievement of domestic net-zero emissions before 2060 and reducing the burden on individual nations to accelerate their domestic net zero timelines.

Furthermore, if sector-specific policies are limited exclusively to historically large emitters while other countries continue with economy-wide, cost-effective approaches, major emitters would need to achieve domestic net-zero emissions earlier compared to scenarios where sector-specific mandates are globally shared. For example, under the SECT scenario, China would need to reach domestic net-zero by 2049. However, if every country adopted sector-specific targets (SECT-AMB or SECT-FAIR), China could relax its decarbonization pace slightly, achieving domestic net-zero emissions 3–5 years later without jeopardizing the global mid-century net-zero goal. The opposite trend emerges for historically lower-emitting countries. Under SECT, Argentina reaches domestic net-zero emissions in 2046, which is about 5 to 7 years later than it would under global sector-specific policies such as SECT-AMB or SECT-FAIR (Supplementary Figure S7 to Supplementary Figure S8).

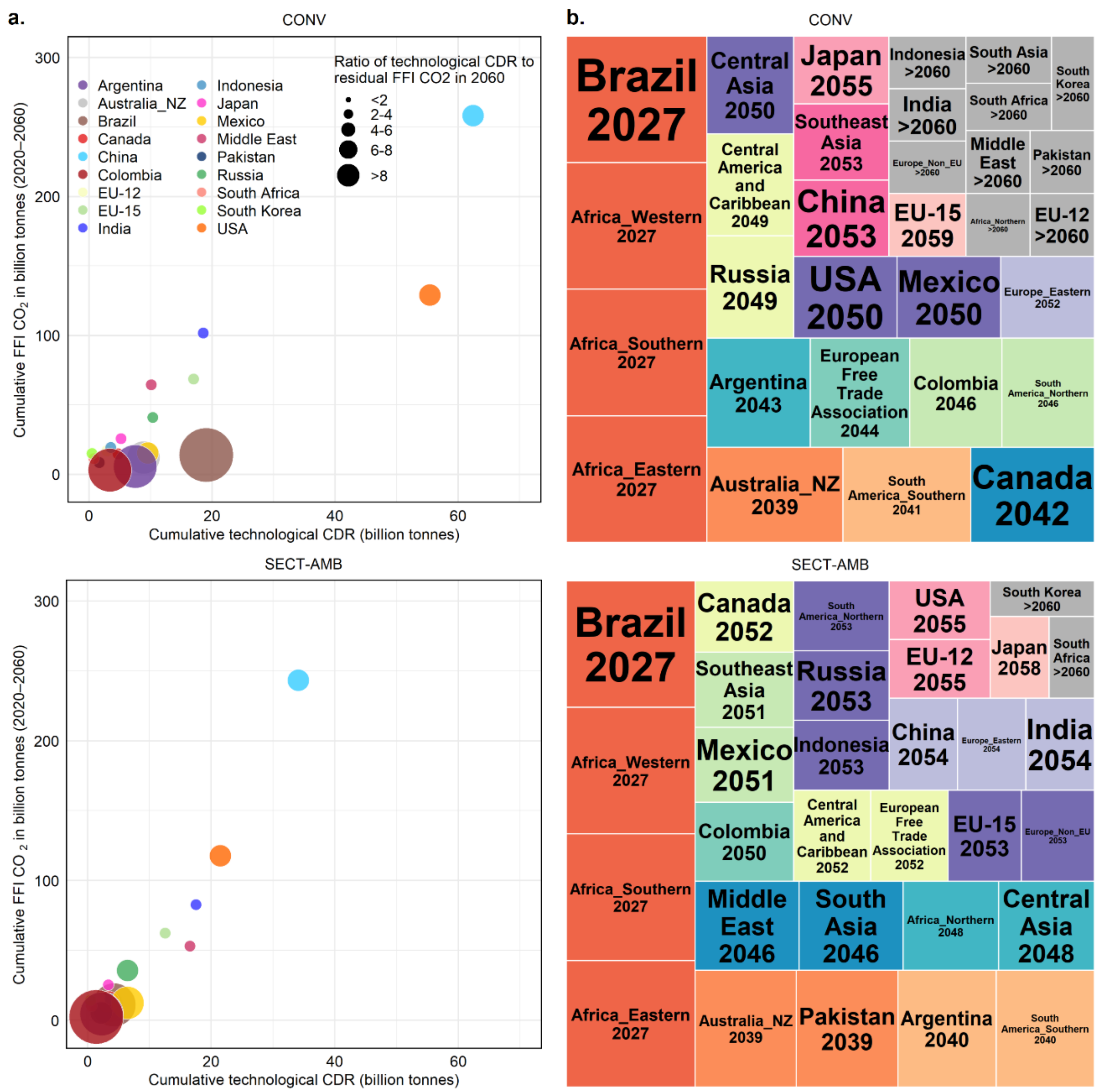


Fig. 5 Impact of sector-specific and economy-wide pathways on emissions, CDR, and net zero timing. (a) Cumulative emissions versus cumulative technological CDR for selected countries and regions. Size of bubble is determined by finding the ratio between technological CDR and residual FFI CO2 in 2060. These ratios can give an indication of whether a region's energy system is at net zero (ratio = 1) or not (ratio <1), or at net-negative (ratio >1). (b) Indicates when countries or regions reach domestic total net zero CO_2

Achieving global net-zero GHG emissions by 2060 places the largest emission-reduction burden on the electricity sector across all scenarios. However, the pace of electricity-sector decarbonization varies notably depending on policy design. Under the conventional economy-wide scenario (CONV), emissions from electricity in 2060 would be approximately 82% lower compared to 2020 levels. In contrast, sector-specific policies (SECT-AMB) achieve over 90% decarbonization in the electricity sector during the same period, representing approximately 10% greater reduction compared to CONV.

Yet, the greatest benefit of sector-specific targets emerges in the traditionally "hard-to-abate" sectors. For example, the SECT-AMB scenario achieves an 82–85% reduction in transport and industrial emissions by 2060 relative to 2020. Under the economy-wide CONV scenario, these sectors undergo much slower decarbonization, with only a 40% reduction for transport and 60% for industry (Fig. 6a). This substantial difference illustrates how explicitly targeted sector-specific policies can significantly accelerate emission reductions using existing technologies rather than relying heavily on future CDR to offset persistent emissions.

However, it is important to acknowledge that aggressive decarbonization of these challenging sectors under sector-specific policies comes with higher costs. For instance, the carbon price on transport emissions in a relatively lower-income country like South Africa would reach $336 per tonne CO_2 (2020$) by 2060 under the CONV scenario. Under SECT-AMB, this price could nearly double to $664 per tonne CO_2. Such cost differences may explain why governments with substantial fossil-fuel interests could prefer relying on cheaper future CDR solutions instead of immediate sector-specific decarbonization efforts.

Electricity is characterized by its high exergy, meaning that 1 EJ of electricity can produce more useful work than an equivalent amount of liquid, solid, or gaseous fuels or heat [41]. Consequently, higher electrification and rapid defossilization under the SECT-AMB scenario lead to lower overall final energy demand. Under scenarios with limited reliance on CDR, such as our sector-specific pathways, fossil fuel use declines rapidly in end-use sectors, replaced by significant growth in electricity consumption from 2020 to 2060. For instance, in the transport sector, the consumption of liquid fuels (primarily oil) by 2060 declines by 57 EJ under SECT-AMB compared to only 26 EJ under the economy-wide CONV scenario. Simultaneously, electricity and hydrogen use in transport increase by 47 EJ under SECT-AMB, compared to 35 EJ under CONV (Fig.6b).

Although SECT-AMB consistently outperforms CONV across all sectors and fuel types, both scenarios follow similar overall energy transition trends, except in the industrial sector's use of coal and gas. Between 2020 and 2060, coal and gas consumption in industry drops by 78 EJ under SECT-AMB but increases by 19 EJ under CONV. This contrast likely reflects the inertia within hard-to-abate industries, where fossil fuel phaseout is technically challenging and financially costly [42]. Under CONV, these emissions are largely left untouched, with the expectation that future large-scale CDR will eventually neutralize them. SECT-AMB, however, operating under the same climate targets but without the cushion of abundant future removals, does not have this luxury. Instead, it drives immediate reductions in fossil fuel use, even in difficult sectors, rather than allowing continued growth over time.

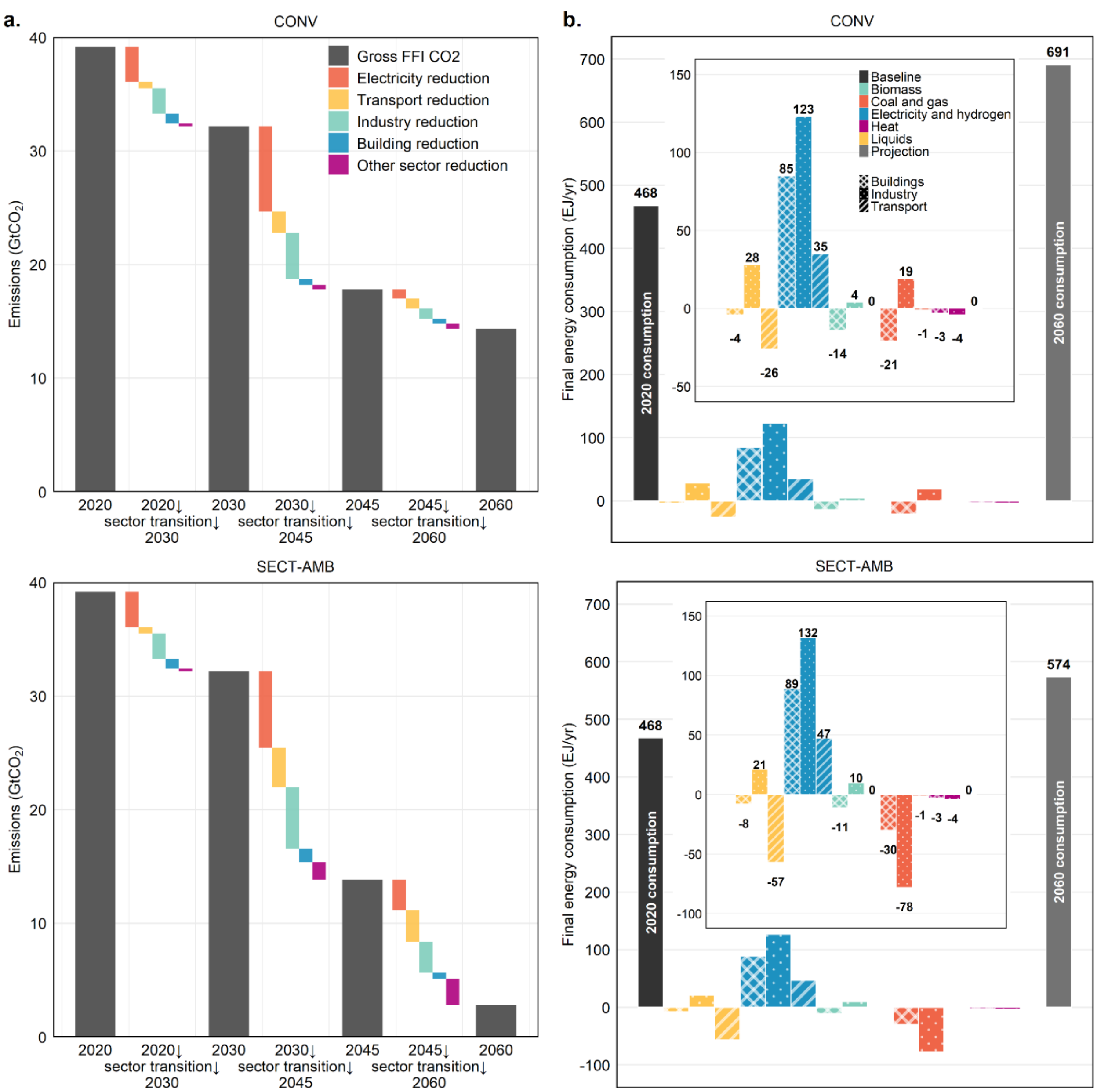


Fig. 6 Impact of sector-specific and economy-wide pathways on sectoral emission reduction and energy consumption. (a) Shows the individual contribution of each sector in reducing 2020 gross FFI CO2 by 2030, 2045, and 2060. "Other sector" includes other energy transformation processes such as hydrogen production and refining (Also see Supplementary Figure S9 and Supplementary Figure S10 for results on SECT and SECT-FAIR). (b) Shows the individual contribution of each end-use sector in phasing-down or upscaling fossil fuel or clean energy by 2060 relative to 2020 levels (Also see Supplementary Figure S11 and Supplementary Figure S12 for results on SECT and SECT-FAIR).

At the global level, equal carbon pricing, as applied in the CONV scenario, tends to perpetuate fossil fuel consumption when compared to differentiated carbon pricing scenarios such as SECT and SECT-AMB/FAIR. This pattern holds not only when comparing CONV to sector-specific pathways but also when comparing sector-specific pathways among themselves: SECT (limited to major emitters) results in more global fossil fuel use than SECT-AMB or SECT-FAIR, where every country takes some level of sectoral action. However, regional trends reveal a more nuanced story, shaped by the dynamic between action by a few countries versus shared global responsibility (Fig. 7).

For example, when sector-specific mandates are limited to historically large emitters under SECT, countries outside that group face fewer constraints. In this case, Brazil consumes more fossil fuels, reaching 376 EJ between 2020 and 2060, compared to 368 EJ under the economy-wide CONV scenario. This highlights how aggressive decarbonization by major emitters under SECT eases the fossil fuel phase-down burden for the rest of the world. On the other hand, historically large emitters benefit when the responsibility is shared globally. Under SECT-AMB or SECT-FAIR, the United States can consume an additional 10–14 EJ of fossil fuels compared to the more restrictive SECT pathway, while still staying on track for net-zero GHG by 2060 (Fig. 7).

Biomass consumption also reveals interesting dynamics. In our analysis, sector-specific scenarios (which deploy significantly less CDR overall) actually consume more biomass globally than the CONV scenario. This is mainly because the reduction in CDR between the scenarios comes from DACCS not BECCS. By 2060, DACCS deployment reaches 14 $GtCO_2$ per year under CONV, compared to only 3–8 $GtCO_2$ per year under sector-specific scenarios. The difference in BECCS use, by contrast, is modest, amounting to less than 0.5 $GtCO_2$ per year. As fossil fuels rapidly phase out under SECT-AMB and SECT-FAIR, rising global energy demand, driven by population growth and industrialization, must be met through other sources, resulting in greater reliance on renewables, nuclear energy, and biomass.

Yet again, this global pattern does not translate uniformly at the regional level. For instance, Canada consumes about 90 EJ of biomass under CONV, but this drops to 53 EJ under SECT. This is because under SECT, aggressive fossil fuel cuts by major emitters allow Canada more flexibility to use fossil fuels, reducing its need for biomass. Conversely, for Russia, a historically large emitter, biomass consumption declines when moving from SECT to SECT-AMB or SECT-FAIR. This is because global participation in sector-specific policies under SECT-AMB/FAIR spreads the decarbonization burden more evenly, easing Russia's need to rapidly phase down fossil fuels and, in turn, lowering its reliance on biomass to fill the energy gap.

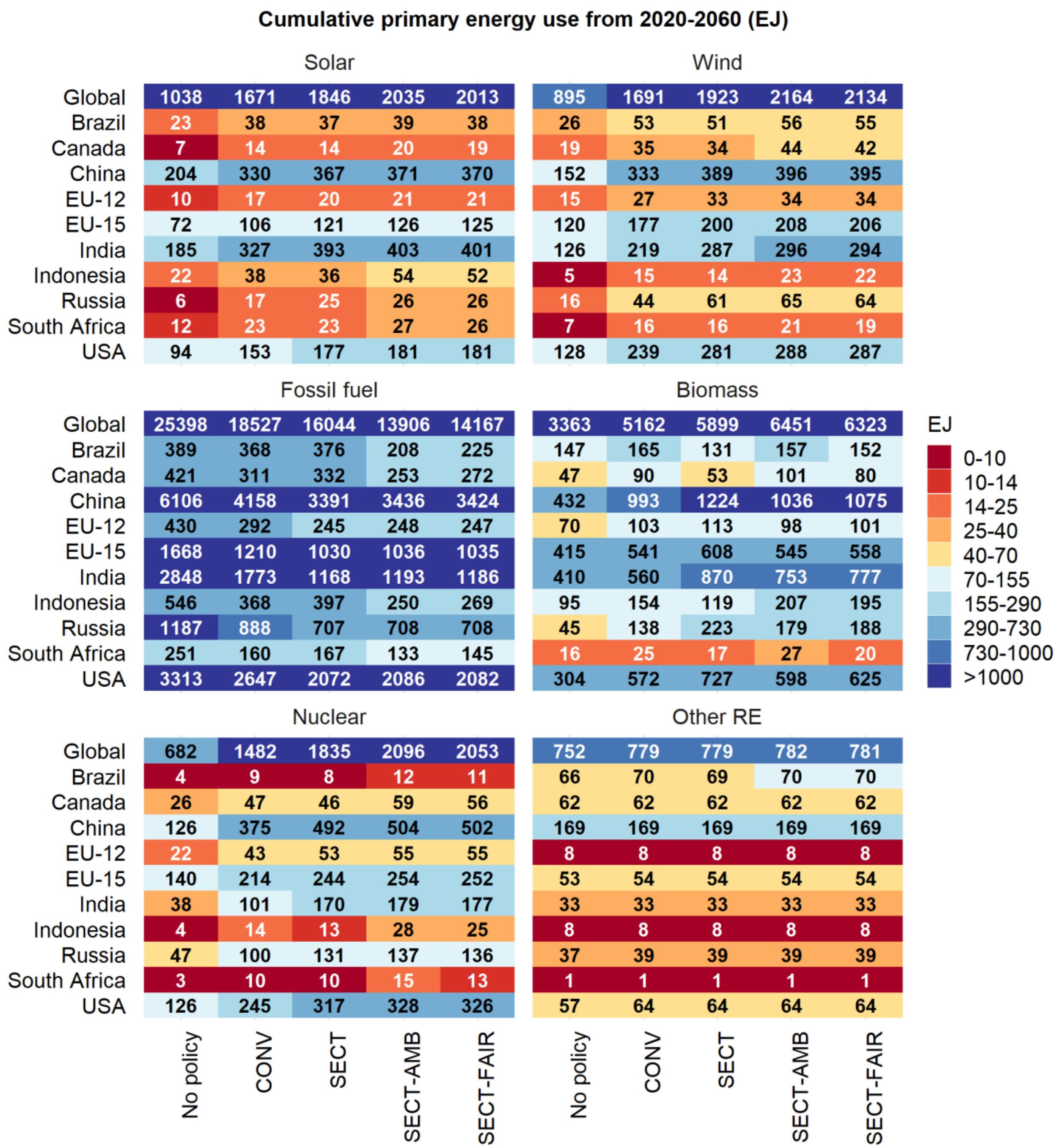


Fig. 7 Impact of sector-specific and economy-wide pathways on primary energy transition for selected regions for 1.5C consistent scenarios against a no policy scenario. "Other RE" represents other renewables i.e., hydro and geothermal

In our central scenarios, we did not impose any constraint on biomass use in order to isolate and examine the full implications of sector-specific policies under net-zero frameworks, without interference from sustainability limits, and to compare them with uniform economy-wide carbon pricing. However, the results show that all scenarios project biomass consumption levels that exceed the widely recognized sustainability threshold of 100 EJ per year [43]. Even if global warming is limited to 1.5°C by 2100, exceeding this threshold could pose serious sustainability challenges [2,23].

To explore how these challenges might affect outcomes under different policy frameworks, we applied a global biomass constraint of 100 EJ/yr and assessed the impacts in Fig. 8. In our unconstrained central scenarios, biomass consumption reaches 191 EJ/yr under CONV and 268 EJ/yr under SECT-AMB, both far beyond sustainable levels.

When we impose the biomass constraint, the results show notable differences between the policy pathways. Under SECT-AMB, limiting biomass use leads to several co-benefits, with one key exception: a rise in LULUCF (land use, land-use change, and forestry) removals via afforestation and reforestation (A/R). This increase occurs because the reduced availability of biomass for BECCS, combined with lower natural gas use for DACCS, creates a shortfall in negative emissions, prompting greater reliance on afforestation and reforestation (A/R) to compensate.

In contrast, the economy-wide CONV scenario faces several setbacks when biomass is limited. The gap left by restricted biomass is partially filled by fossil fuels, which rise by 10%, due to the cost-effective nature of CONV that favors cheaper energy sources over relying solely on an increase in renewables and nuclear. This shift leads to a 3.4% increase in residual FFI GHG emissions, a 9% increase in PM2.5 air pollution, and a 2% increase in novel CDR (nCDR) deployment. Additionally, the drop in BECCS availability and rising residual emissions drive a substantial increase in LULUCF removals under CONV to stay aligned with the net-zero GHG target.

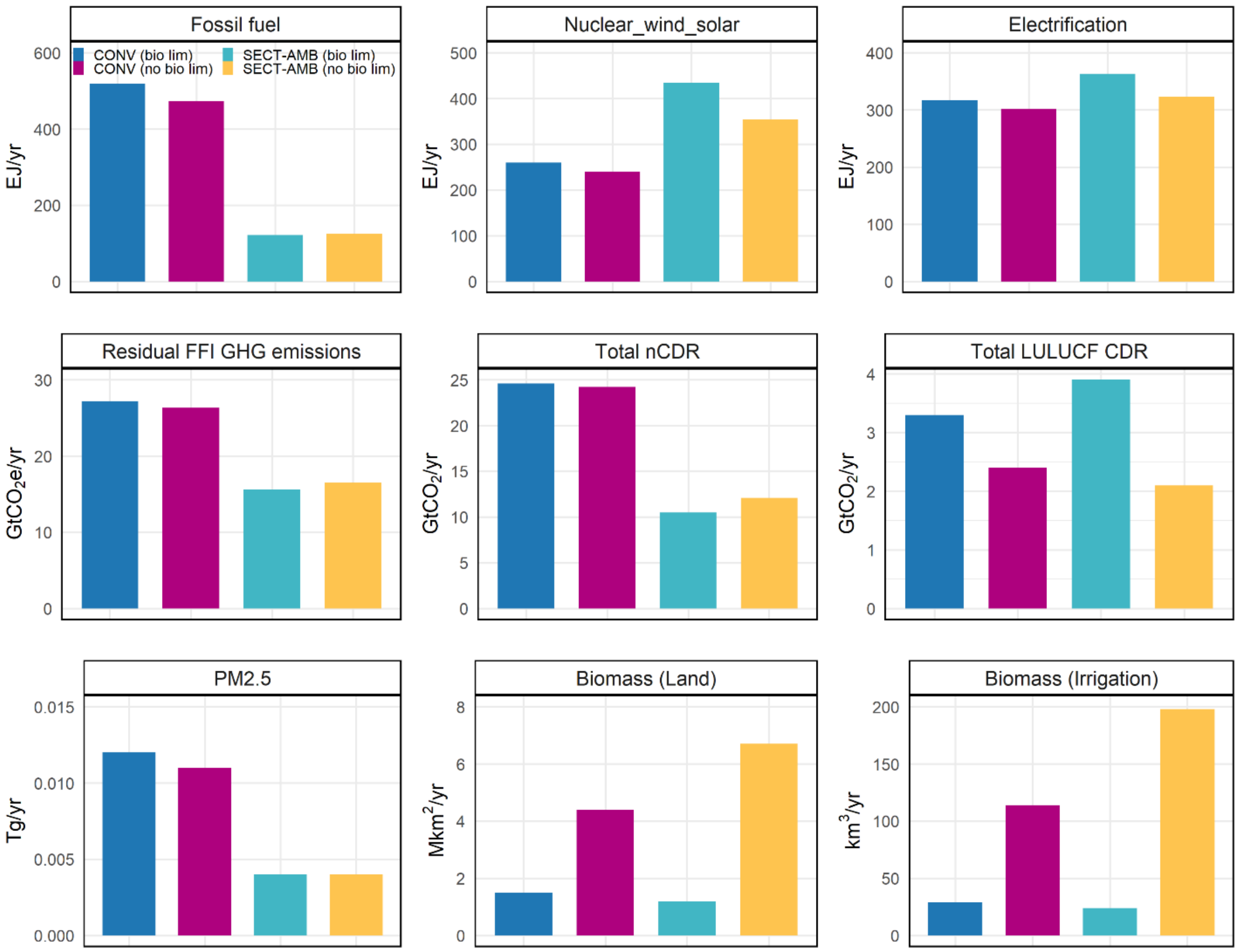


Fig. 8 Impact of biomass supply on key sustainability indicators under SECT-AMB and CONV in 2060. For "bio lim" global sustainable biomass has been limited to 100 EJ/yr. "nCDR" represents novel CDR including BECCS, DACCS, and ERW. All results are global-based except PM2.5 which is only available for the US in our model

Fig. 9 illustrates the sustainability trade-offs and co-benefits of sector-specific pathways (SECT, SECT-AMB, and SECT-FAIR) compared to the conventional economy-wide approach (CONV) by 2060. The results show that sector-specific policies not only accelerate clean energy deployment and emission reductions but also significantly reshape how resources are used, influence transition costs, and impact health and land systems.

From a co-benefits perspective, one clear advantage of sector-specific scenarios is their reduced reliance on carbon removal technologies like DACCS, which results in lower offshore and onshore carbon storage requirements, particularly in SECT-AMB and SECT-FAIR. The rapid phaseout of fossil fuels under these scenarios also brings substantial health benefits, especially through improved air quality. PM2.5 levels decline by more than 50% compared to those under CONV, reflecting the direct benefits of reduced fossil fuel combustion. Additionally, costs associated with oil refining drop significantly, by more than 50%, due to the declining demand for fossil fuels.

However, these gains come with important trade-offs, particularly in terms of transition costs. Higher electrification demand raises electricity generation costs by over 10 percent, while hydrogen production, which is crucial for deep decarbonization in hard-to-abate sectors, becomes 10 to 30 percent more expensive in the absence of large-scale CDR. As a result, the cost of reducing each tonne of CO_2 rises under sector-specific scenarios compared to CONV. The high demand for nuclear energy to support electricity and hydrogen supply also drives up uranium mining and extraction by 30–60%, potentially raising long-term sustainability concerns [44]. Sector-specific pathways increase water use in some areas, such as for biomass irrigation, but reduce it in others, including cooling in fossil-based power plants, fossil fuel extraction, and CDR operations, particularly DACCS. Based on demand across all sectors, total global water demand increases slightly by 1–3% relative to CONV. Moreover, while expanded biomass use does not severely displace cropland, it increases fertilizer demand and encroaches on other productive land types such as grasslands and arable areas. Forest cover declines, contributing to biodiversity loss, which could be one of the critical environmental concerns under sector-specific pathways.

While sector-specific policies deliver faster decarbonization, cleaner air, and a more efficient phaseout of fossil fuels, they also introduce challenges, particularly related to transition costs, land use change, and ecosystem impacts. These issues must be carefully managed to ensure a fair and sustainable path to net zero.

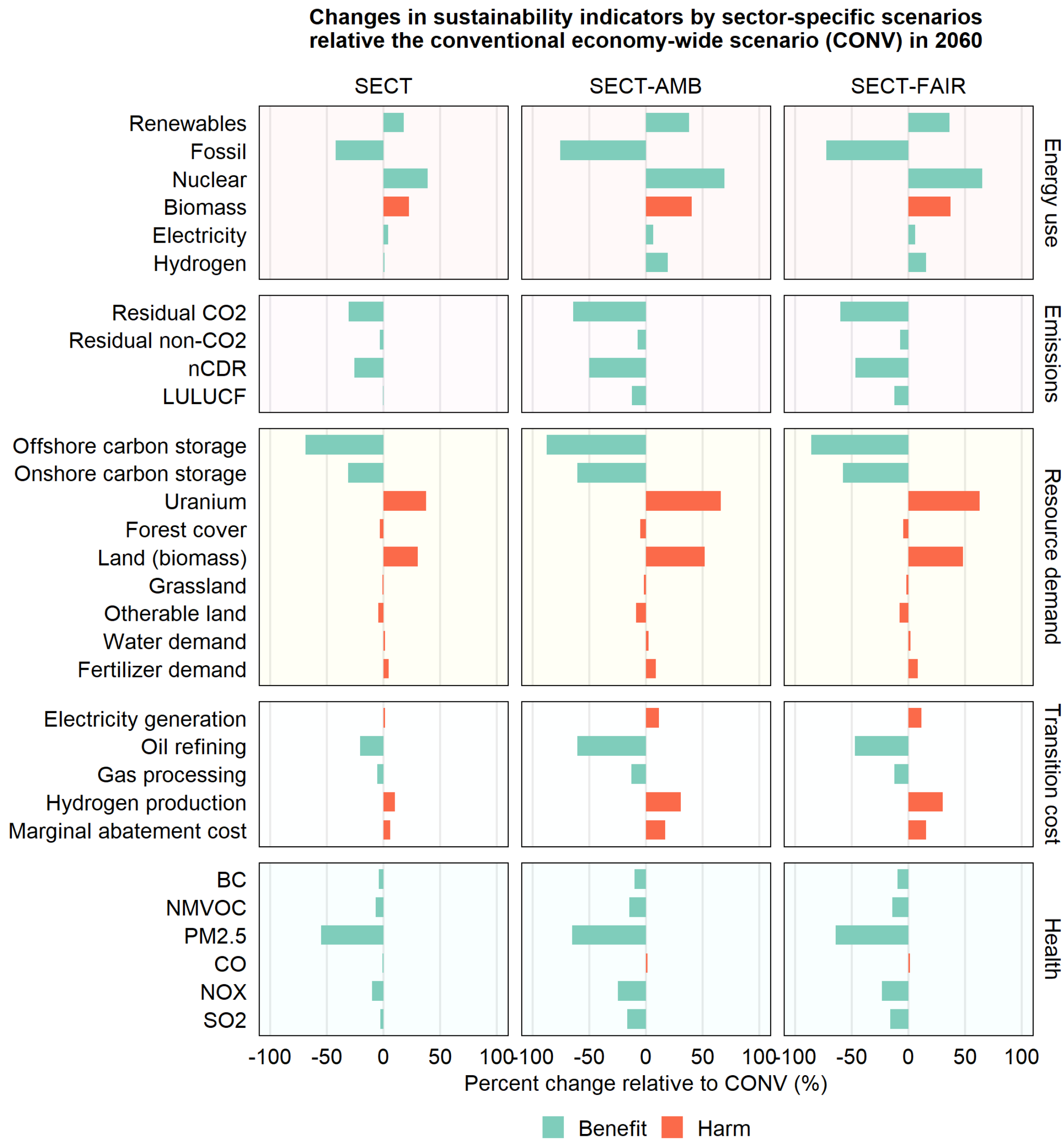


Fig. 9 Synergies and trade-offs between sector-specific scenarios versus economy-wide conventional scenario. "nCDR" represents novel CDR including BECCS, DACCS, and ERW. Renewables here include combined solar and wind in primary energy consumption; Fossil fuel here includes oil, gas, and coal in primary energy consumption. Other arable in GCAM refers to land that could be productive but is not currently cultivated (such as fallow land)[45]*. BC: Black carbon; NMVOC: Non-Methane Volatile Organic Compounds; PM: particulate matter;* NO_X*: nitrogen OXIDES;* SO_2*: Sulphur dioxide. Benefit indicates that the result has positive outcome under sector-specific scenario relative to CONV; Harm indicates that the result has negative outcome under sector-specific scenario relative to CONV. All results are global-based except PM2.5 which is only available for the US in our model*

Discussion

Today, several countries, including major emitters, have set net-zero targets without clearly defining the separate roles of emissions reductions and removals in achieving these goals [6,46]. Such policy designs create fertile ground for delaying emission reductions, relying instead on the promise of unproven CDR technologies that have yet to be scaled [47]. Our findings challenge this approach, urging a more practical inclusion of sector-specific policies alongside net-zero targets in long-term strategy (LTS) submissions or the next cycle of updated nationally determined contributions. By explicitly addressing sectoral decarbonization, these policies can help meet climate goals more effectively while minimizing future reliance on unproven technologies such as CDR to reverse climate impacts.

While sector-specific policies under broad net-zero targets can serve as powerful tools for accelerating climate action, their widespread adoption and implementation may face several challenges. Compared to economy-wide approaches, sector-specific policies are often perceived as less cost-effective, more complex to design, and less transparent [48]. To promote the broader adoption of sector-specific policies, the following supportive and well-aligned policy instruments are necessary.

While all countries must pursue some level of sectoral action, these expectations must be tailored to reflect each country's capacity and historical responsibility. In fossil fuel-dependent regions with limited financial resources, mandating sector-specific policies can lead to the abrupt and economically disruptive shutdown of fossil assets [49]. If not managed carefully, such policies could destabilize energy access and undermine sustainable development, especially where replacements for phased-out fossil infrastructure are lacking. Moreover, political and social resistance can arise in regions where large segments of the population are employed in fossil fuel-related sectors. These concerns must be addressed with clear compensation and transition strategies. Climate finance and technology transfer from high-income, high-emitting countries will be essential for easing the burden on developing regions [50,51]. For example, the "Baku to Belem Roadmap to 1.3T" aim to increase climate finance flows from 300 billion to 1.3 trillion dollars by 2035 [52], offering a critical boost for Global South economies to overcome transition challenges associated with sector-specific policies. Also, targeted compensation schemes for workers and communities are vital to ensure just transitions. A recent global assessment shows that more than 200 billion dollars in compensation is planned for communities and workers affected by coal phase-out programs [53]. If such compensation mechanisms are in place and equitably distributed, the political and economic barriers to adopting sector-specific supply and demand policies such as coal phase-out strategies can be significantly reduced, leading to smoother and more widespread implementation.

Sectors such as steel, shipping, and aviation require scalable alternatives to fossil fuels, yet the high cost of low-carbon substitutes like green hydrogen, green methanol, and green ammonia continues to pose a barrier [54]. Production subsidies and long-term contracts for difference can help close this cost gap, making these alternatives more competitive [55]. A prominent example is the Inflation Reduction Act (IRA) in the United States, which offers unprecedented incentives for deploying low-emission hydrogen and liquid fuels, along with other climate-friendly technologies. A study by Cheng et al.[56] demonstrates that the subsidies provided under the IRA are likely to make clean hydrogen cost-competitive with conventional gray hydrogen. This shift could enable the faster adoption of sector-specific policies aimed at phasing out fossil fuels from hard-to-abate sectors, by making greener fuels both viable and attractive for large-scale industrial use.

Given the stringency and cost-related challenges associated with sector-specific policies, universal adoption across countries is essential to improve both compliance and effectiveness. When strict regulations are implemented in one region but remain weak or absent in others, industries may relocate to avoid compliance. This not only results in carbon leakage but also undermines the overall objective of reducing global emissions. A coordinated international approach helps to prevent such distortions, promotes fair competition, and creates a more stable environment for investment in cleaner technologies. Uniform implementation, when combined with well-designed incentives, can increase industry compliance and accelerate the transition to low-carbon alternatives. A strong example is the International Maritime Organization (IMO), which during its 83rd session (MEPC 83) in April 2025 adopted a legally binding framework to reduce greenhouse gas emissions from shipping. This framework includes a new global fuel standard for ships and a pricing mechanism for emissions, both aimed at achieving net-zero emissions around 2050 [57]. To support compliance and ensure equity, the IMO also announced the establishment of the IMO Net-Zero Fund. The fund will collect contributions from emission pricing and use the revenues to: (1) reward low-emission vessels, (2) support innovation, infrastructure, and just transition initiatives in developing countries, (3) fund training, technology transfer, and capacity building, and (4) mitigate negative impacts on vulnerable states, including Small Island Developing States and Least Developed Countries [57].

In conclusion, our work evaluates whether sector-specific climate policies, within broad net-zero pathways, offer a more effective strategy for achieving global climate goals compared to conventional economy-wide approaches. We designed three sector-specific scenarios: selective (SECT), universal (SECT-AMB), and equity-informed (SECT-FAIR). We assessed their performance against the conventional cost-effective scenario (CONV), all aligned with limiting global warming to 1.5°C. Our findings reveal that by 2060, sector-specific policies could reduce residual GHG emissions by 6–12 $GtCO_2$/year and lower gross CDR requirements as well by 6–12 $GtCO_2$/year compared to CONV. They also achieve slightly lower peak warming (by 0.006–0.01°C) and cut air pollution (PM2.5) by over 50%. However, these gains are accompanied by trade-offs, including higher transition costs, increased demand for biomass, water, uranium, and fertilizer, and potential risks to biodiversity from forest loss and land-use shifts. A crucial takeaway is that while sector-specific policies can drive faster decarbonization, careful attention must be given to managing their negative impacts, such as increased resource demands and potential biodiversity risks, by implementing strategies that prioritize sustainability and minimize unintended consequences. Strategies such as promoting resource efficiency, protecting biodiversity through land-use policies, and encouraging circular economy practices are crucial. Aligning sector-specific actions with broader environmental goals can minimize resource demands and environmental risks while ensuring sustainable climate progress.

While our study provides key insights into sector-specific policies, future research could further enhance these findings by incorporating a diverse ensemble of IAMs. This would strengthen the robustness of our conclusions and offer additional perspectives on co-benefits, such as job creation and destruction, energy security, universal energy access, and improved urban livability. Moreover, we applied a region-specific carbon price uniformly across all energy and industrial sectors while all other sectors face different carbon price for simplicity (as opposed to the uniform carbon price for all countries and sectors under CONV). A more detailed sector-by-sector pricing approach could reveal further insights and refine mitigation strategies. Our analysis also did not account for behavioral shifts, adaptation co-benefits, or evolving technology costs in detail, all of which could influence the pace and burden of the transition. Additionally, our scenarios did not impose any limits on carbon removal, sustainable biomass, water, carbon storage, or land availability. This was an intentional study design choice to assess the full system implications attributed solely to the introduction of sector-specific policies. Future studies could incorporate planetary boundary conditions to explore how resource constraints could alter transition dynamics.

Declarations

Acknowledgements

We are grateful to the National Natural Science Foundation of China for supporting the current study with funding numbers 22461142138 received by H.L. & 52176125 received by C.J. H.M was supported by the National Research Foundation of Korea (Grant: RS-2024-00467678).

Competing Interest

The authors declare no competing interests.

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