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When substitution benefits drift: prospectively assessing what keeps a biomass commitment environmentally justified

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Abstract

A biomass commitment is made once, but its environmental benefit is not fixed. Chips committed to power, fuels or chemicals are unavailable to other uses, yet each is usually defended by an isolated substitution benefit that ignores the uses forgone, the capacity that resists redirection and the decarbonizing energy system. Here we prospectively follow wood-chip allocation in Japan and its 47 prefectures through 2120, assessing greenhouse-gas reduction, avoided fossil demand and useful-product exergy, the work potential retained in products. The strongest sectoral target for mitigation, a 2030 fuel target, captures 44 % of what climate-mitigation-guided allocation achieves. Prioritizing fossil displacement retains at most 24.3 % of its mitigation, and prioritizing exergy at least 87.2 %. Implementation inertia, resistance to moving chips from incumbent use, removes 26 to 30 % when redirection is easy and 45 to 56 % when it is not. Low-inertia allocation delivers more mitigation than any sectoral target across the tested coefficient range. An identical allocation delivers 79 to 119 Mt CO_2e depending only on the decarbonization path. These results suggest that, where redirection is easy, commitments able to follow their changing benefit keep more of it than targets set once and held.

Introduction

Woody biomass can supply electricity and heat, replace fossil fuels and provide renewable carbon for fuels and chemicals (IPCC, 2022), but these uses compete for a finite resource: chips committed to one use are unavailable to every other (Daioglou et al., 2015; Millinger et al., 2025). Japan presents this competition in concentrated form. Feed-in tariffs introduced in 2012 created a domestic power demand for forest and sawmill chips that did not previously exist, and the 2021 Strategic Energy Plan retains

biomass power as a 2030 target (METI, 2011; Agency for Natural Resources and Energy, 2021). A target of a 10 % SAF share in jet fuel by 2030 (MLIT, n.d.) and an ambition of roughly two million tonnes of bio-based plastics (Cabinet Office, Government of Japan, 2024) now lay new claims on the same chips, each justified in part by the environmental benefit of displacing fossil products. The resource these claims draw on is itself moving: forest age structure, harvesting regimes and managed area shape wood supply over time and across regions (Forster et al., 2025; Lan et al., 2025; Han et al., 2026), and construction retains wood in long-lived products from which secondary chips later return (Faraca et al., 2019). A commitment to one use is a decision about how a changing resource is directed through time, and its environmental rationale rests on both the benefits it delivers and the benefits forgone by the uses it displaces.

Comparing alternative uses on a common feedstock basis makes the environmental opportunities associated with biomass allocation explicit. Environmental merit-order analysis compares uses on a common feedstock basis, evaluating mitigation per unit of biomass across products with different substitution functions (Winter et al., 2022). Multiobjective approaches extend allocation analysis to competing environmental objectives under resource, capacity and policy constraints (Vadenbo et al., 2017a, 2018). Comparisons of residual and waste biomass uses further show that their relative performance depends on conversion efficiency and the conventional technology displaced (Steubing et al., 2012). These studies establish a basis for examining the benefits available from competing uses, but judging a commitment also requires considering which benefits a comparison captures. Climate mitigation is one reason to substitute biomass for conventional production; reducing fossil-resource demand is another (Lopez et al., 2023), while limited feedstock availability gives importance to the

useful output obtained from that resource. Exergy-based assessments make that output comparable across products by counting the work it can still deliver, so that heat used on the spot counts for less than a fuel or chemical that can be stored and used later (Risse et al., 2017). Mitigation performance alone cannot establish an allocation's advantage, because comparative benefit depends both on what a commitment delivers relative to competing uses and on which outcomes are favored in that judgment.

An environmentally attractive allocation may nevertheless be difficult to realize. Investment history, infrastructure lock-in and investment risks can constrain technological change (Unruh, 2000; Barazza and Strachan, 2021), while evidence from SAF deployment illustrates that announced capacity need not translate into operating production infrastructure (Martulli et al., 2025). For biomass, resistance to departing from established uses can separate a preferred allocation from the resource use actually realized during a transition. The environmental consequence of this resistance depends on when redirection becomes possible relative to when alternative uses become advantageous. Meanwhile, the environmental value of those uses can change as implementation proceeds. Prospective life-cycle inventories account for evolving energy and industrial backgrounds (Mendoza Beltran et al., 2020), and wood-substitution studies, which summarize the emissions avoided through wood use as displacement factors (Sathre and O'Connor, 2010; Leskinen et al., 2018), show that these factors rest on assumptions about the displaced system (Harmon, 2019; Howard et al., 2021) and that decarbonization and changes in competing systems can alter them (Myllyviita et al., 2022). A resource may consequently reach its intended destination under different substitution conditions from those that initially supported the choice. Successful implementation alone cannot establish that the expected environmental benefit will persist: assessment must consider

both how far a preferred allocation can be realized and what the realized use delivers under the conditions contemporary with its implementation.

These dependencies create a problem not only of prospective assessment, but of interpretation. A difference between two future outcomes may arise for three distinct reasons: because the resource was directed by a different priority, so that the benefit was knowingly traded for another (Javourez et al., 2025); because the preferred allocation could not be fully realized (Blumer et al., 2013); or because the same allocation delivered a different benefit as the surrounding system changed (Brunet-Navarro et al., 2021). We refer to these as questions of comparative benefit, realizability and contemporary environmental value. Existing assessments address these questions largely separately (Supplementary Note 1, Supplementary Table 1). Prospective life-cycle inventories provide approaches for incorporating changing background systems (Sacchi et al., 2022), and scenario-based inventory methods make future drivers and their interrelations explicit (Langkau et al., 2023). These developments support the representation of evolving conditions; interpreting their consequences for a biomass commitment also requires distinguishing where a change enters the allocation problem. The distinction carries different implications: improving implementation may recover an unrealized benefit, but cannot by itself restore a substitution advantage that has eroded. Thus, distinguishing the three is necessary to understand what an outcome difference implies for the allocation being pursued and the conditions supporting its environmental rationale.

In this work, we address how competing commitments and changing transition conditions shape the environmental consequences of allocating a constrained wood-chip resource, using Japan over 2020–2120 at national and prefectural scales. Allocations

pursuing sectoral commitments are contrasted with allocations governed directly by GHG reduction, avoided fossil demand or useful-product exergy, the last measuring how much of the feedstock's exergy each use retains in useful products. Scenarios that prescribe sectoral targets examine how the choice of destination and target timing redistribute benefits among commitments. Scenarios guided by environmental principles examine what each priority preserves or sacrifices of the others, and how implementation inertia separates the allocation preferred under a principle from the allocation realized. These two families address the questions of comparative benefit and realizability. Changing background systems then reveal how an unchanged allocation delivers a different climate benefit as the production and substitution systems around it evolve, which is the question of contemporary environmental value. The design allows allocation to vary under common background conditions, or background performance to vary while the physical allocation is retained, so that each of the three questions can be examined with the others held fixed.

Here we show that the strongest sectoral target captures 44 % of the mitigation available under climate prioritization, and that the priorities themselves are asymmetric: prioritizing fossil displacement retains at most 24.3 % of that mitigation, whereas prioritizing exergy retains at least 87.2 %. Through 2120, inertia reduces national climate-mitigation-guided mitigation by 26–30% under low inertia and 45–56% under high inertia. The loss is governed jointly by how much departure from incumbent use is permitted and when adjustment occurs. We further show that the same allocation delivers a different climate benefit under every background trajectory, and that a stalled decarbonization changes the value of an unchanged allocation without changing a single allocation decision. These results support treating whether a biomass commitment is

environmentally justified as a question to be re-tested rather than settled once: progress towards a sectoral target, or evidence of positive substitution, does not by itself establish that the commitment remains the most beneficial use, that its preferred allocation is being realized, or that the substitution advantage on which its case rested still holds.

Results

Overview of methods and scenarios

Figure 1 summarizes the framework. Each year, the wood chips available in Japan and in each of its 47 prefectures are allocated among three uses: bioenergy, the incumbent, producing electricity and heat in combined heat and power; a biofuel route producing SAF with hydrogen and diesel co-products; and a biochemical route producing benzene, toluene and xylene. The chip supply entering this decision comes from the Forest Management Model for Cyclical Forestry (FM2-CF), which provides roundwood trajectories under a policy-oriented forest transition (Han et al., 2026), and from material flow analysis, which converts roundwood into timber, plywood and chips. Forest and sawmill chips form the primary pool. Timber and plywood enter construction and return as reclaimed chips from 2076, forming an expanded pool (Fig. 1b). Each use is valued by process-based LCA, giving net GHG reduction and avoided fossil demand per kilogram of wet chips relative to functionally equivalent conventional products, and by exergy accounting, giving useful-product exergy. These values are not fixed: electricity and heat emission factors fall to zero by 2050 along five background paths that differ in timing (Fig. 1c), and remain at zero thereafter, so the same allocation can carry a different climate

value in different years and under different paths. Outcomes accumulate from 2021, with 2020 initializing the allocation, and are reported at 2050 and 2120.

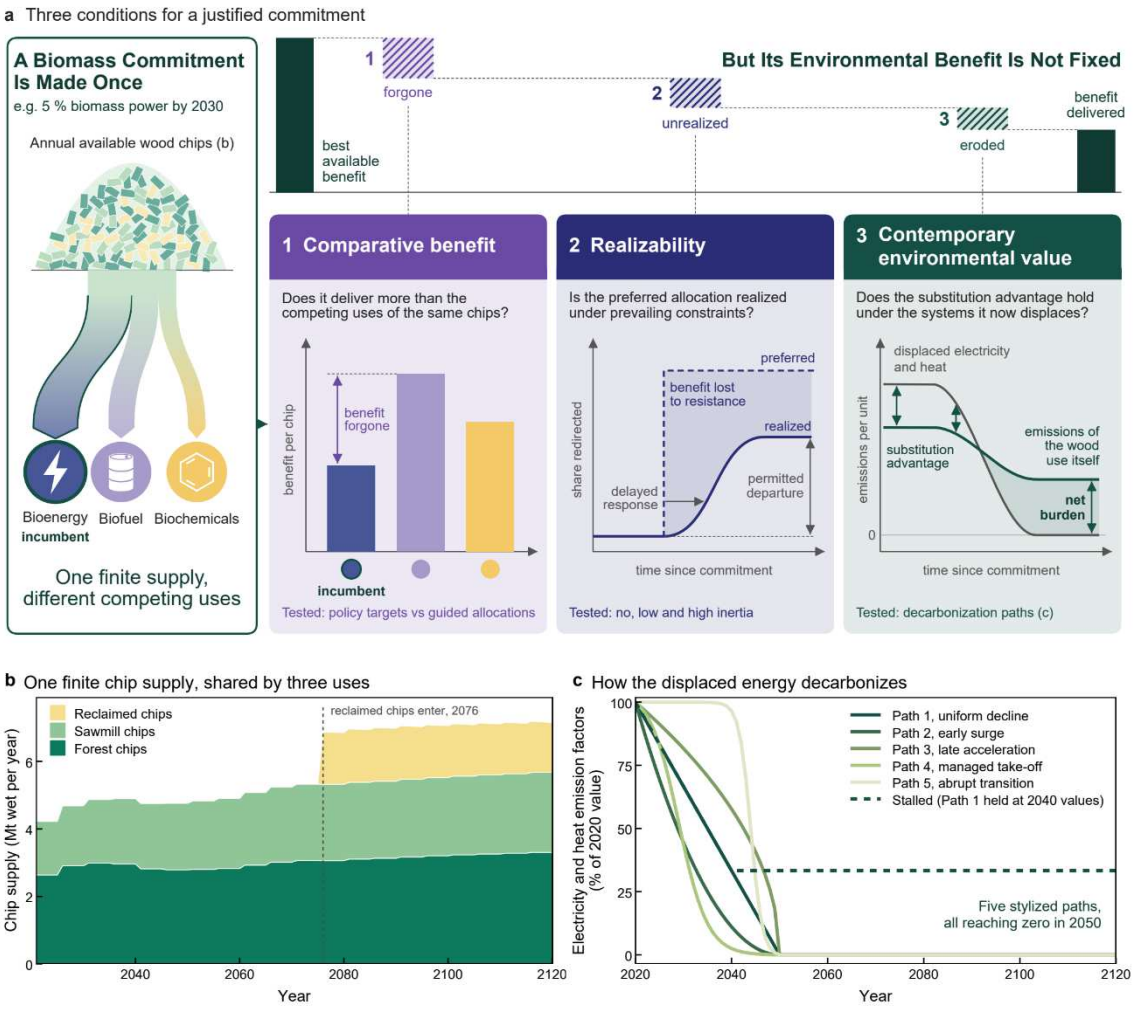


Figure 1 Framework of the assessment. a, A biomass commitment draws on one finite annual supply of wood chips that three uses compete for: bioenergy (electricity and heat from combined heat and power; the incumbent use), biofuel (sustainable aviation fuel with hydrogen and diesel co-products) and biochemicals (benzene, toluene and xylene). The best available benefit is reduced in three steps, each tested separately. Benefit is forgone when a competing use of the same chips would deliver more (comparative benefit; tested with policy targets against guided allocations). It is unrealized when resistance delays and limits the departure from the incumbent use (realizability; no, low and high

inertia). It is eroded when the substitution advantage shrinks as the displaced systems decarbonize (contemporary environmental value; decarbonization paths). The schematic panels are illustrative. **b**, Annual wood-chip supply in Japan by source (Mt wet per year); forest and sawmill chips form the primary pool, and reclaimed chips enter from 2076 to form the expanded pool. **c**, Electricity and heat emission factors under the five background paths and the stalled-decarbonization variant (Path 1 held at its 2040 values), as a percentage of the 2020 value. Source data are provided as a Source Data file.

Two scenario families distinguish the basis of allocation. Prescribed scenarios begin from national policy targets for the three uses: a power target for electricity-oriented bioenergy, a fuel target for sustainable aviation fuel and a chemicals target for biochemical production. Each target is evaluated with a target year of 2030, 2050 or 2080, giving nine prescribed configurations, referred to as the power, fuel and chemicals targets with their year (for example, the 2030 fuel target). Principled scenarios instead allocate chips each year to the use that maximizes one outcome per unit of resource, giving climate-mitigation-guided, fossil-displacement-guided and exergy-efficiency-guided allocations. Within the principled family, no-, low- and high-inertia settings represent stylized resistance to departing from the incumbent all-bioenergy allocation, separating the allocation preferred under a principle from the allocation realized under restricted reallocation. The five background paths (Path 1, uniform decline; Path 2, early surge; Path 3, late acceleration; Path 4, managed take-off; Path 5, abrupt transition) are applied to every configuration. Unless stated otherwise, national examples use the expanded pool under Path 1. Both pools follow the same allocation shares, and primary-chip outcomes are not independently re-optimized. Robustness and attribution analyses, introduced where they qualify a result, test the valuation coefficients, the inertia rule and the

background, and attribute a combined outcome difference to allocation, realization and background (Methods).

Sectoral targets capture a small share of the available climate benefit

Through 2120, the 2030 fuel target led the prescribed configurations on GHG reduction and useful-product exergy, and the 2080 power target led on avoided fossil demand, under all five background paths and both chip pools (Fig. 2a). The two agendas traded these benefits against each other. Under Path 1, the 2030 power target delivered 17.6 % more fossil displacement than the 2030 fuel target, but only 55.6 % of its cumulative mitigation and 22.1 % less exergy.

Postponing a target from 2030 to 2080 increased cumulative fossil displacement through 2120 but reduced mitigation and exergy under every path and pool. The mitigation loss was more than three times larger for the power target, at 72.1 %, than for the fuel and chemicals targets, at 21.0 % and 22.2 % (Fig. 2c). Under the power target, mitigation fell from 94.4 to 26.3 Mt CO_2e. A later power target did not postpone bioenergy use but prolonged it, and because the national requirement is downscaled from supply at the target year, it also fixed a larger post-target feedstock commitment.

Measured against what the same chips deliver when climate mitigation itself guides allocation, the comparative benefit of every prescribed configuration was limited (Table 1, Fig. 2a). Through 2120, the nine configurations retained between 3 % (2080 power target) and 47 % (2030 fuel target) of the mitigation of climate-mitigation-guided allocation without inertia, across the five paths and two pools. Under Path 1 with the expanded pool, climate-mitigation-guided allocation delivered 387.4 Mt CO_2e, against 169.9 Mt for the 2030 fuel target and 94.4 Mt for the 2030 power target. Across the tested

coefficient range, the best of the nine reached at most 52 % of the climate-mitigation-guided reduction, with the spread set mostly by the chemical and fuel credits (Fig. 2d, e).

Table 1 Cumulative GHG reduction and retention by configuration. Values are for Japan, Path 1, expanded pool, with the range over the ten national path–pool settings in parentheses. Retention = outcome / climate-mitigation-guided no-inertia outcome in the same path, pool and horizon. Configurations are named by sector and target year, the year by which the sector's committed chip quantity is reached and after which it is held (2030 is the official deadline; 2050 and 2080 are study-defined later settings). Column years mark the end of the cumulative accounting period (2021–2050 and 2021–2120).

Configuration	2050: Mt CO_2e, retention (range)	2120: Mt CO_2e, retention (range)
Power target 2030	36.8, 0.49 (0.25–0.76)	94.4, 0.24 (0.20–0.31)
Power target 2050	36.1, 0.48 (0.23–0.76)	90.4, 0.23 (0.18–0.31)
Power target 2080	36.1, 0.48 (0.23–0.76)	26.3, 0.07 (0.03–0.16)
Fuel target 2030	52.1, 0.69 (0.55–0.80)	169.9, 0.44 (0.42–0.47)
Fuel target 2050	51.5, 0.68 (0.52–0.82)	163.6, 0.42 (0.39–0.46)
Fuel target 2080	43.3, 0.57 (0.36–0.78)	134.2, 0.35 (0.31–0.41)
Chemicals target 2030	45.1, 0.59 (0.46–0.71)	148.6, 0.38 (0.36–0.41)
Chemicals target 2050	45.9, 0.61 (0.45–0.74)	141.6, 0.37 (0.34–0.41)
Chemicals target 2080	41.0, 0.54 (0.34–0.75)	115.6, 0.30 (0.26–0.36)
Climate-mitigation-guided, high inertia	44.0, 0.58 (0.35–0.81)	190.9, 0.49 (0.44–0.55)
Climate-mitigation-guided, low inertia	63.4, 0.84 (0.75–0.93)	276.9, 0.71 (0.70–0.74)
Climate-mitigation-guided, no inertia	75.8, 1.00	387.4, 1.00

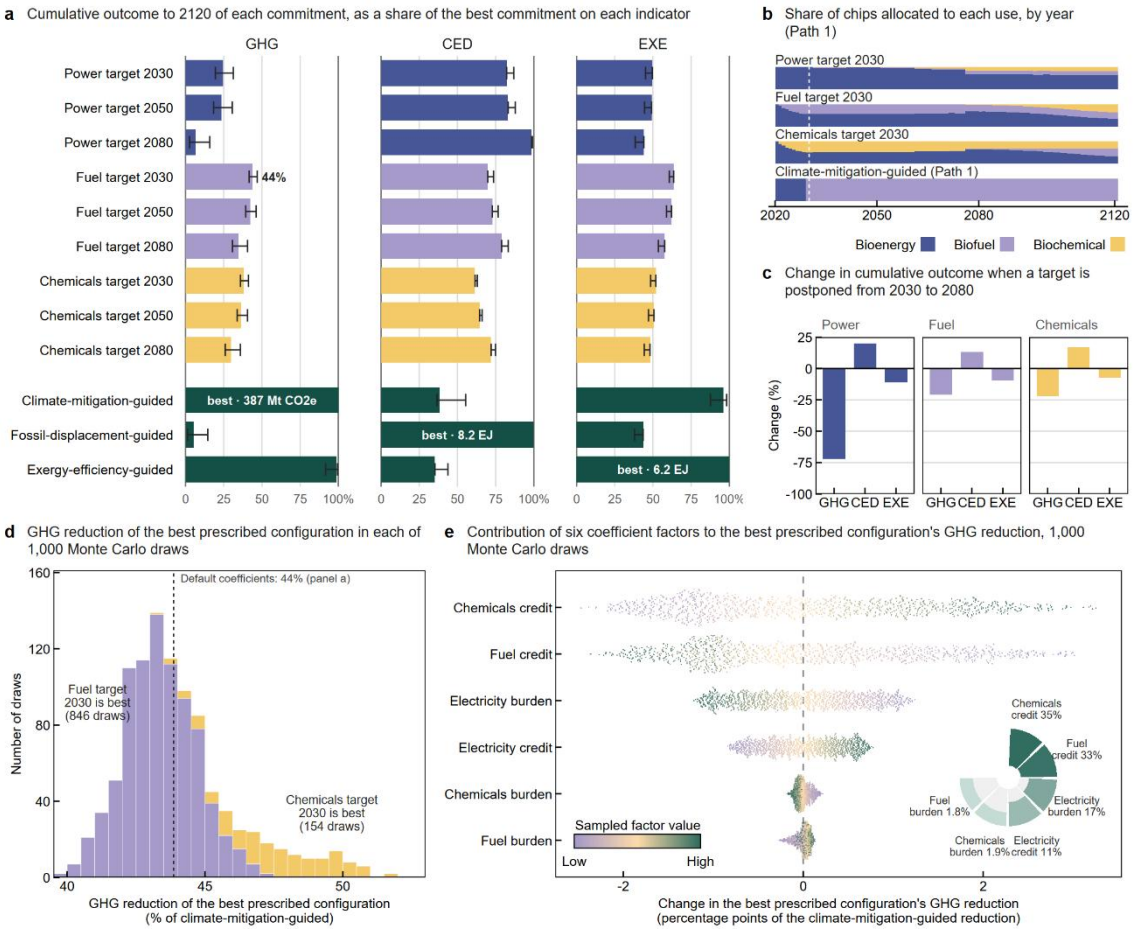


Figure 2 Prescribed targets trade indicators against each other, and the climate-mitigation-guided allocation recovers most of what they forgo.

a, Cumulative outcome to 2120 of the nine prescribed configurations and the three principled commitments without inertia, as a percentage of the best commitment on each indicator. Bars give Path 1 with the expanded pool; whiskers give the range over the ten path and pool settings, each normalized to the best commitment in the same setting. The best commitment on each indicator is labelled with its absolute value. The 44 % label marks the best prescribed configuration on GHG, the 2030 fuel target. **b**, Share of chips allocated to bioenergy, biofuel and biochemical use in each year under the three 2030 targets and climate-mitigation-guided allocation without inertia (Path 1). The dashed line marks 2030. **c**, Change in cumulative outcome to 2120 when each target is postponed

from 2030 to 2080, relative to the same target in 2030 (Path 1, expanded pool). For every target type, GHG and EXE fall and CED rises; the GHG loss is largest for the power target, whose benefit depends on displacing an electricity mix that has largely decarbonized by 2080. **d**, Cumulative GHG reduction to 2120 of the best prescribed configuration in each of 1,000 Monte Carlo draws, as a percentage of the climate-mitigation-guided reduction without inertia in the same draw (Path 1, expanded pool). Colors show which configuration is best: the 2030 fuel target in 846 draws and the 2030 chemicals target in 154. The vertical line marks the value in the main results (44 %, panel a). **e**, Contribution of each of the six coefficient factors to the share in panel d, in percentage points of the climate-mitigation-guided reduction, relative to the mean over all draws. Each point is one draw, colored by the sampled value of that factor. Contributions are exact Shapley values of a quadratic surrogate (linear, squared and pairwise terms; $R^2 = 0.96$) fitted to the 1,000 draws. The ring gives each factor's share of the summed mean absolute contribution. Factors are defined in Methods. GHG, cumulative GHG reduction; CED, cumulative avoided fossil demand; EXE, cumulative useful-product exergy. Source data are provided as a Source Data file.

Environmental priorities retain competing benefits asymmetrically

Only climate-mitigation-guided allocation changed its preferred use over time. It preferred bioenergy at first and switched to biofuel between 2025 and 2035 under Paths 1 to 4 and in 2043 under Path 5, with no later reversal (Fig. 2b). Bioenergy lost its advantage because its substitution credit is entirely electricity and heat, which decarbonize, whereas the fossil fuels and chemicals displaced by the other routes retain

residual emissions, mostly the fossil carbon these products release at end of life. Exergy-efficiency-guided allocation selected biofuel from 2021 under every path. Fossil-displacement-guided allocation retained bioenergy throughout, because avoided fossil demand is evaluated against fixed 2020 reference technologies and does not fall with the grid. The biochemical route was never preferred.

Through 2120, climate mitigation and exergy efficiency largely preserved each other's benefit, whereas fossil displacement preserved little of the climate benefit. Without inertia, exergy-efficiency-guided allocation retained 87.2 % to almost 100 % of climate-mitigation-guided mitigation across national and prefectural comparisons, all five paths and both pools. In the other direction, climate-mitigation-guided allocation retained 82.0 to 98.8 % of exergy-efficiency-guided exergy. Fossil-displacement-guided allocation retained between −0.9 % and 24.3 % of climate-mitigation-guided mitigation, a negative value indicating a net adverse GHG outcome. Climate-mitigation-guided allocation, by contrast, retained 38.1 % of the avoided fossil demand of fossil-displacement-guided allocation nationally under Path 1 with the expanded pool (Fig. 2a). Compatibility between priorities was asymmetric. It also changed as benefits accumulated: through 2030, climate retention under exergy-efficiency-guided allocation was as low as 48.7 % in some settings, before the two priorities converged on biofuel (Supplementary Fig. 1).

In the Monte Carlo analysis (Methods), climate-mitigation-guided allocation still switched from bioenergy to biofuel across almost the whole tested coefficient range, under every path. The exceptions lay where the fuel credit was at least 14 % lower and the chemicals credit at least 11 % higher than in the main results. The median switch year ranged from about 2025 (Path 2) to 2043 (Path 5) (Fig. 3d). The biochemical route became

preferred mainly where its credit was sampled above the fuel credit, early under Paths 1 to 4 and near the later switch under Path 5 (Supplementary Note 3).

Realized mitigation depends on how far, how fast and when allocation can change

Under inertia, climate-mitigation-guided allocation realized between about half and three quarters of its mitigation. Low inertia combines an earlier response, peaking in 2053, with a larger permitted departure from the incumbent allocation ($\lambda = 0.7$). High inertia combines a later response, peaking in 2087, with a smaller departure ($\lambda = 0.5$). Under Path 1 with the expanded pool, cumulative mitigation through 2120 fell from 387.4 Mt CO_2e without inertia to 276.9 Mt under low inertia and 190.9 Mt under high inertia (Fig. 3a). Across the ten national path and pool settings, low inertia retained 70.0 to 74.4 % of the no-inertia outcome and high inertia 44.3 to 55.2 %. Fossil-displacement-guided allocation carried no inertia penalty, because its preferred use was already the incumbent (Fig. 3a).

The cost of inertia was largest where the preferred use changed early, because the allocation lagged while the incumbent use was losing its value (Fig. 3d). Through 2050, high inertia retained 81.5 % of the no-inertia reduction under Path 5, where biofuel became preferred only in 2043, but 37.8 and 35.1 % under Paths 2 and 4, where the switch came in 2025 and 2027. By 2120 the range narrowed to 44.3 to 55.2 %.

Permitted departure governed most of this loss, but the timing of the response carried a cost of its own. Within the evaluated ranges, raising λ from 0.1 to 1 changed retention through 2120 by 56 to 89 percentage points, while moving the response peak at fixed λ changed it by 2 to 36 points (Supplementary Note 2). Under Path 1 with the expanded pool at $\lambda = 0.7$, a response peaking in 2087 instead of 2053 lowered retention from 83.7

to 62.3 % through 2050 but only from 71.5 to 66.8 % through 2120, so delay cost most in the first decades. The timing cost persisted even at $\lambda = 1$, which permits full reallocation: the latest response windows retained as little as 64.5 % through 2120. Reaching the preferred allocation also did not recover the benefit lost on the way. Under Path 1 with the expanded pool, with full departure and annual reallocation capped at five percentage points (Methods), the preferred allocation was reached in 2048. Retention rose from 86.5 % through 2050 to 97.4 % through 2120, while the accumulated shortfall of 10.2 Mt CO_2e remained (Supplementary Note 2).

Even after these losses, climate-mitigation-guided allocation exceeded the best of the nine prescribed configurations through 2120 in all ten national settings, by 57 to 68 % under low inertia and by 4.5 to 19.9 % under high inertia (Fig. 3b). In the Monte Carlo analysis, the low-inertia advantage held across the whole tested coefficient range, for all five paths, both pools and both horizons. The high-inertia advantage was narrower. Through 2120, it was lost only where the chemicals credit was high relative to the fuel credit, mostly under Paths 2 and 4. Through 2050, it reversed under Paths 1 to 4 even in the main results (Supplementary Note 3). Under low inertia, climate-mitigation-guided allocation kept its comparative benefit despite a substantial realization loss and coefficient uncertainty.

The same allocation is worth different amounts under different backgrounds

Contemporary environmental value changed with the background even when the allocation did not. The 2030 power target delivered between 79.4 Mt CO_2e (Path 4) and 119.1 Mt (Path 5) of cumulative GHG reduction through 2120, a factor of 1.50, with no change in what any chip was used for. When decarbonization stalled after following Path 1 to 2040 (Methods), climate-mitigation-guided allocation preferred the same use in every

year as under Path 1 and realized the same shares in all three inertia settings. Its no-inertia GHG reduction through 2120 nevertheless fell from 387.4 to 321.3 Mt CO_2e (Fig. 3c). The difference was a change in the value of an unchanged allocation. The same change raised the value of every 2030 target and of high-inertia allocation, by 29 to 74 Mt, without changing the ordering of the configurations shown (Fig. 3c, Supplementary Note 4).

The value of added chips depended on the use that received them. Reclaimed chips entered the expanded pool from 2076. Under Path 1, they raised the no-inertia climate-mitigation-guided GHG reduction through 2120 from 340.0 to 387.4 Mt CO_2e (Fig. 3a). Directed by fossil-displacement-guided allocation, the same chips added 2,306 PJ of avoided fossil demand but lowered GHG reduction from 24.48 to 20.73 Mt. The loss arose because, after 2050, chips sent to bioenergy still carried their pathway burdens while displacing electricity and heat that no longer emitted, a net −54 kg CO_2e per wet tonne (Supplementary Note 4). The stalled background reversed that valuation to +517 kg CO_2e per wet tonne.

The factor that explained most of a shortfall differed among commitments. An exact Shapley decomposition attributes the gap between the no-inertia climate-mitigation-guided allocation under Path 1 and each alternative configuration under high inertia and stalled decarbonization to three factors, one for each of the three questions: the allocation rule, the inertia and the background (Fig. 3e). For the fossil-displacement-guided alternative, allocation accounted for 208 Mt of the 248 Mt gap through 2120 in the expanded pool, realization for 82 Mt and background for −42 Mt. For the exergy-efficiency-guided alternative, the 168 Mt gap was mostly realization (147 Mt) and

background (19 Mt), because exergy-efficiency-guided and climate-mitigation-guided allocation preferred the same use in every year after 2028. Under high inertia, the larger term for the 2030 fuel target changed with the horizon, from realization at 2050 to allocation at 2120, under every background tested. The 2030 chemicals target showed the same change under the stalled background shown, but not under Paths 3 and 5. Under low inertia, allocation was the larger term at both horizons (Supplementary Note 5). In every contrast shown, the conditional background effect took both signs, depending on which other factors were already in place. Each factor's contribution is conditional on the state of the other two.

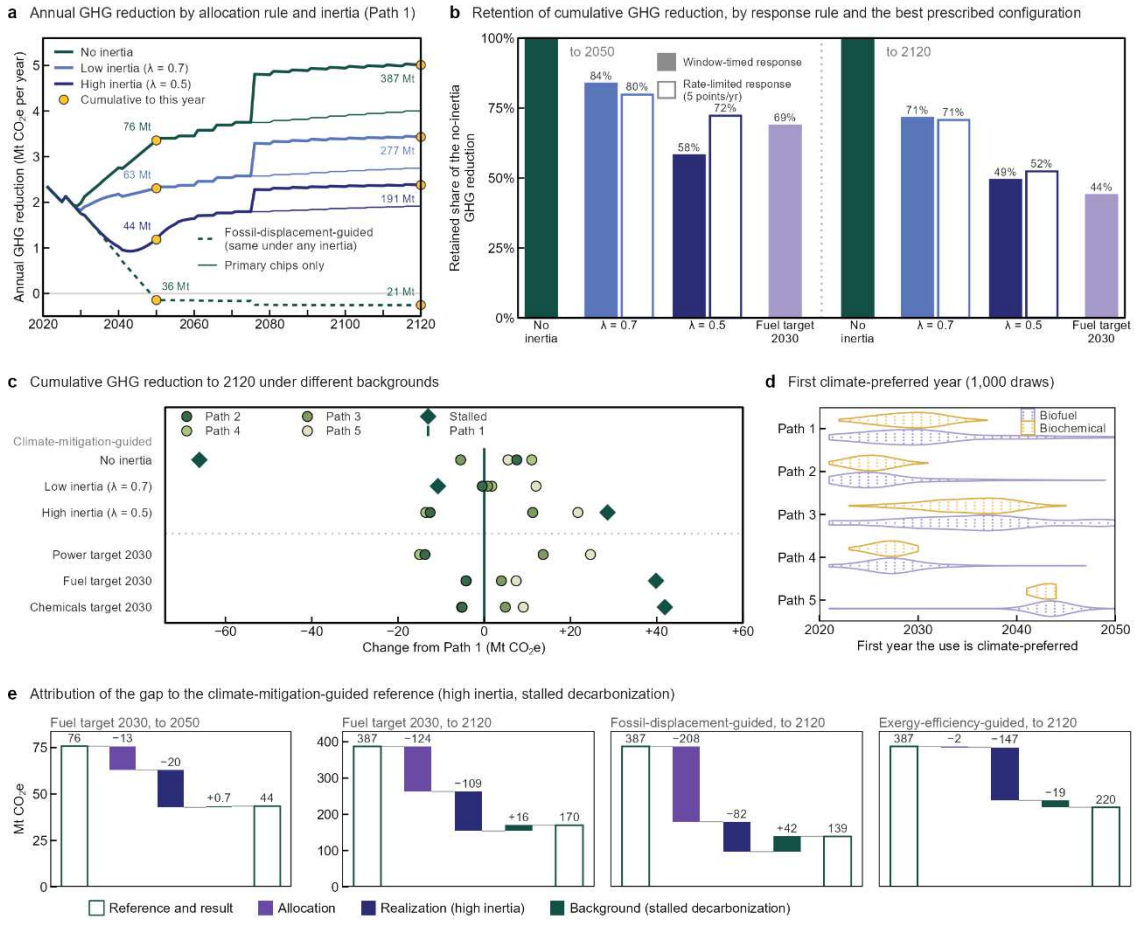


Figure 3 What a climate-mitigation-guided commitment delivers depends on how far and how fast allocation can change and on the energy background.

a, Annual GHG reduction under climate-mitigation-guided allocation without inertia and with low inertia ($\lambda = 0.7$, response peak 2053) and high inertia ($\lambda = 0.5$, response peak 2087), and under fossil-displacement-guided allocation, which is identical under every inertia setting because its preferred use is the incumbent (Path 1, expanded pool). No inertia means full permitted departure with immediate response. Gold markers give cumulative GHG reduction to 2050 and 2120. Thin lines give the primary pool, so their gap to the thick lines from 2076 is the contribution of reclaimed chips. **b**, Cumulative GHG reduction retained relative to no inertia under the window-timed response of panel a (solid) and a rate-limited response that reallocates at most five percentage points of the pool per year (outline), with the best prescribed configuration, the 2030 fuel target (Path 1, expanded pool). **c**, Change in cumulative GHG reduction to 2120 when the background changes from Path 1 to Paths 2 to 5 (circles) or to stalled decarbonization (diamonds), in the expanded pool. The prescribed configurations keep the same allocation under every background, whereas climate-mitigation-guided allocation follows the preferences of each path, which under stalled decarbonization are the same as under Path 1. The stalled case follows Path 1 to 2040 and then holds electricity and heat emission factors at their 2040 values. The ordering of configurations is the same under every background. **d**, First year in which biofuel and biochemical use is climate-preferred in 1,000 Monte Carlo draws per path. Each draw scales pathway burdens (±20 %) and displacement credits for electricity and heat (±10 %), fuels (±20 %) and chemicals (±25 %) by independent uniform factors. One draw per path with a first biofuel year of 2076 is omitted. Biochemical use is never preferred in the main results (Supplementary Note 3). **e**, Exact

Shapley attribution of the gap between climate-mitigation-guided allocation without inertia under Path 1 and four alternatives under high inertia and stalled decarbonization. Intermediate levels are averages over factor orderings, not modelled runs, and inertia applied to the 2030 fuel target is a diagnostic counterfactual. The change of the larger term between horizons holds under high inertia only (Supplementary Note 5). Source data, including ranges over the ten path and pool settings, are provided as a Source Data file.

Shared pathway preferences coexist with local exceptions

Prefectures shared the national preferred use, but the effect of target timing could reverse locally. Because the pathway coefficients are the same everywhere, the national and prefectural preferred uses agreed in all 1,515 combinations of rule, path and year under the principled allocations without inertia. What differed locally was the resource trajectory that a commitment binds. In Shizuoka, postponing the fuel target from 2030 to 2080 raised cumulative GHG reduction through 2120 from 3.56 to 3.83 Mt CO_2e under Path 1 with the expanded pool, opposite to the national direction. The reversal held under all five paths and both pools (Supplementary Note 6). The target quantity is downscaled from each prefecture's share of primary-chip availability at the target year, and Shizuoka's availability nearly doubled between 2030 and 2080 (+92.7 %, against +13.6 % nationally), so the later target committed more chips to biofuel in the decades when biofuel was the climate-preferred use. Across all 4,230 prefectural comparisons, the ordering between the 2030 and 2050 targets ran opposite to the national direction in 1,493 cases (35 %; Fig. 4d), against 87 (2.1 %) for 2030 versus 2080 and 55 (1.3 %) for 2050 versus 2080.

The national advantage of climate-mitigation-guided allocation over the best prescribed configuration held in almost every prefecture under low inertia and in most under high

inertia. At 2120, low-inertia climate-mitigation-guided allocation exceeded the locally best prescribed configuration in 460 of 470 prefectural path and pool settings (47 prefectures, five paths, two overlapping pools), with all ten exceptions in Okinawa, where the 2050 power target was the strongest local alternative. High-inertia allocation exceeded it in 409 of 470 settings and fell below it in 61 (Fig. 4a). The best local comparator itself varied among four prescribed configurations, led by the 2050 fuel target in 284 settings (Fig. 4e), so the local alternative often differed from the 2030 fuel target used in the national comparison. The 11 prefectures where high inertia fell short in some setting held 24.5 % of national primary-chip supply and included the five with the thinnest margins, all among the ten whose supply shrank between 2030 and 2050 (Fig. 4b, c). The losses themselves were nearly uniform, 48 to 52 % under high inertia and 16 to 18 % under stalled decarbonization in every prefecture (Fig. 4f). Broad agreement on what the chips should be used for coexisted with different consequences of committing to it under local resource trajectories.

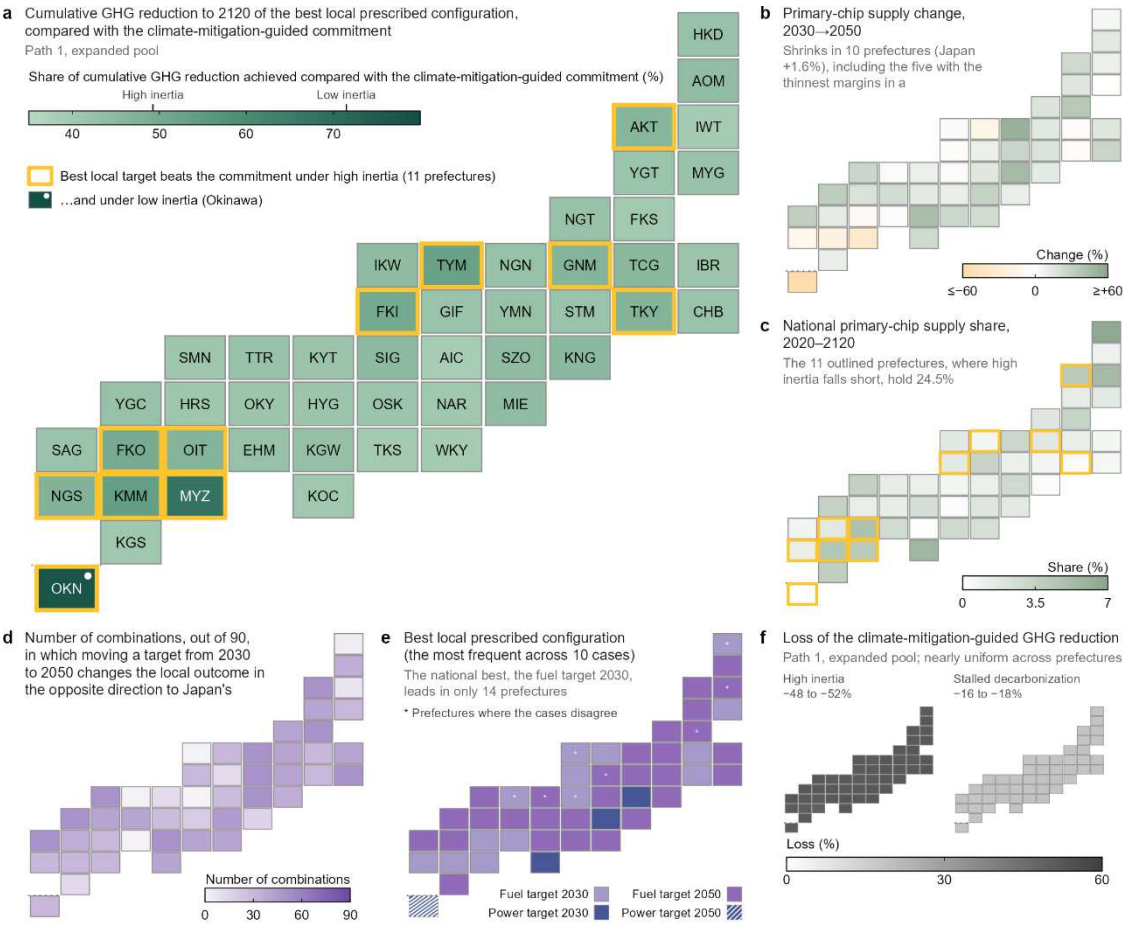


Figure 4 The national case for climate-mitigation-guided allocation holds in most prefectures, but its margin, the best local alternative and the effect of target timing vary.

a, Cumulative GHG reduction to 2120 of the best local prescribed configuration as a share of climate-mitigation-guided allocation without inertia, with the high- and low-inertia retention of the commitment marked on the color bar (Path 1, expanded pool). Gold outlines mark the 11 prefectures in which the best local target exceeds high-inertia allocation in at least one of the ten path and pool settings (61 of 470 settings); the dot marks Okinawa, the only prefecture where it also exceeds low-inertia allocation (10 settings). **b**, Change in primary-chip supply from 2030 to 2050 (Japan +1.6 %). **c**, Each

prefecture's share of national primary-chip supply over 2020 to 2120; the outlined prefectures of panel a hold 24.5 %. **d**, Number of the 90 combinations (three targets, five paths, two pools, three indicators) in which postponing a target from 2030 to 2050 changes the local outcome in the opposite direction to Japan's (1,493 of 4,230 in total). **e**, Best local prescribed configuration, the most frequent across the ten settings; asterisks mark prefectures where the settings disagree. The national best, the 2030 fuel target, is the local best in 14 prefectures. **f**, Loss of climate-mitigation-guided GHG reduction to 2120 under high inertia and under stalled decarbonization, relative to no inertia under Path 1 (expanded pool). Source data are provided as a Source Data file.

Discussion

Whether a biomass commitment is environmentally justified depends on three conditions, and reaching its target is not one of them. A justified commitment outperforms competing uses of the same feedstock, is realizable under prevailing constraints, and remains valuable under the production systems contemporary with its implementation. Our results show each condition failing in a different way. The best prescribed configuration, the 2030 fuel target, retained 44 % of the cumulative GHG reduction delivered by climate-mitigation-guided allocation. That allocation in turn realized 71 % of its own benefit under low inertia and 49 % under high inertia. Held unchanged, the same allocation without inertia delivered 66 Mt CO2e less when decarbonization stalled. A commitment can pass one test while failing another. As with the committed emissions of long-lived infrastructure (Davis et al., 2010; Seto et al., 2016), a biomass commitment binds a resource trajectory long after the conditions that justified it have changed.

The first condition, comparative benefit, measures a wood-based product against the other uses of the same feedstock, not only against its conventional counterpart. Competition between biomass uses alters mitigation across sectors and value chains (Daioglou et al., 2015; Millinger et al., 2025; Forster et al., 2023). In Japan, the ambitions for the three uses are set in separate plans, each with a target for 2030 (Agency for Natural Resources and Energy, 2021; MLIT, n.d.; Cabinet Office, Government of Japan, 2024). Our prescribed configurations show that a target specifies a trajectory as well as a destination. The same fifty-year postponement had different climate consequences because each agenda translated its target year into allocation timing and commitment quantity differently. A target year reads as a deadline but works as a commitment.

Removing the prescription shows that the benefits forgone are unequal and directional. Environmental merit-order analysis ranks uses per unit of biomass (Winter et al., 2022), and multiobjective optimization shows how the preferred allocation shifts with the criterion (Vadenbo et al., 2017a, 2018). Evaluating each principled allocation through all three indicators asks instead what remains of the benefits that the other principles favored. Nationally under Path 1, fossil-displacement-guided allocation preserved 5.4 % of the climate benefit, whereas climate-mitigation-guided allocation preserved 38 % of the fossil displacement. Climate-mitigation- and exergy-efficiency-guided allocation were far more compatible, because their preferred uses converged on biofuel between 2025 and 2043, depending on the path. Measured over the whole century, the two allocations look largely interchangeable. Before they converged, choosing one still cost part of the benefit the other would have delivered. Compatibility between priorities followed from the pathway alternatives and their evolving performance, so the climate–exergy compatibility found here is specific to these routes rather than a general synergy.

Useful-product exergy measures the thermodynamic quality of useful outputs, not the resource efficiency assessed in exergetic studies of wood cascades (Risse et al., 2017).

The second condition, realizability, asks whether the preferred allocation is reached. Investment history and infrastructure lock-in reinforce incumbent technologies (Unruh, 2000; Barazza and Strachan, 2021; Seto et al., 2016), and implementation conditions materially affect transition outcomes (Fisch-Romito et al., 2025). In our framework, this inertia has two components: a permitted departure, which limits how far the realized allocation moves from the incumbent use toward the preferred one, and a response window, which sets when it moves. The cost of inertia was largest where the preferred use changed early, because the allocation lagged while the incumbent use was losing its value. Fossil-displacement-guided allocation shows that realization and comparative benefit are separate tests. Its preferred use is the incumbent, so inertia left its realized allocation unchanged, yet it retained almost none of the available mitigation. Full realization could coexist with a large climate opportunity cost, while incomplete realization could obscure an advantage that remained available.

Each component of the inertia operator corresponds to an instrument that already governs woody biomass in Japan, which indicates where resistance to reallocation could be lowered. Permitted departure, which governed most of the modeled loss, corresponds to how much of the chip supply remains bound to bioenergy by support and supply terms. Since July 2012, the feed-in tariff has guaranteed woody biomass power a fixed purchase price for 20 years (Shiraishi and Park, 2026), and long-term fuel contracts add further inertia (Honda, 2026). The expiry of these terms, from about 2032 for the earliest plants, is the point at which chips can be released without breaking a commitment, provided that

503 support is not renewed by default and the next use is judged on its current value. The
504 response window corresponds to the lead time of receiving capacity. In our scenarios,
505 benefit lost to delay was not recovered by later full departure, so fuel and chemical
506 capacity would need to be in place before those chips are released. Where departure
507 remains limited, a steady schedule helps. At the high-inertia departure, a five-point annual
508 cap on reallocation outperformed the late response in every national setting, and staged
509 revisions of fuel-supply contracts could be its practical form. Prefectural biomass plans,
510 so far formulated in 19 prefectures (MAFF, 2022), are where the order of release could
511 be coordinated against the local alternative. These correspondences are qualitative,
512 because our inertia settings are stylized rather than calibrated from such evidence.

513 A preferred allocation may not be realized, and a realized allocation may lose the
514 value that justified it. The latter concerns contemporary environmental value, which
515 prospective LCA has made measurable. Inventories can now follow future background
516 systems (Mendoza Beltran et al., 2020; Sacchi et al., 2022), with their drivers specified
517 through scenarios (Langkau et al., 2023) and their processes traced through time (Pigné
518 et al., 2020; Müller et al., 2025). Databases coupled to integrated assessment models, such
519 as premise, transform several energy-intensive sectors at once along the model's socio-
520 techno-economic pathways (Sacchi et al., 2022). For one technology in one country, the
521 future reaches the substitution credit mainly through the energy system, in the conversion
522 chains, the displaced grid energy and the production of the displaced fossil products.
523 Japan's net-zero target fixes the 2050 endpoint, so our five paths represent only the timing
524 and shape of the route to it, without requiring a specific decarbonization plan. Prospective
525 LCA typically takes the use itself as given. Our framework separates the two by design:
526 the background can be changed while the physical allocation is retained, and realization

can be changed while the background stays fixed. This separation is analytical and does not assume that allocation, implementation and background systems evolve independently in the real world. Implementation progress and a positive substitution balance each establish only part of the comparative environmental case. Plants approved under the feed-in tariff or premium since fiscal 2022 must demonstrate lifecycle GHG savings of 50 % against a fixed fossil reference of 0.65 kg CO2e per kWh of electricity, rising to 70 % for fuels used from 2030, while earlier plants are exempt (Agency for Natural Resources and Energy, 2022). The reference stays fixed as the grid decarbonizes, so a plant can keep passing the criterion after, in our scenarios, its use has lost its climate advantage over the alternatives.

More secondary resource does not by itself resolve the allocation question. Research on cascading wood use ties environmental outcomes to material quality, subsequent use and recovery timing (Faraca et al., 2019; Navare et al., 2022). Those outcomes also depend on the production displaced (Vadenbo et al., 2017b; Howard et al., 2021), and displacement benefits erode as reference systems change (Harmon, 2019; Myllyviita et al., 2022). Our results add a fourth dependence: the use that receives the chips. The same reclaimed chips, entering under unchanged allocation shares, raised cumulative mitigation by 47 Mt CO2e when climate-mitigation-guided allocation received them. They lowered it when fossil-displacement-guided allocation sent them to bioenergy after the energy background had decarbonized, and the stalled background reversed the sign of that valuation. Benefits established for retaining wood in circulation leave a subsequent question: whether the use that receives the recovered feedstock can turn it into an environmental gain under the production systems it then displaces. Recovery and subsequent allocation contribute different parts of the environmental case

for circular resource use. Japan's recycling indicators capture only the first. The Construction Material Recycling Act counts making waste wood available for combustion as recycling, and the national indicator, 96.2 % of construction waste wood recycled or reduced in 2018, combines fuel and material use, although MLIT's analysis of the same survey traced 59 % of the wood leaving sites to fuel (MLIT, 2024). Targets on that destination, as well as on the rate, would make the second part visible before reclaimed supply grows.

Distinguishing the three conditions matters because each calls for a different response. When competing uses retain substantially greater benefits, the remedy is redirection. When the preferred allocation keeps its advantage but is incompletely realized, lowering resistance to reallocation can recover part of the unrealized benefit, while the benefit forgone before the preferred allocation is reached stays lost. When the surrounding production system has changed, the commitment needs to be justified again on the value it delivers now. Each judgment is made against an alternative, and the best alternative to a climate-mitigation-guided commitment differed among prefectures, so each comparison needs the local alternative rather than a national one.

Whether a biomass commitment is environmentally justified is better treated as an evolving property of the commitment than as a fixed attribute of its sectoral destination. The three conditions need not move together, nor does a change in one by itself identify a new preferred destination. A commitment instead stays justified insofar as it remains advantageous relative to competing uses, realizable under prevailing constraints, and environmentally valuable under the conditions contemporary with its implementation. Dynamic adaptive policy pathways link present decisions to future options and

reassessment under changing conditions (Haasnoot et al., 2013). Our analysis identifies the environmental relationships such reassessment should test, not an economically preferred pathway. Reassessment, in this sense, is not a search for a permanently optimal destination, but a means of testing whether the environmental rationale for an existing commitment still holds as alternatives, realization conditions and substitution opportunities evolve.

Several limitations bound these results. The model lets the resource and the energy background change over a century, while the technologies are represented at their present performance and markets are not represented. The biofuel and biochemical routes are taken from process simulation and laboratory yields and bioenergy from a commercial combined heat and power unit, with performance that does not vary with scale, learning or the quantity displaced. Whether a commitment remains justified as these routes mature, and how uncertain the avoided-fossil and exergy coefficients are, remain open. The chip pool is likewise domestic, nationally and in each prefecture. Without prices, capacity costs or imports, whether chips withdrawn from power would be replaced by the grid or by imported pellets, on which Japanese biomass power already draws (Honda, 2026; Shiraishi and Park, 2026), is not resolved here. The valuation follows one convention throughout: every tonne counts alike from 2021 to 2120, biogenic carbon is neutral without a credit for carbon held in chemical products, and displaced electricity and heat are valued at average emission factors. Other conventions would value the same allocation differently, and which indicator should take priority is left to the decision maker. Each of these conditions is an input to the framework rather than part of its structure, and applying the framework elsewhere requires locally appropriate resource trajectories, pathway performance and realization conditions.

Methods

Scenario design and allocation trajectories

We evaluated how alternative allocation choices and realization conditions changed the environmental outcomes obtained from a common, time-varying wood-chip resource. Annual resource availability, realized allocation and contemporary pathway performance were linked for Japan and its 47 prefectures over 2021–2120, with 2020 used for initialization. Prescribed scenarios determined allocation from sectoral commitments and target years. Principled scenarios selected preferred uses according to environmental performance, with alternative inertia settings restricting their realization. Background trajectories varied the GHG performance associated with resource use and could also alter preferred allocation under climate-mitigation-guided allocation.

Annual allocation shares connected the available resource to its destinations. Shares were denoted by $x_{g,u,t}^{\gamma,b}$, where g denotes geography, u use, t year, γ the allocation scenario and b the background trajectory. All available chips were assigned to the modeled uses, without interannual storage or a separate unused-resource option. The two scenario families were represented as:

$$\begin{aligned} x_{g,u,t}^{\gamma,b} &= F_{p,u}\left(t; T^*, \Theta_{g,p,T^*}, R_g\right), \quad \gamma = (p, T^*), \\ x_{g,u,t}^{\gamma,b} &= \mathcal{M}_\iota\left[z_g^{j,b}\right]_{u,t}, \quad \gamma = (j, \iota). \end{aligned} \tag{1}$$

In the prescribed branch, $F_{p,u}$ determines allocation from sectoral agenda p, target year T^*, committed feedstock quantity Θ_{g,p,T^*} and resource trajectory R_g. In the principled branch, environmental criterion j determines preferred allocation z, and the inertia operator $\mathcal{M}_\iota$ translates its history into realized allocation under inertia setting ι.

In the main text, prescribed configurations are named by target type and year (for example, the 2030 fuel target) and principled configurations by the indicator that guides them (climate-mitigation-guided, fossil-displacement-guided and exergy-efficiency-guided allocation). Data files, Supplementary Methods and Supplementary Tables retain the computational labels ELC, SAF and CHM for the three prescribed agendas, GHG, CED and EXE for the three guiding indicators, and no_inertia, low and high for the inertia settings (Supplementary Table 2).

Scenarios with prescribed policy targets

Prescribed scenarios compared the environmental consequences of alternative sectoral commitments and target-year configurations under common resource and background conditions. Policy ambitions supplied the starting points for three targets: a power target for electricity-oriented bioenergy, a fuel target for sustainable aviation fuel and a chemicals target for biochemical production, each evaluated at target years of 2030, 2050 and 2080. The year 2030 is the official policy deadline, while 2050 and 2080 were study-defined timing settings. Each ambition was first converted into the chip quantity needed to meet it from domestic wood chips and compared with national chip supply, and the operative commitment was then set according to the role of the use (Supplementary Tables 3 and 4). Bioenergy is the incumbent use, so its target describes how long existing use continues. Fuels and chemicals are new claims that must draw chips away from it, so the size of their commitments governs how much they can deliver. Transition functions and residual-routing rules then determined how the available resource was distributed as each commitment was pursued.

The power target represented continued priority for bioenergy, motivated by the electricity-generation ambition of the Strategic Energy Plan (Agency for Natural Resources and Energy, 2021). Supplying 5% of the 934 TWh of electricity demand projected for 2030 from domestic chips would require about 57 Mt of chips, twelve times the national supply in that year. Its operative commitment was therefore set to the total chip quantity available in the selected target year and held fixed thereafter. All chips remained in bioenergy up to and including that year; subsequent supply exceeding the committed quantity was divided equally between biofuel and biochemical production. Consequently, changing the power target year changed both the timing of diversification and the absolute quantity committed to bioenergy.

The fuel target directed chips towards aviation-fuel production. Meeting the 2030 target of a 10% SAF share in jet fuel, about 1.72 million kL of SAF (MLIT, n.d.; Agency for Natural Resources and Energy, 2024), from domestic chips would require about 18.5 Mt of chips at the SAF yield of the biofuel route and a fuel density of 807.5 kg m^{-3}, four times the national supply in 2030. A commitment of that size would leave no chips for other uses and would make the fuel target nearly indistinguishable from climate-mitigation-guided allocation, which prefers biofuel from 2029 under Path 1. The fuel commitment was instead fixed at a study-defined scale of 2.06 Mt of chips per year, 44% of national supply in 2030. This places it on the same scale as the chemicals commitment (48%), so that the two new claims draw on comparable shares of the resource. At this scale the committed chips supply about 11% of the 2030 SAF demand. Because this quantity is not derived from the policy target, Supplementary Note 7 reports how the results depend on the sizes of both new commitments. The commitment remained constant across target years, allowing national timing comparisons around a common

commitment quantity. Biofuel was the principal destination, biochemical production developed as a secondary destination after the target year, and bioenergy received the remaining resource. The common transition rules below specified how these shares evolved with the commitment and annual availability.

The chemicals target directed chips towards chemical production as a source of renewable feedstock. Its national requirement was derived from the two-million-ton bio-based plastics ambition (Cabinet Office, Government of Japan, 2024), assuming that bio-based plastics follow the current composition of domestic plastics input, so that only the aromatic-linked polymers draw on BTX; the requirement then followed from their aromatic precursor demand and BTX yields (Supplementary Table 4). The resulting 2.27 Mt of chips per year, 48% of national supply in 2030, lies within domestic supply, so the ambition was used at its full size. This national feedstock commitment was held constant across target years. Biochemical production was the principal destination, biofuel became the secondary destination after the target year, and bioenergy received the remaining resource.

A common allocation function represented how the principal commitment, secondary use and remaining allocation jointly distributed the available resource among competing destinations:

$$F_{p,u} = m_{g,p,t}^{T^*}\mathbf{1}(u = \mu_p) + n_{g,p,t}^{T^*}\mathbf{1}(u = \nu_p) + \left(1 - m_{g,p,t}^{T^*} - n_{g,p,t}^{T^*}\right)\pi_{p,u}. \quad (2)$$

Here, m is the principal share assigned to destination μ_p, n is the secondary share assigned to ν_p, and $\pi_{p,u}$ distributes the remaining resource. Under the power target, the residual was divided equally between biofuel and biochemical production. For the fuel

and chemicals targets, the secondary destinations were biochemical and biofuel production, respectively, and the final residual was assigned to bioenergy.

For the fuel and chemicals targets, principal shares increased smoothly towards their target-year levels. Thereafter, each committed feedstock quantity determined the principal share of annual availability, capped at full allocation. Secondary use developed progressively after the target year, subject to the remaining resource. These rules specified when each destination received feedstock, and with it when its environmental contribution accrued. The transition functions and residual-routing rules were study-defined; their formulations and parameters are provided in the Supplementary Methods, and the resulting annual allocation shares of every configuration are shown in Supplementary Fig. 2.

Prefectural commitments were obtained by multiplying each national commitment by the prefecture's share of national forest- and sawmill-chip availability at the corresponding target year. The national pre-target share endpoints were retained, while post-target shares reflected the resulting local commitments and local availability. Full piecewise functions, conversion calculations and parameters are provided in Supplementary Methods, Eqs. S16–S33.

Scenarios guided by environmental principles

Principled scenarios used the environmental concerns assessed in the prescribed scenarios to guide allocation directly, allowing the consequences of prioritizing each to be compared. Climate-mitigation-guided allocation prioritized net GHG reduction per unit of feedstock, accounting for biomass-chain burdens and displaced reference production. Fossil-displacement-guided allocation prioritized net avoided fossil demand

per unit of feedstock, emphasizing defossilization. Exergy-efficiency-guided allocation prioritized useful-product exergy efficiency, the fraction of feedstock exergy retained in useful outputs. The preferred destination under this principle followed from efficiency rankings, while useful-product exergy was the outcome reported for the resulting allocation.

To identify the preferred use for the chip mixture available in each geography and year, source-specific pathway coefficients were weighted by the corresponding resource quantities:

$$V_{g,u,t}^{j,b} = \frac{\sum_s R_{g,s,t}\,\kappa_{s,u,t}^{j,b}}{\sum_s R_{g,s,t}},$$
$$u_{g,t}^{*,j,b} \in \arg\max_u V_{g,u,t}^{j,b}, \tag{3a}$$
$$z_{g,u,t}^{j,b} = \mathbf{1}\left(u = u_{g,t}^{*,j,b}\right).$$

The ranking coefficient κ represented GHG reduction, avoided fossil demand or exergy efficiency according to priority j. The selected destination received a preferred share of one. The ranking coefficients were not converted into proportional shares, and preferences were determined annually rather than through intertemporal optimization. Climate-mitigation-guided preferences could change with prospective background conditions, whereas the avoided-fossil-demand and exergy coefficients were background-independent. Definitions of the performance coefficients are provided in the pathway-assessment section.

A preferred destination need not be immediately realizable. We introduced implementation inertia to represent resistance to reallocating biomass away from an incumbent allocation, making the realizability of the preferred allocation explicit within the current framework. We specified an all-bioenergy allocation, $\mathbf{e} = (1,0,0)$, as the

incumbent reference. Realization was governed by two components: a response window, the calendar-dependent profile of adjustment, and a permitted departure, the parameter limiting departure from the incumbent:

$$\tilde{\mathbf{z}}_{g,t}^{j,b,\iota} = \mathbf{e} + \lambda_\iota\left(\mathbf{z}_{g,t}^{j,b} - \mathbf{e}\right),$$
$$\mathbf{x}_{g,t}^{j,b,\iota} = \mathcal{M}_\iota\left[z_g^{j,b}\right]_{u,t} = \mathbf{x}_{g,t-1}^{j,b,\iota} + G_\iota(t)\left(\tilde{\mathbf{z}}_{g,t}^{j,b,\iota} - \mathbf{x}_{g,t-1}^{j,b,\iota}\right). \quad (3b)$$

The inertia operator $\mathcal{M}_\iota\left[z_g^{j,b}\right]_{u,t}$ was governed by three parameters: α_ι, β_ι and λ_ι. The parameter λ_ι determined how far the adjustment target could depart from the incumbent. Parameters α_ι and β_ι shaped the temporal profile of adjustment towards that target, controlling the response $G_\iota(t)$, a Beta density evaluated on normalized calendar time $(t - 2020)/100$ and divided by its maximum over the 2020–2120 annual grid. Realized allocation was initialized at $\mathbf{e}$, and the recursive update retained the effects of preceding allocations.

Without inertia, allocation followed the annually preferred use directly, defined separately by $\mathbf{x}_t = \mathbf{z}_t$. Low and high inertia used $(\alpha_\iota, \beta_\iota, \lambda_\iota) = (3,5,0.7)$ and $(5,3,0.5)$, respectively. The former provided an earlier response profile and permitted a larger departure from incumbent use; the latter provided a later profile and retained a larger incumbent component. These labels identify two stylized configurations, rather than a universal ordering for every possible preference trajectory. The response functions and parameters were study-defined, without empirical calibration. Beyond the two adopted settings, the inertia operator was examined over a response surface that varied permitted departure, the timing of the response peak and its concentration. An alternative realization rule capped annual reallocation at a fixed number of percentage points of the pool, and was evaluated against the original response at the same permitted departure, to separate

753 the speed of reallocation from its permitted extent. Detailed implementation is provided
754 in Supplementary Methods, Eqs. S38–S44, and Supplementary Table 5. The analytical
755 characterization of the inertia operator is presented in Supplementary Note 2.

756

757 *Wood chip resource availability*

758 The allocation trajectories were applied to annual, source-resolved wood-chip
759 availability, denoted by $R_{g,s,t}$ for source s, geography g and year t, in tonnes of wet chips
760 per year. Forest chips, sawmill-residue chips and reclaimed chips contributed different
761 quantities over the transition. Retaining these sources separately allowed their changing
762 proportions to enter the pathway rankings and their source-specific burdens and outputs
763 to enter environmental accounting. Resource supply was specified independently of
764 downstream allocation, without feedback from the selected uses to forest management or
765 roundwood production.

766 Primary-chip availability was derived from roundwood trajectories generated by
767 the Forest Management Model for Cyclical Forestry (FM2-CF) under a policy-oriented
768 forest transition (Han et al., 2026). Five-year harvest and thinning outputs were converted
769 to annual flows by distributing each block uniformly across its constituent years.
770 Material-flow calculations then translated roundwood volumes into timber, plywood and
771 chips using wood-quality fractions, processing routes, yields, density and moisture
772 conversions. Forest chips originated from the direct-chip route, while sawmill chips were
773 produced from residues of timber and plywood processing.

774 Construction use introduced a delay before wood returned as an additional chip
775 resource. Prospective reclaimed supply followed the timber and plywood that entered new

776 wooden housing, whose demand declines with Japan's projected population; product
777 exceeding that demand was not counted as a reclaimed resource. These products returned
778 after a 55-year lifetime and were converted to chips with a recovery fraction, the chipping
779 yield and moisture conversions. This supply entered from 2076 and did not include
780 returns from historical construction stock.

781 Annual source trajectories were supplied separately for Japan and the 47
782 prefectures (Supplementary Data 1). The national calculation used an independent Japan
783 series rather than the sum of prefectural inputs. Within each geography and year, the full
784 available source mixture determined the weights used for principle-guided ranking.
785 Primary and expanded reporting scopes subsequently included forest and sawmill chips,
786 or all three sources, respectively. Both resource scopes retained the same allocation
787 trajectory. The material-flow calculation of the source series, its parameters and input
788 provenance are provided in Supplementary Methods, Section 3 (Eqs. S1–S15;
789 Supplementary Table 6).

790

791 *Conversion pathways and performance assessment*

792 Wood-chip uses were represented by conversion pathways supplying electricity
793 and heat through bioenergy, hydrogen, sustainable aviation fuel and biodiesel through the
794 selected biofuel pathway, and benzene, toluene and xylene (BTX) through biochemical
795 production (Supplementary Methods, Section 8; Supplementary Tables 7–10; system
796 boundary in Supplementary Fig. 3). Source-specific inventories accounted for feedstock
797 supply, preparation and conversion; the biofuel and biochemical routes, not yet
798 deployed at scale, were represented from process simulation and experimental yields,

following recommendations for the prospective assessment of emerging technologies (Arvidsson et al., 2018). Conversion yields and foreground process requirements were held constant across scenarios, while background electricity and heat emission factors varied through time.

Pathway performance was assessed through GHG reduction, avoided fossil demand and useful-product exergy. Using process-based life-cycle assessment (LCA) following ISO 14040 and ISO 14044 (International Organization for Standardization, 2006a, 2006b), GHG reduction was calculated by system expansion as the burden of functionally equivalent reference production, including the fossil carbon that the displaced products release, minus the biomass-chain burden (Ekvall and Weidema, 2004), with background inventories from the IDEA v3.4 database (National Institute of Advanced Industrial Science and Technology, 2024; Supplementary Methods). GHG burdens were expressed in kg CO_2e with the climate-change characterization of the LIME2 method supplied with the database (Inaba and Itsubo, 2018). Biogenic CO2 was treated as climate-neutral, so that the carbon fixed in the chips and released in conversion or use cancels (Supplementary Methods). Avoided fossil demand was calculated analogously using the fossil-resource component of cumulative energy demand (Huijbregts et al., 2006; Frischknecht et al., 2015). Useful-product exergy quantified the capacity of useful outputs to perform work (Dewulf et al., 2008) and was calculated from output quantities using product-specific exergy factors (Song et al., 2011; Supplementary Methods). All three indicators were evaluated for every realized allocation trajectory, to establish comparative benefits and trade-offs.

Prospective background conditions changed the GHG performance of both biomass pathways and displaced reference production. Five controlled trajectories varied electricity and heat emission factors from common 2020 values to zero in 2050, remaining at zero thereafter. They represented study-defined alternatives for the timing of decarbonization rather than forecasts . Path 1 declined linearly and served as the reference (uniform decline). The other four paths formed a two-by-two design. Paths 2 and 3 declined gradually, one front-loading and the other back-loading the reduction (early surge and late acceleration), while Paths 4 and 5 followed S-shaped transitions placed early and late (managed take-off and abrupt transition). Paths 2 and 4 shared an early timing, reaching half of the 2020 level in 2029–2030, and Paths 3 and 5 shared a late timing, reaching it around 2043–2044. Because every path reached zero in 2050, all paths shared the same coefficients and preferred uses thereafter. Later differences between paths were carried over from earlier years, through the cumulative outcomes accumulated before 2050 and, under inertia, through allocations still adjusting to the earlier preference history. A stalled-decarbonization variant followed Path 1 to 2040 and then held the electricity and heat factors at their 2040 values, one third of their 2020 levels (0.180 kg CO2e per kWh and 0.0215 kg CO2e per MJ), through 2120. Preferences and allocations under this variant were derived from its own coefficients. These paths changed the contemporary environmental value of biomass use, measured as GHG reduction, in each year. Non-energy inventory components, fossil-carbon credits, fossil CED and exergy coefficients remained fixed. Detailed inventories, substitution conventions, mass bases, coefficient equations and background functions are provided in Supplementary Methods, Eqs. S45–S60, and Supplementary Tables 11 and 12. Annual coefficients for every path are provided as Supplementary Data 2 and shown in Supplementary Fig. 4.

Calculation and analysis of environmental outcomes

Annual environmental outcomes were calculated by multiplying source-specific chip availability by realized allocation shares and the corresponding pathway coefficients, then summing across uses and included sources (Eq. 4a). The factor 1000 converted wet tonnes to kilograms. Annual outcomes were accumulated from 2021 without discounting or temporal reweighting (Eq. 4b), with 2020 used for initialization. Cumulative results were primarily evaluated through 2120, supported by annual and earlier cumulative records to examine their development over time. Retention was defined as the cumulative outcome of a configuration divided by that of no-inertia climate-mitigation-guided allocation in the same geography, path, chip pool and horizon. National results span ten settings (five paths and two pools), and prefectural results span 470 (Supplementary Table 13). The best prescribed configuration was selected separately in each setting. Annual allocation shares and the cumulative and annual outcomes of every configuration are provided as Supplementary Data 3 and 4.

$$Y_{g,t}^{k,\gamma,b,\sigma} = 1000 \sum_{s \in S_\sigma} R_{g,s,t} \sum_{u} x_{g,u,t}^{\gamma,b} \, \phi_{s,u,t}^{k,b}, \tag{4a}$$

$$C_{g,H}^{k,\gamma,b,\sigma} = \sum_{t=2021}^{H} Y_{g,t}^{k,\gamma,b,\sigma}. \tag{4b}$$

Primary and expanded outcomes retained the same allocation trajectory, allowing their difference to identify the contribution of reclaimed chips under that allocation. Prefectural comparisons examined variation in environmental outcomes and preferred uses under local resource trajectories and commitment quantities, with source-specific pathway coefficients shared across locations. Detailed definitions, numerical conventions

and spatial counting procedures are provided in Supplementary Methods, Eqs. S61–S74. Prefectural quantities and comparisons are provided as Supplementary Data 5.

Robustness and attribution analyses

The robustness of preferences and rankings to coefficient error was tested with 1,000 Monte Carlo draws (Metropolis and Ulam, 1949) of six independent multipliers on pathway burdens and substitution credits, sampled uniformly over study-defined ranges rather than calibrated distributions, so shares of draws are not probabilities. Sampling-based propagation of this kind is the most widely used approach to parameter uncertainty in LCA (Lloyd and Ries, 2007; Groen et al., 2014). The multipliers were applied to GHG coefficients only, and preferences and allocations were recalculated in each draw. An exact Shapley decomposition (Shapley, 1953) attributed the gap between the reference and each alternative configuration to the allocation rule, realization and background, averaging each factor's contribution over all orders in which the factors can be switched, so that, unlike a sequential decomposition, it leaves no residual and does not depend on the order chosen (Ang et al., 2003). For the stalled variant, the change from Path 1 was separated into a valuation term and an allocation-response term, and the second was zero in all inertia settings. Grids, parameter ranges and counting conventions are given in Supplementary Notes 3, 4 and 5. The Monte Carlo, stalled-decarbonization and response-rule results are provided as Supplementary Data 6, and the Shapley decomposition as Supplementary Data 7.

The allocation framework, scenario design, model and analysis methods were conceived by the authors, and the model and its deterministic analyses were first implemented and

checked by hand in a spreadsheet model. Generative AI tools (Claude, Anthropic; ChatGPT, OpenAI) were used to write code that reproduces, extends and verifies these calculations at scale, including the Monte Carlo and Shapley analyses, which were implemented directly in code, and to produce the figures; all code outputs were checked against the spreadsheet model. The authors take full responsibility for the work.

Data availability

Model inputs and results are provided as Supplementary Data 1–7: chip availability (Supplementary Data 1), pathway coefficients (2), allocation shares (3), environmental outcomes (4), prefectural comparisons (5), robustness analyses (6) and the Shapley decomposition (7). The full model release, including inputs, outputs and validation records, is archived at Zenodo (https://doi.org/10.5281/zenodo.24073031). Background inventory data are from the IDEA v3.4 database, which is available under licence and is not redistributed; the derived pathway coefficients are provided in Supplementary Data 2. Source data are provided with this paper.

Code availability

The scenario model and the analysis and plotting scripts used in this study are archived at Zenodo (https://doi.org/10.5281/zenodo.24073031).

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Author contributions

Z.H.: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Funding acquisition, Writing – original draft. H.Y.T.: Conceptualization, Methodology, Supervision, Writing – review & editing. Y. Kanematsu: Supervision, Writing – review & editing. Y. Kikuchi: Supervision, Project administration, Funding acquisition, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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