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Market Creation Without Market Authority: Ex-Ante Evidence from European Emissions Trading

Market Creation without Market Authority: Ex-Ante Evidence from European Emissions Trading

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By extending carbon pricing to buildings and road transport through ETS2, the European Union is undertaking a major policy experiment in market creation. ETS2 overlaps national emissions budgets and technology requirements, raising a general question: when does a legal market govern allocation? We distinguish three functions of market effectiveness: scarcity, exchange, and allocation authority. Completing exchange and allocation authority lowers present-value EU policy costs over 2028–2048 by 25.5%, or EUR 1.33 trillion relative to legal market creation only. Allocation authority accounts for 76% of savings; 88% of member states benefit. Compensating remaining losses requires EUR 6 billion, only 0.2% of ETS2 revenues. Restoring allocation authority raises the allowance price but lowers policy cost, implying that the endogenous carbon price in an ETS is not a sufficient statistic for welfare across institutional designs.

Keywords: Carbon pricing, Emissions trading, Market design, EU ETS2, Effort Sharing Regulation, Equilibrium modelling
JEL: H23, Q54, Q58, C68

The economic promise of market-based regulation is to delegate adjustment to a price. In a tradable-permit system, the regulator defines rights over a scarce object and allows heterogeneous agents to exchange them until marginal compliance costs are equalized. This decentralized allocation, rather than the legal existence of the allowance, is the source of cost-effectiveness (Coase, 1960; Dales, 1968; Montgomery, 1972; Weitzman, 1974). Yet policy-created markets are rarely introduced into an institutional vacuum. They coexist with jurisdictional budgets, technology mandates, performance standards, and fiscal arrangements that may continue to determine where and how compliance occurs. An allowance may trade even though its price governs only the adjustment left by these institutions.

This paper distinguishes legal market creation from market effectiveness. Legal market creation establishes an allowance, a cap, and a trading mechanism in law. Market effectiveness requires that the market govern the marginal allocation of emissions and abatement. We distinguish three allocative functions. Scarcity determines whether an

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allowance represents a claim on an effective constraint. Exchange determines whether scarcity can be reallocated among agents with heterogeneous marginal costs. Allocation authority determines whether the common price governs the relevant technology, fuel, and demand margins. Revenue and transfer rules constitute a separate system of distributional governance. Market creation is incomplete when one or more allocative functions remain with other institutions.

This distinction connects the theory of tradable permits to market design and second-best policy analysis. Market-design research emphasizes that workable markets depend on the rules and institutions through which exchange occurs (Roth, 2002). Second-best and environmental policy-mix theory show how the effects of one instrument depend on the constraints that remain in place (Lipsey and Lancaster, 1956; Bennear and Stavins, 2007; Goulder and Parry, 2008). Research on overlapping and fragmented climate regulation likewise establishes that market segmentation and interacting instruments can be costly (Böhringer, Koschel and Moslener, 2008; Eichner and Pethig, 2019; Perino, Ritz and van Benthem, 2025). Existing analyses generally evaluate policy instruments or policy regimes as institutional bundles, treating the assignment of market functions as a feature of the regime rather than as an object of analysis. We instead ask how this assignment determines whether a legally created market governs allocation. When market functions are divided across institutions, what is the relative value of enabling exchange and allowing the common price to govern marginal adjustment?

We study this question through a new emissions market established by the European Union (EU): the Emissions Trading System (ETS) for buildings, road transport, and additional small industrial sources, known as ETS2. The existing EU ETS—now also referred to as ETS1 to distinguish it from ETS2—has become a central example of market-based climate regulation (Ellerman, Marcantonini and Zaklan, 2016); ETS2 extends this architecture to emissions closely tied to household transport and energy use. Its introduction is therefore a major policy experiment in market creation. It establishes a common allowance market, but the same emissions remain within national budgets under the Effort Sharing Regulation (ESR). Trading in the associated national emission allocations is legally possible but institutionally thin, while national technology and performance policies extensively regulate the same adjustment margins. ETS2 thus creates an EU-wide asset inside an architecture in which scarcity, adjustment authority, and distributional claims remain partly located elsewhere.

Our analysis combines institutional evidence, a stylized framework, and a dynamic general equilibrium model. We first document how the ETS2 architecture assigns the three allocative functions across ETS2, the ESR, intergovernmental trading, and national policies. The conceptual framework then establishes the consequences of this assignment. If ETS2 is fully nested in national ESR budgets and cross-country exchange remains inactive, its legal introduction can leave equilibrium quantities unchanged. Only the combined ESR and ETS2 marginal incentive is identified, and a slack national budget can force the common ETS2 price to zero. Operational exchange creates gains by reallocating emissions and abatement across countries. Allocation authority creates a different gain by allowing the common price to govern technology, fuel, and service-demand choices. When national technology-mix requirements bind, their shadow values govern part of this adjustment and can lower the observed allowance price while raising the welfare cost of achieving a given emissions path.

We develop and apply a calibrated dynamic, multi-country model of the European economy, to evaluate alternative institutional designs ex ante. ETS2 has not yet generated outcomes that permit quasi-experimental evaluation. We thus use the observed institutional architecture to define counterfactual experiments of market rights and constraints and quantify their welfare and country-level distributional effects under explicit assumptions about substitution, technology, trade, and carbon-revenue recycling.

The model links the EU's layered climate architecture to the adjustment margins central to ETS2: where abatement occurs across member states and how technology, fuel, and demand choices adjust in mobility and heating. ETS1 and ETS2 are represented as EU-wide caps, the ESR as national emissions budgets, and national heating and mobility requirements as minimum clean-technology shares. Starting from legal market creation only, the counterfactuals separately activate exchange and allocation authority and add a single EU-wide ETS as a full-integration benchmark. Emissions targets and revenue rules remain fixed, so the comparisons measure cost-effectiveness and country incidence at a common level of climate ambition.

Completing exchange and allocation authority reduces the aggregate EU welfare cost of meeting the fixed emissions path over 2028–2048 by EUR 1.33 trillion in present value, or 25.5% relative to legal market creation only. A symmetric decomposition attributes 76% of this gain to allocation authority and 24% to exchange. Exchange has the larger annual effect in 2028, but allocation authority dominates as targets tighten because binding national technology-mix requirements increasingly limit what exchange alone can achieve. Importantly, the dominant margin is institutionally decentralized: whereas activating exchange requires a coordinated change in ESR compliance, each member state can expand the scope for ETS2 price steering by redesigning the binding elements of its national technology-policy package. Once ETS2 is effective within its own sectors, merging ETS1 and ETS2 lowers aggregate present-value policy costs by only a further 2.2%. Thus, most of the efficiency gains from a fully integrated EU carbon market would already be reaped by creating an effective ETS2 market.

The quantity and price results explain this ranking. Exchange primarily changes where ETS2 emissions and abatement occur across countries. Allocation authority instead changes how abatement is delivered, relaxing prescribed technology switching in household mobility and heating and shifting adjustment toward less costly margins elsewhere in the economy. Along the reform path from exchange only to an effective ETS2, restoring allocation authority raises the common ETS2 allowance price by 40.0% in 2048 even as it lowers aggregate EU present-value policy costs over 2028–2048 by 21.1%. A low allowance price can hence indicate that binding national technology-mix requirements have suppressed residual allowance demand, rather than that the emissions target is inexpensive to achieve. The allowance price is not a sufficient statistic for welfare across institutional architectures. The allocation-authority counterfactual concerns requirements that prescribe the technology mix within ETS2-covered services. We call their effect price-displacing when a requirement binds, so that its shadow value, rather than the allowance price alone, governs the technology margin.[1]

Allocative market completion also broadens country participation under the maintained carbon revenue rules. Over 2028–2048, an effective ETS2 produces positive present-value welfare effects for 88% of represented member states, which account for 99% of aggregate baseline income. The share with positive annual welfare effects reaches 83% in 2048. Country incidence from exchange is systematically related to changes in real abatement burdens, while incidence from allocation authority is closely associated with the value of the technology-mix constraints it relaxes. Changes in net carbon rents alter the composition of the winning coalition and modestly reduce its breadth; broad participation is already present in the welfare component net of those rents. The remaining cumulative country losses—the compensation gap—total EUR 6 billion, equivalent to 0.2% of aggregate present-value ETS2 revenues over the same horizon. Allocative market completion and broad country participation therefore largely point in the same direction; the remaining losses can be addressed through distributional governance rather than by weakening market authority.

The paper makes three contributions. First, it contributes to the economics of environmental markets and market design. Research on implemented permit systems shows how transaction costs, banking, monitoring, enforcement, and other design choices shape trading and welfare (Stavins, 1995; Schmalensee and Stavins, 2017; Toyama, 2024; Greenstone et al., 2025). We study a distinct institutional margin: whether a legally created market governs the decisions that determine compliance or merely clears the residual allowance demand left by other policies. The framework makes this margin measurable by separating scarcity, exchange, and allocation authority within a common policy environment.

Second, the paper contributes to research on policy mixes and overlapping climate regulation. This literature asks when additional instruments correct distinct market failures and when they instead introduce second-best distortions (Bennear and Stavins, 2007; Fischer and Newell, 2008; Goulder and Parry, 2008; Holland, 2012). Work on European carbon regulation has quantified the costs of segmented carbon markets, technology-specific support, and unilateral policies operating within a wider cap-and-trade system (Böhringer, Koschel and Moslener, 2008; Abrell, Rausch and Streitberger, 2019; Perino, Ritz and van Benthem, 2025). We add a decomposition that holds climate ambition fixed and separately values exchange across jurisdictions and allocation authority over real decisions. This decomposition also shows why a lower allowance price need not imply lower welfare costs when other policies determine residual allowance demand.

Third, the paper contributes to the emerging analysis of ETS2 and to the literature on the incidence of European burden sharing. Existing ETS2 studies examine

[1] Our analysis does not represent non-carbon market failures or the benefits that national measures may provide by addressing them. Potential rationales for these measures include credit constraints, information problems, infrastructure externalities, agency frictions, innovation spillovers, and distributional objectives. The counterfactual therefore identifies the cost-effectiveness loss from the modeled technology constraint at a fixed emissions path, not the net welfare effect of reforming any specific policy.

allowance-price formation under accompanying policies and the effects of carbon pricing on consumer prices and household welfare (Günther et al., 2026; Markaki et al., 2026); related work evaluates flexibility and burden sharing under national EU emissions budgets (Babonneau, Haurie and Vielle, 2018; Vielle, 2020). We instead ask how completing the allocative functions of ETS2 redistributes welfare across member states under the enacted revenue architecture. The country decomposition separates real abatement reallocation from carbon-rent allocation and measures the compensation gap associated with the remaining country losses. It therefore connects market effectiveness to distributional governance without treating distributional objectives as a reason to weaken marginal price incentives.

The remainder of the paper is organized as follows. Section I documents the institutional setting of the EU carbon budget and carbon market (pricing) architecture. Section II develops the conceptual framework and derives qualitative results. Section III describes the quantitative model. Sections IV and V present the aggregate and country-level quantitative results. Section VI concludes. The appendices provide supplementary institutional evidence, proofs, model and calibration details, and formal derivations for the quantitative measures.

I. Context

The EU is extending carbon pricing through ETS2 without dismantling the national budgets and policy systems that already govern the same emissions. This section documents how the resulting architecture assigns scarcity, exchange, and allocation authority across institutions, and how separate revenue rules govern country incidence.

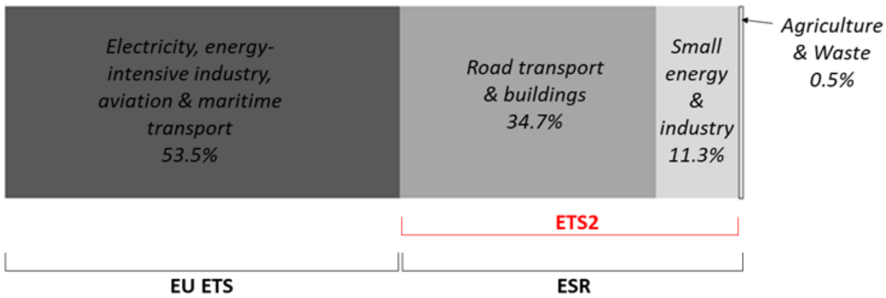
A. The EU carbon-budget architecture

The EU has adopted a binding net-zero target for mid-century, a 2030 target of at least 55% lower greenhouse-gas emissions relative to 1990, and a 2040 target of 90% lower net greenhouse-gas emissions (European Commission, 2021a, 2023a; European Parliament and Council of the European Union, 2026). These targets establish aggregate emissions constraints. Their implementation is divided across the EU ETS, the ESR, and ETS2 rather than assigned to a single market.

ETS1 is a mature EU-wide cap-and-trade system for electricity, energy-intensive industry, and aviation. The ESR assigns binding national emissions budgets to member states for sectors outside ETS1, including road transport, buildings, agriculture, waste, and small industry. ETS2 adds an EU-wide cap-and-trade system for fuel combustion in buildings, road transport, and additional small industrial sources. The resulting architecture separates the tradable allowance from other components of market allocation. ETS2 creates a new EU-wide asset, but its covered emissions remain largely inside national ESR compliance obligations, and the decisions that determine abatement costs remain partly governed by national policies. Figure 1 summarizes this architecture and shows the key institutional fact: ETS2 emissions are almost fully nested in the ESR.

ETS1.—ETS1, launched in 2005, covers electricity and heat generation, industrial

Figure 1. **EU carbon-pricing architecture and ETS2–ESR overlap**



Notes: The figure shows the percentage shares of CO_2 emissions by sector covered by ETS1, the Effort Sharing Regulation (ESR), and ETS2. Emissions data and sector definitions are based on the European Environment Agency (2023, 2025a) and on European Commission (2023b, 2021b), and refer to 2022 values. The key institutional fact is that ETS2-covered emissions are a near-strict subset of ESR emissions. ETS2 therefore creates a tradable allowance for emissions that remain subject to national ESR compliance authority. For the small energy and industry component, we adjust coverage for fuels excluded from ETS2 (European Commission, 2024b); these excluded fuels account for less than 3% of emissions in that component based on International Energy Agency (2021), implying that ETS2 emissions account for about 98.9% of ESR emissions.

manufacturing, and aviation, together accounting for roughly 40% of EU greenhouse-gas emissions.[2] Firms surrender EU Allowances (EUAs), which are auctioned or freely allocated and can be traded. Within its sectoral scope, ETS1 bundles scarcity, exchange, and price-based allocation more tightly than the rest of EU climate policy (European Commission, 2020a; Ellerman, Marcantonini and Zaklan, 2016). Its cap requires emissions in covered sectors to be at least 62% below 2005 levels by 2030.

ESR.—The ESR assigns national emissions budgets to member states for sectors outside ETS1 (European Commission, 2018). By 2030, ESR emissions must be at least 40% below 2005 levels. Annual Emission Allocations (AEAs) decline over time and differ across member states, with 2030 targets ranging from 10% to 50% below 2005 levels (Table D.3). Member states may bank, borrow within limits, and transfer AEAs. But the compliance obligation is national, and private firms and households do not trade AEAs. Economically, the ESR keeps part of allocation authority at the member-state level: it can generate country-specific shadow prices for non-ETS1 emissions even when those prices are not observed as market prices.

ETS2.—ETS2 will become fully operational in 2028 as a separate cap-and-trade system for CO_2 emissions from fuels used in road transport, buildings, and additional small industrial sources (European Commission, 2023b; European Parliament and Council of the European Union, 2026). Regulation is upstream: fuel suppliers, rather than households or drivers, surrender allowances. There is no free allocation; allowances are auctioned, with revenues directed to member states and the Social Climate Fund. The ETS2 cap requires covered emissions to fall by 42% by 2030 relative to 2005 levels. ETS2 therefore creates a scarce EU-wide allowance and a legal exchange mechanism. It does not, by itself, create a unified compliance system, a

[2]ETS1 operates in all EU countries plus Iceland, Liechtenstein, and Norway, and has been linked to the Swiss ETS since 2020. It covers CO_2 and selected non-CO_2 greenhouse gases.

Table 1. **Market functions and distributional governance in ETS2**

Institutional margin	*Effective-market requirement*	*ETS2 institutional design*	*Observable evidence*
Scarcity	Allowance is backed by an effective, nonredundant emissions constraint	ETS2 cap overlaps national ESR budgets; ETS1 remains separately capped	ETS2 emissions remain under ESR budgets; ETS1 and ETS2 have separate caps
Exchange	Rights move across agents with heterogeneous marginal costs	ETS2 allowances trade; AEA transfers are legal but intergovernmental	Limited AEA transfer history; no private AEA market; no continuous AEA price
Allocation authority	Common price governs marginal technology, fuel, and demand choices	National requirements can prescribe mobility and building heat choices	Reported policy packages include technology and performance requirements on ETS2-covered margins
Distributional governance	Transfers address incidence without changing marginal incentives	ETS2 auction revenues and the Social Climate Fund allocate resources by fiscal rules	Legislated ETS2 auction shares and Social Climate Fund allocation rules

private market for AEA flexibility, or authority over all real adjustment margins in buildings and transport.

B. *Institutional assignment of market functions*

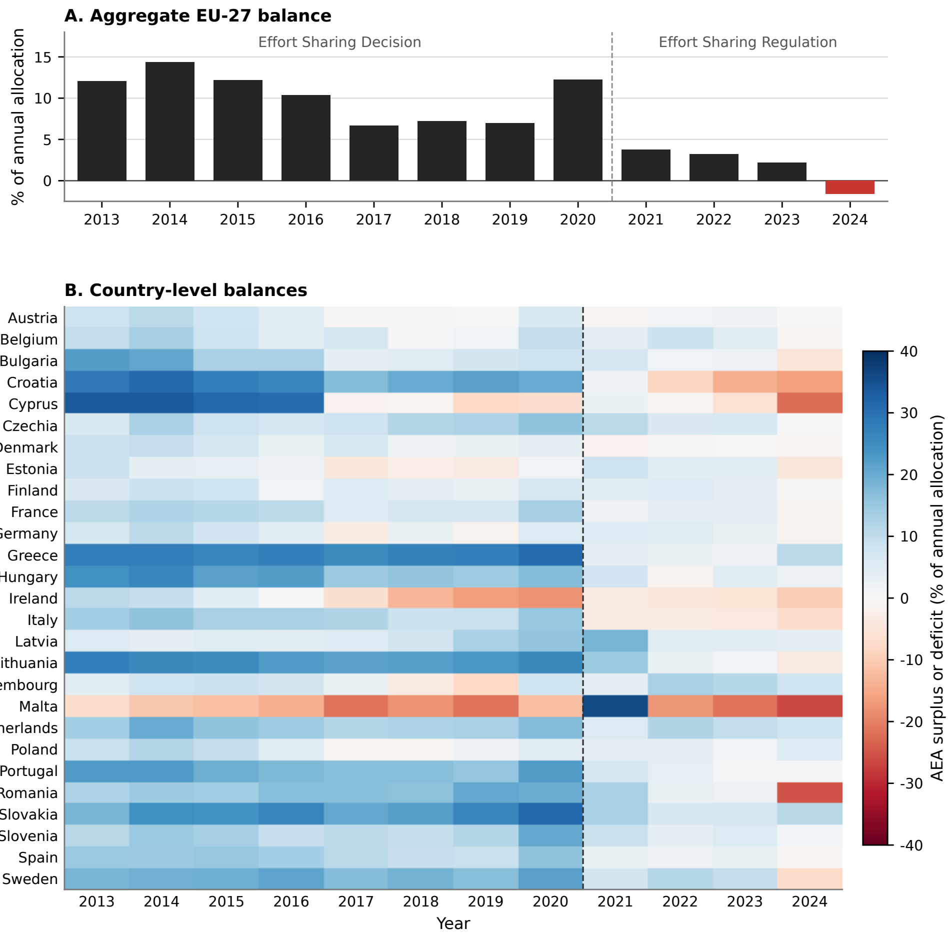
ETS2 establishes an allowance, a cap, and a trading mechanism in law. Whether it governs marginal allocation depends on how scarcity, exchange, and allocation authority are assigned across the surrounding institutions. Table 1 summarizes this assignment and the separate distributional governance problem created by revenue and transfer rules.

SCARCITY RIGHTS.—ETS2 creates an EU-wide cap for covered emissions, but those emissions remain almost entirely within national ESR budgets. The central scarcity issue is therefore the overlap between an EU-wide ETS2 constraint and national ESR constraints on the same emissions. If both bind, an ETS2 allowance is one component of the marginal compliance incentive rather than the only scarcity claim governing these emissions. If a national ESR budget is slack, by contrast, it does not add marginal scarcity.

ETS1 and ETS2 also remain legally separate, and limited flexibility between ETS1 and the ESR does not create an integrated carbon market. This separation does not prevent ETS2 from becoming effective within its own scope; it limits reallocation across scopes. Existing legislation requires the Commission to assess the feasibility of integrating ETS2 sectors into the EU ETS by 2031 (European Commission, 2023b). The single EU-wide ETS in the quantitative analysis is therefore a full-integration benchmark, not the definition of an effective ETS2.

EXCHANGE RIGHTS.—The ESR contains legal flexibility, but it is not organized as a liquid market for where-flexibility. AEAs are compliance units held by governments. Member states can transfer AEAs bilaterally, but private firms and households cannot use AEAs to arbitrage abatement costs across countries, and there is no centralized

Figure 2. **Annual AEA balances under effort sharing**



Notes: Panel A reports the EU-27 annual AEA balance, defined as total annual allocations minus emissions covered by effort sharing, divided by total annual allocations. Panel B reports the same measure by member state and year. Positive values indicate emissions below that year's allocation; negative values indicate emissions above it. These annual balances are flow measures rather than banks: compliance can also draw on banked AEAs and permitted transfers. The dashed line separates the 2013–2020 Effort Sharing Decision period from the 2021–2024 ESR period. Emissions for 2024 are approximated inventory estimates. The United Kingdom is excluded. Sources: own calculations based on European Commission AEA allocations (European Commission, 2013, 2017, 2020b) and European Environment Agency effort-sharing emissions (European Environment Agency, 2025a).

trading platform or continuously observed AEA price. Observed use of this flexibility has been limited. From 2013 to 2023, the European Union Transaction Log (EUTL) extract compiled through EUETS.info (Abrell, 2026) contains 14 country-pair-year transfer records involving only 5 bilateral pairs. Aggregate transfers peaked in 2022 at roughly 0.5% of that year's EU-27 AEA allocation (Table A.1).

Figure 2 places this limited use of exchange against the evolution of AEA scarcity. At the aggregate level, annual AEA allocations exceeded effort-sharing emissions by substantial margins throughout 2013–2020. The surplus narrowed sharply from 2021 onward, and the estimated EU-27 balance turned negative in 2024. Panel B shows that this aggregate path is not sufficient to characterize scarcity: deficits arose in some member states even while the EU-wide balance remained positive, whereas sizeable surpluses persisted elsewhere. Tightening aggregate scarcity therefore coexists with heterogeneous national compliance positions.

These patterns qualify the historical transfer record. Thin AEA trading was observed largely when aggregate annual allocations were ample; it does not establish that exchange will remain unimportant as budgets tighten. Moreover, the ESR gives only governments access to exchange, not the private actors making abatement decisions. If national budgets bind unevenly and transfers remain bilateral, tighter scarcity can produce divergent national shadow values rather than convergence through exchange. This is the institutional basis for the paper's exchange counterfactual: it asks what is gained when legal transfer rights become effective cross-country flexibility.

ALLOCATION AUTHORITY.—ETS2, like ETS1, creates a cap and an allowance price. For market allocation, however, what matters is whether that price governs the choices that determine abatement costs. ETS2 prices upstream fuel combustion, but the relevant choices in buildings and road transport are shaped by national policy systems. Member states report existing and planned policies and measures under the EU governance framework, and the resulting policy packages are central to projected emissions pathways in non-ETS1 sectors (European Parliament and Council of the European Union, 2018; European Environment Agency, 2025b; European Commission, Directorate-General for Climate Action, 2025). These policies are heterogeneous, but they operate through recurring adjustment margins that matter for ETS2: technology choice, fuel choice, energy-service demand, infrastructure availability, and pass-through to households. In road transport, national and EU-level policies influence vehicle technology, fleet turnover, fuel use, and infrastructure. They include vehicle CO_2 standards, zero-emission vehicle targets, purchase subsidies, scrappage or registration rules, charging-infrastructure programs, alternative-fuel infrastructure plans, and fuel-content requirements. In buildings, national policies influence heating technology, energy efficiency, and fuel choice. They include building codes, minimum energy-performance standards, renovation obligations, insulation subsidies, heat-pump support, heating-system standards, and restrictions or phase-outs for fossil heating. Their presence documents an already regulated choice environment, not that every measure displaces price steering.

REVENUE RIGHTS AND DISTRIBUTIONAL GOVERNANCE.—Allowance revenues add a distributional dimension to market design. ETS2 allowances are auctioned, and revenues accrue to member states and the Social Climate Fund rather than to a single EU-wide compensation account. By contrast, ESR compliance creates national shadow values without an equivalent private allowance market or revenue stream. Revenue allocation therefore affects country incidence even when aggregate emissions are fixed. This separation matters because market completion can create aggregate gains while reallocating costs, allowance positions, and revenues across member states. Revenue and transfer rules can support participation in an effective market without altering its allocative functions.

Taken together, these institutional facts place ETS2 in an architecture that assigns scarcity, exchange, and allocation authority across ETS2, the ESR, and national policy packages. The legal market is therefore not sufficient to establish market effectiveness: that depends on which overlapping constraints bind and whether exchange and the common price govern marginal adjustment. Revenue rules separately determine how the resulting costs and rents are distributed across member states.

II. Conceptual Framework

This section develops a stylized static model of nested EU carbon markets that distinguishes legal market creation from market effectiveness. The propositions establish when an overlapping ETS2 cap leaves allocation unchanged, what operational exchange adds, and how binding technology-mix requirements alter adjustment margins and the information contained in allowance prices. Revenue and transfer rules remain a separate system of distributional governance.

A. Setup

COUNTRIES, TECHNOLOGY, AND DEMAND.—Consider a jurisdiction composed of countries $r, s \in \mathcal{R}$ and sectors $i, j \in \mathcal{I}$. Sectoral output is q_{ir} and emissions are e_{ir}. Preferences over output are represented by a quasi-linear utility index $U_{ir}(q_{ir})$, with $U'_{ir} > 0$ and $U''_{ir} < 0$. Production costs are $C_{ir}(q_{ir}, e_{ir})$, continuously differentiable, increasing and convex in output, and decreasing and convex in emissions. Marginal abatement cost is $MAC_{ir}(q,e) := -\frac{\partial C_{ir}(q,e)}{\partial e} > 0$, and marginal production cost is $MC_{ir}(q,e) := \partial C_{ir}(q,e)/\partial q > 0$. For the allocative results in this section, we use a quasi-linear surplus criterion and abstract from household budget constraints and income effects. Aggregate allocative surplus and its regional components are given by:[3]

$$W = \sum_{r \in \mathcal{R}} W_r, \qquad W_r := \sum_{i \in \mathcal{I}} \left[U_{ir}(q_{ir}) - C_{ir}(q_{ir}, e_{ir}) \right] . \tag{1}$$

Carbon payments and scarcity rents are transfers within the jurisdiction and therefore do not enter aggregate surplus. The regional components W_r consequently measure contributions to allocative surplus, not complete country welfare or incidence.

CARBON-MARKET ARCHITECTURE.—The jurisdiction has an emissions budget $\overline{E}$. ETS1 covers sectors $\mathcal{T} \subset \mathcal{I}$ and is represented by an EU-wide cap:

$$\lambda \overline{E} \geq \sum_{r} \sum_{i \in \mathcal{T}} e_{ir} \qquad (\tau^{ETS1}) . \tag{2}$$

The multiplier τ^{ETS1} is the ETS1 allowance price.

Outside ETS1, sectors $\mathcal{N} = \mathcal{I} \setminus \mathcal{T}$ are subject to the ESR. Country r receives a share

[3] As we study the problem of cost-effective implementation of the EU's carbon budget, aggregate emissions are treated as exogenous. We can thus abstract from climate damages and endogenous environmental quality.

ϕ_r of the non-ETS1 budget, where $\sum_r \phi_r = 1$, so the country-level ESR constraint is

$$\phi_r(1-\lambda)\overline{E} \geq \sum_{i\in\mathcal{N}} e_{ir} \ , \forall r \qquad (\tau_r^{ESR}) \,. \tag{3}$$

The shadow value τ_r^{ESR} is country-specific when AEA trading is inactive. With operational AEA trading, the country constraints are pooled into a common EU-wide ESR scarcity value.

ETS2 applies to a subset $\mathcal{B} \subset \mathcal{N}$ of non-ETS1 emissions, with remaining ESR-only sectors denoted by $\mathcal{A} = \mathcal{N} \setminus \mathcal{B}$. It is represented by an EU-wide cap on overlapping emissions:

$$(1-\lambda)\overline{E} \geq \sum_r \sum_{i\in\mathcal{B}} e_{ir} \qquad (\tau^{ETS2}) \,. \tag{4}$$

The scarcity benchmark in Subsection B imposes exact scope overlap, $\mathcal{B} = \mathcal{N}$, and equality between the ETS2 cap in (4) and the aggregate ESR budget implied by (3). Under these two assumptions, the ETS2 constraint duplicates the aggregate ESR constraint. The multiplier τ^{ETS2} is the ETS2 allowance price.

National technology-mix constraints.—We model national technology-mix requirements as non-tradable quota-type restrictions on the permissible mix of "clean" and "dirty" energy inputs used to deliver an energy service (or output) q_{ir} in sector i and country r. This reduced-form representation captures the subset of national regulations and mandates that prescribe the technology or fuel mix in ETS2-covered building and road-transport services.[4] We represent the requirement by an emissions-intensity constraint:

$$\frac{e_{ir}}{q_{ir}} \leq \bar{\gamma}_{ir} \qquad (\mu_{ir}), \qquad i \in \mathcal{B} \tag{5}$$

where $\bar{\gamma}_{ir}$ denotes the policy-imposed emissions-intensity standard (i.e., the maximum admissible emissions per unit of energy service output) and $\mu_{ir} \geq 0$ is the shadow value of the technology-mix constraint.[5]

This representation isolates the specific institutional margin studied here: a requirement that restricts feasible technology and fuel choices and imposes an upper bound on the average emissions intensity of providing energy services. It does not

[4]Examples include binding electrification or zero-emission-vehicle requirements, fuel-share obligations, and performance standards that impose an effective upper bound on emissions intensity. A measure is not included merely because it affects technology adoption; its operative effect must be representable as a restriction on the permissible input or technology mix.

[5]A microfoundation for (5) is a quota on the clean-to-dirty energy mix used to provide the energy service q_{ir}. Let the service be produced with an energy aggregate $z_{ir} = c_{ir} + d_{ir}$ composed of a clean input c_{ir} (zero- or low-emitting) and a dirty input d_{ir} (emitting), with emissions given by $e_{ir} = \theta_i d_{ir}$, where θ_i is the emissions intensity of the dirty input. A clean-share mandate requiring $c_{ir}/z_{ir} \geq \gamma_{ir} \in (0,1)$ implies $d_{ir} \leq (1-\gamma_{ir})z_{ir}$ and thus $e_{ir} \leq \theta_i(1-\gamma_{ir})z_{ir}$. If the marginal energy requirement is approximately constant (or normalized), $z_{ir} = \alpha_{ir}q_{ir}$, this yields $e_{ir}/q_{ir} \leq \alpha_{ir}\theta_i(1-\gamma_{ir}) \equiv \bar{\gamma}_{ir}$. The same mapping applies to other requirements that effectively constrain average emissions intensity, such as performance standards, technology mandates (e.g., electrification requirements), or binding building and vehicle regulations, which can be interpreted as imposing an upper bound on e_{ir}/q_{ir} via restrictions on the feasible set of input mixes and technologies.

classify national climate policies as a whole. Measures that change adjustment costs or expand the feasible set are not represented by this constraint, and any benefits from correcting distinct market failures are outside the model's welfare metric.

FIRM BEHAVIOR AND EFFECTIVE INCENTIVES.—Let P_{ir} denote the marginal carbon-scarcity component applying to sector i in country r. It combines observed allowance prices with, for the ESR, the implicit marginal value of national compliance. A decentralized equilibrium can be represented by a price-taking firm facing P_{ir} and the national constraint (5). The firm chooses (q_{ir}, e_{ir}) to maximize profits, taking the output price p^Y_{ir} as given, yielding

$$(6) \qquad MAC_{ir}(q_{ir}, e_{ir}) = P_{ir} + \mu_{ir}, \qquad p^Y_{ir} = MC_{ir}(q_{ir}, e_{ir}) - \mu_{ir}\bar{\gamma}_{ir}\,.$$

where the carbon-scarcity component depends on the policy environment:

$$(7) \qquad P_{ir} = \begin{cases} \tau^{ETS1}, & i \in \mathcal{T}, \\ \tau^{ESR}_r, & i \in \mathcal{A}, \\ \tau^{ESR}_r + \tau^{ETS2}, & i \in \mathcal{B}. \end{cases}$$

When the technology-mix constraint is slack, $\mu_{ir} = 0$ and it has no allocative effect. When it binds, $\mu_{ir} > 0$ and its shadow value adds an implicit emissions wedge to the carbon-scarcity component. It also creates an implicit per-unit output wedge $\mu_{ir}\bar{\gamma}_{ir}$ because the requirement constrains average emissions intensity rather than charging for marginal emissions from expanding activity. We call this equilibrium effect price-displacing because the allowance price alone no longer governs the technology margin.

COMPETITIVE EQUILIBRIUM.—Given $\overline{E}$, λ, the ESR budget shares $\{\phi_r\}$, and the national technology-mix parameters $\{\bar{\gamma}_{ir}\}$, a competitive equilibrium consists of quantities, output prices, carbon prices, and constraint shadow values such that output demand satisfies $p^Y_{ir} = U'_{ir}(q_{ir})$, firms satisfy (6), and the technology-mix and carbon-market constraints (2)–(5) hold with market clearing and complementary slackness. Equivalently, the equilibrium allocation maximizes allocative surplus W in (1) subject to these constraints; τ^{ETS1}, τ^{ESR}_r, τ^{ETS2}, and μ_{ir} are the associated multipliers.

LEGAL MARKET CREATION AND MARKET EFFECTIVENESS.—We define legal market creation as adding the ETS2 constraint (4) and a common multiplier $\tau^{ETS2} \geq 0$, satisfying market clearing and complementary slackness, to the pre-existing ETS1–ESR equilibrium. This definition does not require the ETS2 constraint to bind, to be independent of the ESR constraints, or to change the equilibrium allocation. Legal creation is therefore a property of the policy architecture; market effectiveness concerns whether that architecture gives the allowance market allocative content. Effectiveness depends on three allocative market functions: scarcity, which determines whether ETS2 adds an independent constraint; exchange, which determines whether non-ETS1 scarcity is pooled across countries; and allocation authority, which determines whether the common carbon price governs marginal adjustment rather than clearing only the demand left by technology-constraint wedges. Revenue and transfer rules remain separate because they affect country income and incidence without changing these marginal conditions. These three market functions and distributional governance organize the analysis that follows.

B. Scarcity: when a new cap does not change allocation

The first function of market creation is scarcity. A permit has allocative content only if it represents a claim on a constraint that is not already imposed by another institution. ETS2 is distinctive because its covered emissions remain inside the ESR. If the ETS2 cap is fully nested in national ESR budgets and AEA trading remains inactive, non-ETS1 scarcity is still allocated through country-level ESR constraints. The ETS2 allowance exists legally, but it need not change the feasible set faced by firms and households.

PROPOSITION 1: *Suppose ETS2 fully overlaps the ESR scope, $\mathcal{B} = \mathcal{N}$, its cap equals the aggregate ESR budget, and cross-country AEA trading is inactive. Introducing ETS2 leaves the set of equilibrium allocations unchanged. The post-ETS2 multipliers satisfy*

$$\tau_r^{ESR} + \tau^{ETS2} = \tau_r^{ESR,0} \quad \textit{and} \quad 0 \leq \tau^{ETS2} \leq \min_r \tau_r^{ESR,0}.$$

If every national ESR budget binds, only the sums $\tau_r^{ESR} + \tau^{ETS2}$ are pinned down and the decomposition between the national and common components is non-unique.

Proof: See Appendix B.1.

Proposition 1 establishes an invariance result. Because the ETS2 cap duplicates the aggregate restriction already implied by the national budgets, legal market creation adds no new feasible adjustment margin. When all national budgets bind, a common ETS2 component can relabel part of the scarcity previously represented by national ESR shadow values: national components fall correspondingly, leaving total marginal incentives and their cross-country dispersion unchanged. The lowest pre-ETS2 ESR shadow value limits how much scarcity can be assigned to the common component. Thus, even a positive ETS2 price need not imply that the new market has changed allocation or integrated national scarcity.

COROLLARY 1: *The ETS2 price is zero if at least one country-level ESR budget is non-binding in the pre-ETS2 benchmark.*

Proof: See Appendix B.2.

Corollary 1 exposes a minimum-shadow-value property of the fragmented carbon market architecture. If one national ESR budget is slack, aggregate emissions lie strictly below the sum of national budgets, so the duplicate ETS2 constraint is also slack and complementary slackness sets its price to zero. This can occur even when other countries face binding budgets and high ESR shadow values. A zero ETS2 price can thus coexist with substantial but fragmented scarcity. Pooling national budgets through exchange removes this dependence on the least-constrained country, motivating the second market function.

C. Exchange: when legal flexibility becomes reallocation

The second function is exchange. If country-level ESR constraints remain binding and AEA trade is inactive or thin, marginal abatement costs can differ across member states. Operational exchange pools scarcity across heterogeneous costs. In the ETS2 context, this can occur through active AEA trading, an ETS2/AEA architecture that effectively reallocates compliance across countries, or a stronger institutional decoupling of ETS2 emissions from national ESR anchors.

PROPOSITION 2: *Holding the ETS1 and ETS2 caps and national technology-mix constraints fixed, replacing country-level ESR constraints with an operational EU-wide ESR market through AEA trading weakly increases cost-effectiveness relative to the no-trading regime. The welfare gains come from pooling ESR scarcity across countries, not from the legal introduction of ETS2 itself.*

Proof: See Appendix B.3.

Proposition 2 identifies exchange as an expansion of the feasible set, not as a new source of scarcity. Pooling national budgets preserves aggregate emissions but allows their allocation across countries to change. Gains are strict when national scarcity values differ and sufficient adjustment margins remain for emissions to move toward lower-cost locations. Exchange can therefore complete the geographic allocation of abatement while leaving technology, fuel, and demand choices constrained by national technology-mix requirements. This distinction between where abatement occurs and how it is achieved motivates the third market function: allocation authority.

D. Allocation authority and price steering

The third function is allocation authority. Even with an active EU-wide allowance price, the market may clear only a residual emissions demand if other institutions determine technology, fuel, or energy-service choices. The welfare question is therefore not whether national technology-mix requirements increase or reduce emissions in isolation. Holding the emissions path fixed, the question is whether they restrict the set of cost-minimizing responses available to the carbon price.

PROPOSITION 3: *Consider any fixed carbon-budget architecture built from the ETS1, ESR, and ETS2 constraints. Let $W(\bar{\gamma})$ denote maximal allocative surplus subject to that architecture and to the national technology-mix constraints $e_{ir}/q_{ir} \leq \bar{\gamma}_{ir}$. If the constraints are relaxed, $\bar{\gamma}'_{ir} \geq \bar{\gamma}_{ir}$ for all (i, r), then*

$$W(\bar{\gamma}') \geq W(\bar{\gamma}),$$

with strict inequality whenever at least one strictly relaxed constraint binds with a positive shadow value on an active margin at the optimum.

Proof: See Appendix B.4.

Proposition 3 identifies allocation authority with the set of real choices governed by the carbon price. It provides a cost-effectiveness benchmark: holding the carbon budget fixed, its allocative-surplus ranking follows from feasible-set expansion. The quantitative analysis therefore asks how large the gain is, how it evolves as climate policy tightens, how it compares with exchange, and how it is distributed across countries. When the intensity constraint binds, its shadow value raises the incentive to reduce emissions conditional on output but, through $\mu_{ir}\bar{\gamma}_{ir}$, implicitly subsidizes output. The requirement therefore tilts adjustment toward technology and fuel switching and away from reductions in energy-service demand. Relaxing the constraint leaves the carbon budget unchanged; it allows the carbon price to select the least-cost combination of intensity and scale responses. An active allowance market can thus allocate scarcity across countries yet fail to govern how abatement is achieved.[6]

COROLLARY 2: *Across architectures that differ in their binding national technology-mix constraints, the ETS2 allowance price is not a sufficient statistic for welfare. It identifies neither the total marginal emissions incentive nor the output wedge and therefore cannot rank welfare across architectures.*

Proof: See Appendix B.5.

Corollary 2 distinguishes the allowance price from the welfare cost of the climate policy architecture. The ETS2 price clears the allowance demand left after national technology-mix constraints have restricted technology, fuel, and demand choices. When those constraints bind, their shadow values carry part of the marginal emissions incentive, while their output wedges distort the composition of adjustment. A binding requirement can therefore suppress residual allowance demand, but the corollary does not by itself sign the resulting change in the ETS2 price. That sign is an equilibrium outcome determined in the quantitative analysis. A higher ETS2 price after the constraints are relaxed can accordingly coexist with improved welfare. The allowance price is informative within a given institutional architecture, but price comparisons across architectures need not preserve their welfare ranking.

Propositions 1–3 define the allocative margins embedded in the quantitative model. Section III represents these margins in a dynamic general equilibrium setting. For the quantitative analysis, it replaces the surplus criterion in (1) with household equivalent variation, which incorporates equilibrium goods and factor prices, household income, country entitlements to carbon rents, and other general-equilibrium effects. In the quasi-linear benchmark, revenue and transfer rules do not alter the marginal conditions when implemented through nondistortionary transfers, but they determine how the resulting gains are distributed across countries; Section V examines this incidence.

III. Quantitative Model

To quantify the welfare and distributional effects of the three allocative market functions—scarcity, exchange, and allocation authority—and of distributional governance, we embed the institutional carbon market framework of Section II in a general

[6]The comparison is conditional on the conceptual model's allocative-surplus criterion, which assigns the constraint no separate benefit beyond changing the covered technology mix. It does not evaluate measures that address other market failures or expand price-responsive adjustment. Relaxing $\bar{\gamma}_{ir}$ therefore represents restructuring the modeled technology requirement, not withdrawing national climate policy.

equilibrium setting. We develop WEDGE (Welfare, Energy and Decarbonization in General Equilibrium), a dynamic multi-country, multi-sector general equilibrium model of the EU economy. The model makes explicit the adjustment margins left implicit in the conceptual analysis: firms and households respond to changes in market architecture through fuel use, technology choice, production, consumption, and trade, while carbon rents are distributed across countries according to the prevailing governance rules. We take the model to the data and discipline it with institutional detail—including the EU carbon-market architecture, national transport and heating policies, and the EU's carbon budget trajectory—to evaluate incomplete carbon market creation in its real-world policy setting.

Subsection III.A provides an overview of the model. Subsection III.B shows how explicit carbon prices and implicit policy wedges determine firms' and households' emissions choices and allowance demand, and how the associated scarcity rents and revenues accrue across countries and enter welfare. Subsection III.C describes the model's sectoral and regional resolution, data, and calibration. Appendix C provides the full algebra and equilibrium conditions.

A. Overview

The model represents EU member states individually and links them to the rest of Europe and the rest of the world through bilateral trade. Competitive firms produce primary and secondary energy, electricity from multiple technologies, energy-intensive manufactures, transport, building services, and other goods. A representative household in each country supplies labor, owns capital, consumes goods and leisure, and chooses mobility and heating services. Household mobility distinguishes electric from internal-combustion vehicles; heating distinguishes electric heat pumps from fossil-based systems. These technology pairs make the clean–dirty choice explicit, while nested constant-elasticity-of-substitution technologies determine fuel switching, energy-service demand, production, and trade. The economy evolves recursively. In each period, firms and households choose production, consumption, inputs, technologies, and energy services given the inherited stocks of physical and energy-service knowledge capital. Saving and investment update physical capital, while research directed toward mobility and heating technologies updates knowledge capital. Population and labor productivity evolve exogenously. Market architecture therefore affects current abatement and, through investment and innovation, the future cost and composition of adjustment. Holding the emissions-target path fixed, alternative market architectures vary the exchange of emissions rights, available adjustment margins, and distribution of scarcity rents and revenues, generating changes in equilibrium prices, income, welfare, and cross-country incidence.

B. Mapping carbon markets, emissions, and welfare

EMISSIONS AND ALLOWANCE DEMAND.—We derive emission choices e_{ir} for sector i in country r from profit- and utility-maximizing behavior of firms and households, which we characterize by zero-profit conditions for output (utility) and the conditional fossil-fuel demand functions. Emission choices e_{ir} enter the carbon market equilibrium conditions (2)–(4), which equate total emissions demand in a given market with the policy-determined allowance supplies.

CO_2 emissions arise from coal, natural gas, and refined oil used to produce goods and energy services such as heating and mobility. Let $\boldsymbol{m}$ denote the institutional carbon-market architecture: it specifies which carbon constraints are operative, whether emissions rights can be exchanged across countries, whether national technology-mix requirements restrict firms' and households' adjustment margins, and how carbon rents are distributed across countries. Firms and households choose output and inputs to maximize profits and utility, respectively, taking carbon-market architecture $\boldsymbol{m}$, technologies and preferences $\boldsymbol{\Sigma}$, and equilibrium output and input prices $\boldsymbol{p}(\boldsymbol{m})$ as given.[7] Let

$$\boldsymbol{\tau}(\boldsymbol{m}) = \left(\tau^{ETS1}(\boldsymbol{m}), \{\tau_r^{ESR}(\boldsymbol{m})\}_{r\in\mathcal{R}}, \tau^{ETS2}(\boldsymbol{m})\right)$$

collect the equilibrium explicit carbon prices under architecture $\boldsymbol{m}$. The carbon-scarcity component $P_{ir}(\boldsymbol{m})$, defined in (7), selects and, where carbon pricing systems overlap, sums the components of $\boldsymbol{\tau}(\boldsymbol{m})$ that apply to sector output q_{ir}. We keep the shadow value $\mu_{ir}(\boldsymbol{m})$ of binding national technology constraint separate as it affects both emissions and output. Emissions associated with sectoral output q_{ir} are:

$$e_{ir}(\boldsymbol{m}) = \sum_f \underbrace{\beta_f}_{\substack{\text{Carbon}\\ \text{content}}} \underbrace{a^*_{fir}(\boldsymbol{p}(\boldsymbol{m}), P_{ir}(\boldsymbol{m}), \mu_{ir}(\boldsymbol{m}); \boldsymbol{\Sigma})}_{\substack{\text{Fossil-fuel use}\\ \text{per unit of output}}} \underbrace{q_{ir}(\boldsymbol{m})}_{\text{Output level}}, \tag{8}$$

where β_f is the carbon content of fuel f. a^*_{fir} denotes the optimal use of fossil fuel f per unit of output q_{ir}. Equation (8) makes the two policy signals affecting conditional fuel demand explicit: the carbon price $P_{ir}(\boldsymbol{m})$ and the technology-constraint wedge $\mu_{ir}(\boldsymbol{m})$. Policy signals increase the cost of using fossil fuels directly, while architecture $\boldsymbol{m}$ also affects emissions through general-equilibrium changes in the economy-wide price system $\boldsymbol{p}(\boldsymbol{m})$.

To derive a^*_{fir}, let c^q_{ir} denote the the minimum expenditure required to produce one unit of sectoral output q_{ir}, i.e. the unit-cost function for sectoral output. In equilibrium, the unit cost in each sector is greater than or equal to the output price p^q_{ir}. The zero profit condition for q_{ir} is therefore:

$$c^q_{ir}(\underbrace{\boldsymbol{p}(\boldsymbol{m})}_{\substack{\text{Non-}\\ \text{carbon}\\ \text{inputs}}}, \underbrace{P_{ir}(\boldsymbol{m}), \mu_{ir}(\boldsymbol{m})}_{\substack{\text{Cost of}\\ \text{carbon}}}; \underbrace{\boldsymbol{\Sigma}(\boldsymbol{\theta}, \boldsymbol{\sigma})}_{\text{Technology}}) - \underbrace{\mu_{ir}(\boldsymbol{m})\bar{\gamma}_{ir}}_{\substack{\text{Implicit output}\\ \text{subsidy from}\\ \text{technology constraint}}} \geq p^q_{ir}(\boldsymbol{m}) \quad \perp \quad q_{ir}(\boldsymbol{m}) \geq 0\,. \tag{9}$$

Equation (9) separates the determinants of output choice. The unit-cost function depends on non-carbon input prices, the explicit and implicit carbon prices P_{ir}, the shadow value of the emissions intensity constraint μ_{ir}, and technology $\boldsymbol{\Sigma}(\boldsymbol{\theta}, \boldsymbol{\sigma})$, where, adopting CES functional forms, $\boldsymbol{\theta}$ denotes benchmark shares and $\boldsymbol{\sigma}$ substitution elasticities. The multiplier μ_{ir} affects output decisions in two ways: it raises the user

[7]Throughout this section, we omit the time index t for notational simplicity.

price of fossil fuel in (11) and subsidizes output at rate $\mu_{ir}\bar{\gamma}_{ir}$ in (9), reflecting the emissions-pricing and output-subsidy components of the technology-mix constraint.[8] Complementarity implies equality whenever output is positive.

By Shephard's lemma, differentiating the unit-cost function with respect to the user price of fossil fuel f yields the conditional use of that fuel per unit of q_{ir}:

$$a^*_{fir} = \frac{\partial c^q_{ir}(\boldsymbol{p}(\boldsymbol{m}), P_{ir}(\boldsymbol{m}), \mu_{ir}(\boldsymbol{m}); \boldsymbol{\Sigma}(\boldsymbol{\theta}, \boldsymbol{\sigma}))}{\partial \widehat{p}_{fir}}, \tag{10}$$

where the user price of fossil fuel $\widehat{p}_{fir}$ in sector i is related to the producer price of fossil fuel p_{fr} according to:

$$\widehat{p}_{fir}(\boldsymbol{m}) = p_{fr}(\boldsymbol{m}) + \underbrace{\beta_f \left[P_{ir}(\boldsymbol{m}) + \mu_{ir}(\boldsymbol{m})\right]}_{\substack{\text{Climate-policy wedge} \\ \text{for sector i in region r}}}. \tag{11}$$

The sector- and region-specific climate-policy wedge depends on architecture $\boldsymbol{m}$ and it varies across sectors and regions. β_f converts the applicable emissions prices into a charge per unit of fuel. The price $P_{ir}(\boldsymbol{m})$ collects the ETS1, ETS2, and national ESR shadow-price components that apply to sector i in region r, while $\mu_{ir}(\boldsymbol{m})$ is the shadow price of carbon due to the sector-specific national emissions-intensity constraint.

DISTRIBUTION OF CARBON RENTS.—Emission limits generate scarcity rents. ETS1 and ETS2 do so through EU-wide allowance prices, while national ESR budgets do so through country-specific shadow prices. Country r's carbon-rent income is

$$\Psi_r(\boldsymbol{m}) = \underbrace{\overline{E}}_{\substack{\text{EU carbon} \\ \text{budget}}} \Big[\underbrace{\tau^{ETS1}(\boldsymbol{m})\xi_r\lambda}_{\substack{\text{Value share} \\ \text{from ETS1}}} + \underbrace{\tau^{ETS2}(\boldsymbol{m})\pi_r(1-\lambda)}_{\substack{\text{Value share} \\ \text{from ETS2}}} + \underbrace{\tau^{ESR}_r(\boldsymbol{m})\phi_r(1-\lambda)}_{\substack{\text{Value share} \\ \text{from ESR}}}\Big], \tag{12}$$

where ξ_r and π_r denote country r's shares of ETS1 and ETS2 revenues, respectively, where $\sum_r \xi_r = \sum_r \pi_r = 1$. This provides a transparent way of how the scarcity value of the EU carbon budget accrues to countries through the the three regulatory systems. The ETS terms capture country entitlements under EU carbon revenue-allocation rules: ETS rents accrue according to regulatory shares, not according to where covered emissions occur. We assume that carbon revenues are returned lump-sum to households. Under the ESR, by contrast, the national budget determines both the rent base and its recipient: each country is credited with the shadow value of its own emissions-budget endowment.[9]

WELFARE AND MEASUREMENT.—For all quantitative welfare and incidence results,

[8]The constraint is $\bar{\gamma}_{ir}q_{ir} - e_{ir} \geq 0$. Its Lagrangian term is $\mu_{ir}(\bar{\gamma}_{ir}q_{ir} - e_{ir})$: $-\mu_{ir}e_{ir}$ prices emissions, whereas $+\mu_{ir}\bar{\gamma}_{ir}q_{ir}$ rewards output because each additional unit expands permitted emissions by $\bar{\gamma}_{ir}$. Per unit of output, this reward is $\mu_{ir}\bar{\gamma}_{ir}$ and is therefore subtracted from unit cost, i.e. it subsidizes output.

[9]National emissions-intensity constraints indexed by μ_{ir} generate no net rent. When the constraint binds, $e_{ir} = \bar{\gamma}_{ir}q_{ir}$, so the implicit emissions charge $\mu_{ir}e_{ir}$ is exactly offset by the implicit output subsidy $\mu_{ir}\bar{\gamma}_{ir}q_{ir}$; when it is slack, $\mu_{ir} = 0$. The constraint therefore redistributes within the regulated sector without creating income for redistribution.

we replace the allocative-surplus criterion in (1) with household equivalent variation. Each region contains a representative household that supplies labor, owns capital, and receives transfers, including the carbon rents $\Psi_r(\boldsymbol{m})$. A fixed share of income finances investment; let $M_r(\boldsymbol{m})$ denote the remaining income available for consumption and leisure under carbon-market architecture $\boldsymbol{m}$. Let $\boldsymbol{c}_r = (\{c_{ir}\}_i, \ell_r)$ collect household demand for sectoral outputs q_{ir} and leisure ℓ_r. Fossil fuels used to provide household heating and mobility generate direct emissions, while fossil energy used to produce other consumption goods generates emissions upstream. Both enter emissions and allowance demand through (8).

Let $\mathcal{C}_r(\boldsymbol{m}, M_r(\boldsymbol{m}))$ denote the household's budget set. It incorporates equilibrium goods and factor prices $\boldsymbol{p}(\boldsymbol{m})$, the applicable explicit and implicit carbon-policy wedges $P_{ir}(\boldsymbol{m})$ and $\mu_{ir}(\boldsymbol{m})$. The household chooses

$$\boldsymbol{c}_r^*(\boldsymbol{m}) \in \underset{\boldsymbol{c}_r \in \mathcal{C}_r(\boldsymbol{m}, M_r(\boldsymbol{m}))}{\arg\max} U_r(\boldsymbol{c}_r).$$

Prices and carbon policy wedges restrict the budget set. The resulting indirect utility at time t is: $v_{rt}(\boldsymbol{m}) = U_{rt}(\boldsymbol{c}_{rt}^*(\boldsymbol{m}))$. It depends on the carbon-market architecture through equilibrium prices, policy wedges, and household income, including carbon rents.

Let $\boldsymbol{m}^0$ denote the reference architecture without carbon pricing or national technology requirements, and let $e_{rt}(\boldsymbol{p}_t^0, u)$ be the expenditure function evaluated at reference prices. Country equivalent variation is

$$\text{EV}_{rt}(\boldsymbol{m}; \boldsymbol{m}^0) = e_{rt}\Big(\boldsymbol{p}_t^0, v_{rt}(\boldsymbol{m})\Big) - e_{rt}\Big(\boldsymbol{p}_t^0, v_{rt}(\boldsymbol{m}^0)\Big). \tag{13}$$

A negative value is the money-metric welfare cost of architecture $\boldsymbol{m}$ relative to the no-policy reference. We define the aggregate annual policy cost as

$$C_t(\boldsymbol{m}) := -\sum_r \text{EV}_{rt}(\boldsymbol{m}; \boldsymbol{m}^0)$$

and its present value over the evaluation horizon $\mathcal{Y}$ as

$$C^{PV}(\boldsymbol{m}) = \sum_{t \in \mathcal{Y}} (1+d)^{-(t-\underline{t})} C_t(\boldsymbol{m}), \tag{14}$$

where d is the annual discount rate and $\underline{t}$ is the first evaluation year. The percentage policy-cost saving from architecture $\boldsymbol{m}'$ to $\boldsymbol{m}''$ is

$$S(\boldsymbol{m}' \to \boldsymbol{m}'') = 100 \, \frac{C^{PV}(\boldsymbol{m}') - C^{PV}(\boldsymbol{m}'')}{C^{PV}(\boldsymbol{m}')}. \tag{15}$$

Because country EV is measured in a common monetary unit, summing across countries gives an unweighted Kaldor–Hicks efficiency criterion. We examine distribution separately through country incidence, participating, and the compensation gap.

Table 2. **Quantitative model resolution: sectors and goods, regions, and primary factors.**

Sectors ($i \in \mathcal{I}$)	**Countries and regions ($r \in \mathcal{R}$)**
Energy supply sectors ($i \in \mathcal{E}$)	*EU27 countries*[1]
Coal	Austria (AUT), Belgium (BEL),
Crude oil	Bulgaria (BGR), Croatia (HRV),
Natural gas	Czechia (CZE), Denmark (DNK), Estonia (EST),
Refined oil products (ETS1)	Finland (FIN), France (FRA), Germany (DEU),
Electricity, with technologies ($n \in \mathcal{N}$) (ETS1)	Greece (GRC), Hungary (HUN), Ireland (IRL),
fossil-based	Latvia (LVA), Lithuania (LTU), Netherlands (NLD),
hydro	Poland (POL), Portugal (PRT), Slovakia (SVK)
renewables (wind & solar)	Slovenia (SLN), Spain (ESP), Sweden (SWE)
nuclear	*Other regions*
Energy-intensive and/or trade-exposed sectors	Rest of Europe (REU)
Non-metalic minerals (ETS1)	Rest of the World (ROW)
Iron & steel, metals, metal products (ETS1)	
Chemical, rubber, plastic, paper (ETS1)	**Primary production factors**
Light manufacturing (ETS2)	*Capital*
Construction (ETS2)	Physical capital
Transport sectors	Knowledge capital (accumulated through DTC)
Air transport (ETS1)	Energy resource capital ($z \in \mathcal{Z}$)
Water transport (ETS1)	Coal
Road transport (excl. households) (ETS2)	Oil
Other sectors	Natural gas
Agriculture	Renewables (wind & solar)
Services (ETS2)	*Labor*
Food (ETS2)	
Household energy services	
Heating: fossil vs. electric	
Mobility: combustion vs. electric vehicles	
Goods for final demand	**Bilateral intra-EU and international trade**
Private consumption	
Investment	
Government consumption	

Notes: The sectoral and regional classifications are aggregations of the 65 sectors and 141 countries and regions in the GTAP 11 database (Aguiar et al., 2022). The detailed sectoral concordance is available from the author upon request. [1] Owing to their small economic size, Cyprus, Luxembourg, and Malta are included in the rest-of-Europe (REU) aggregate. ETS1 and ETS2 denote coverage of sectoral emissions by the respective trading systems. We assign the services sector to ETS2 because approximately 98% of its emissions arise from fuel use in buildings and heating. In the food, light-manufacturing, and construction sectors, emissions from large installations—and hence potential ETS1 coverage—are negligible in the calibration data. We therefore treat these activities as small installations covered by ETS2 under its "small energy & industry" category. DTC=directed technical change.

C. Data and Calibration

BENCHMARK DATA AND MODEL RESOLUTION.—We calibrate the model to a 2017 benchmark constructed from version 11 of the Global Trade Analysis Project database (GTAP, Aguiar et al., 2022). GTAP provides mutually consistent country accounts for production, intermediate use, consumption, investment, bilateral trade, energy flows, and fossil-fuel CO_2 emissions. We supplement these accounts with country-level electricity generation by technology and technology-specific input structures from Global Change Data Lab (2024) and Abrell, Rausch and Streitberger (2019). Table 2 reports the policy-relevant resolution. It preserves cross-country and sectoral heterogeneity in carbon intensity, adjustment opportunities, and trade while explicitly resolving the heating, mobility, and electricity margins through which ETS2 and national policies operate.

Calibration strategy.—We use the calibrated-share-form approach standard in multi-sector general equilibrium analysis (Rutherford, 1995; Harrison, Rutherford and Tarr, 1997; Böhringer, Carbone and Rutherford, 2016). The constructed 2017 social accounting matrix is treated as an observed equilibrium. Conditional on the model's nesting structure and externally specified substitution elasticities, benchmark value flows and observed fiscal wedges determine the share parameters and normalizations of the production, trade, energy-service, and household-demand systems. The calibrated model therefore reproduces the constructed benchmark exactly: value shares determine the allocation at that point, while the elasticities govern adjustment away from it. We discipline these elasticities with empirical estimates and established quantitative models. Appendix D gives the normalized CES representation, parameter sources, and benchmark-replication checks.

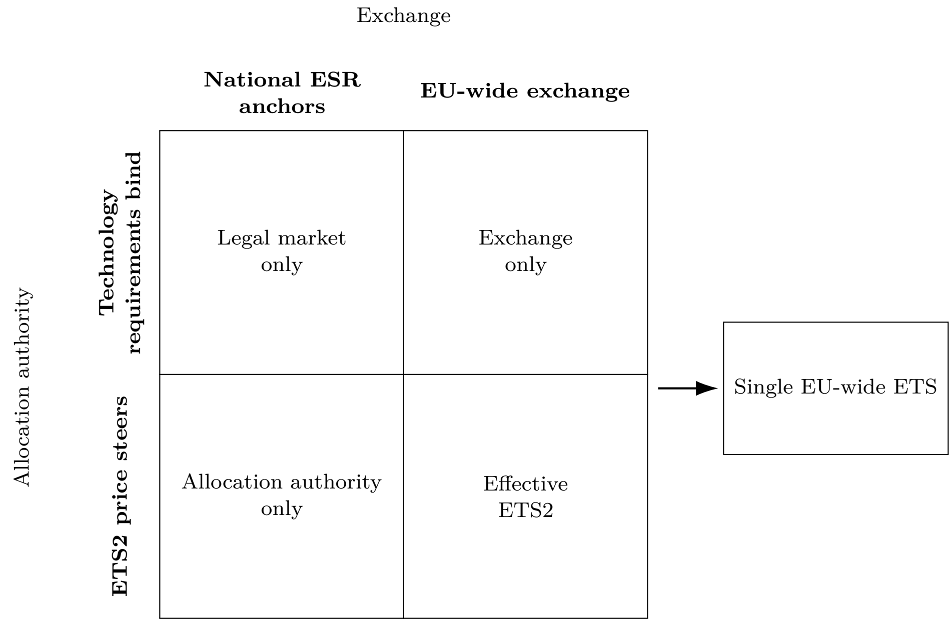
Reference path.—Starting from the replicated 2017 equilibrium, we construct the economic reference path in two stages. We first forward-calibrate each country to 2028 using observed real-GDP growth through 2025 and its 2025 growth rate for 2026–27 (Eurostat, 2026c). Thereafter, the model is solved recursively in five-year steps through 2048. Country population and labor-productivity paths govern effective labor, while endogenous investment and directed research update physical and energy-service knowledge capital. These exogenous demographic and productivity assumptions are common across architectures; investment and directed technical change respond to equilibrium prices and policy wedges.

Climate-policy calibration.—We map the institutional architecture into four sets of inputs: regulatory coverage, emissions budgets, carbon-rent entitlements, and national technology-mix requirements. Appendix Figure D.2 plots historical emissions and the target paths imposed in the quantitative experiments, separately for the ETS1 and ETS2 partitions. Through 2030, the paths are anchored in legally adopted targets and member-state projections under existing and additional measures (European Parliament and Council of the European Union, 2018; European Environment Agency, 2025b; European Commission, Directorate-General for Climate Action, 2025); beyond 2030, they are continued consistently with the EU's trajectory toward climate neutrality and its 2040 intermediate target (European Parliament and Council of the European Union, 2026). We map these targets into the model's domain of positive CO_2 emissions from fossil-fuel combustion.

Appendix Table D.3 reports the emissions targets that determine aggregate scarcity and national ESR budget positions, together with the country shares used to allocate ETS1 and ETS2 revenues. The latter calibrate the rent entitlements in (12). Keeping these objects distinct is central to the counterfactual design: emissions budgets govern the scarcity value created by climate policy, whereas revenue-allocation rules govern where that value accrues.

National transport and heating measures enter as country- and time-specific minimum shares of clean service output. We construct the mobility paths from Eurostat passenger-car-stock data and the heating paths from Eurostat renewable-energy indicators, supplemented by member states' updated National Energy and Climate Plans, the Commission reference-scenario update used in the 2024 planning cycle, and European Heat Pump Association market reports (Eurostat, 2026b,a; European

Figure 3. **Counterfactual design: exchange and allocation authority**



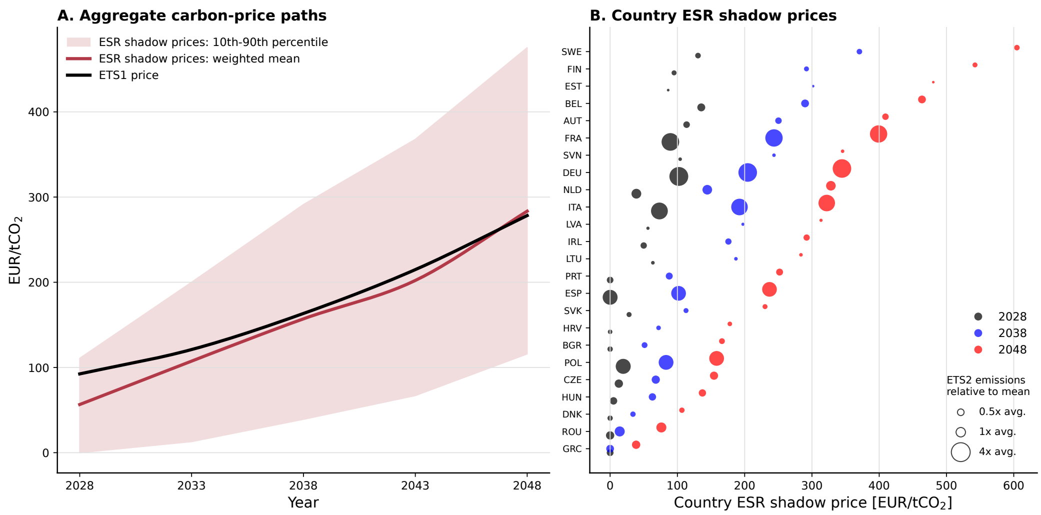
Notes: Moving right activates EU-wide exchange across national ESR anchors. Moving down removes binding national clean-technology requirements so that the ETS2 price governs the covered adjustment margins. The single EU-wide ETS additionally merges the ETS1 and ETS2 scopes. All cases use the same emissions-target trajectories.

Commission, 2024c,a; European Heat Pump Association, 2024). Electric-vehicle stock shares and constructed heat-pump shares of heating services are mapped into minimum clean-output requirements. The resulting constraints restrict the technology margin left to the carbon price and generate the technology-constraint wedge $\mu_{ir}(\boldsymbol{m})$ in Subsection III.B. They summarize the direction and stringency of the modeled technology-mix requirements rather than reproduce individual instruments or value policies that address separate market failures. Appendix D documents the construction and implementation.

IV. The Value Of Market Effectiveness

How much does an effective market reduce the cost of complying with a common statutory emissions-target trajectory, and how much of this gain comes from exchange versus allocation authority over real adjustment decisions? This section first defines counterfactual experiments that vary these two functions, then documents price fragmentation under legal market creation, and finally examines their effects on policy costs, carbon prices, and emissions allocation.

Figure 4. **Carbon-price fragmentation under legal market creation**



Notes: Panel A shows the ETS1 allowance price and the ETS2-emissions-weighted mean of country ESR shadow prices under legal market creation; the shaded area spans the 10th–90th percentiles of country ESR shadow prices. Panel B reports the country shadow values in selected years using ISO alpha-3 country codes. Bubble area is proportional to country ETS2-sector emissions in the same year; the size legend reports emissions relative to the country mean.

A. Counterfactual experiments

Figure 3 varies the two allocative functions that determine whether a common allowance market governs abatement. Columns replace national ESR anchors with EU-wide exchange. Rows remove binding national clean-technology requirements in household heating and mobility, giving the ETS2 price authority over those choices. The four cases impose the same statutory target trajectories. Realized emissions can nevertheless differ because overlapping constraints may induce emissions below the available budgets.

The upper-left cell, legal market creation only, combines ETS1, national ESR caps, and the modeled technology requirements. The simulation omits a redundant common ETS2 constraint and therefore does not compute a separate ETS2 multiplier in this cell. Proposition 1 establishes its allocation equivalence to a nested legal ETS2 that adds no independent scarcity: national ESR shadow values and policy wedges remain the relevant marginal incentives. Moving right replaces the national caps with a common ETS2 cap while retaining the requirements (exchange only). Moving down removes the requirements while retaining national ESR caps (allocation authority only). The lower-right cell combines both functions in an effective ETS2.

Scarcity and distributional governance remain part of the design, but are not additional axes in the matrix. The same EU target trajectory governs all four cells; the exchange margin changes whether that scarcity is allocated through national caps or a common ETS2 cap. ESR cases assign national pollution rights to representative agents, while ETS2 cases allocate auction revenue through the maintained 75% ETS2 and

25% Social Climate Fund shares. Section IV does not vary these distributional rules independently; Section V examines the resulting country incidence. The *Single EU-wide ETS* benchmark separately asks how much further value arises from integrating the ETS1 and ETS2 scopes.

B. *Fragmented carbon prices under legal market creation*

Legal market creation leaves scarcity fragmented when national constraints continue to determine marginal adjustment. Figure 4 reports the explicit ETS1 price and the implicit ESR scarcity values in the allocation-equivalent legal-market benchmark. The emissions-weighted mean of ESR shadow prices rises as targets tighten, but it conceals substantial and increasing dispersion across countries. The legal architecture therefore supplies neither a common price across member states nor a common scarcity value across ETS1 and ETS2-covered emissions.

Panel B makes the fragmentation quantitative. Several national ESR budgets are slack in 2028, so their shadow prices are zero, while binding budgets elsewhere carry positive scarcity values. As national budgets tighten, this dispersion widens rather than disappears. This is the quantitative counterpart of Proposition 1: legal creation of a redundant nested allowance market does not integrate national scarcity or alter the total marginal incentives governing emissions. Figure 4 therefore establishes the failure of a single price to summarize marginal incentives within the legal-market architecture; Subsection IV.D establishes the corresponding welfare-ranking failure across institutional designs.

Panel A adds a distinct scope dimension: ETS1 and ETS2-covered emissions remain governed by separate institutions and generally follow different scarcity-value paths. This margin is not part of the exchange-by-allocation-authority matrix; it is evaluated through the *Single EU-wide ETS* benchmark.

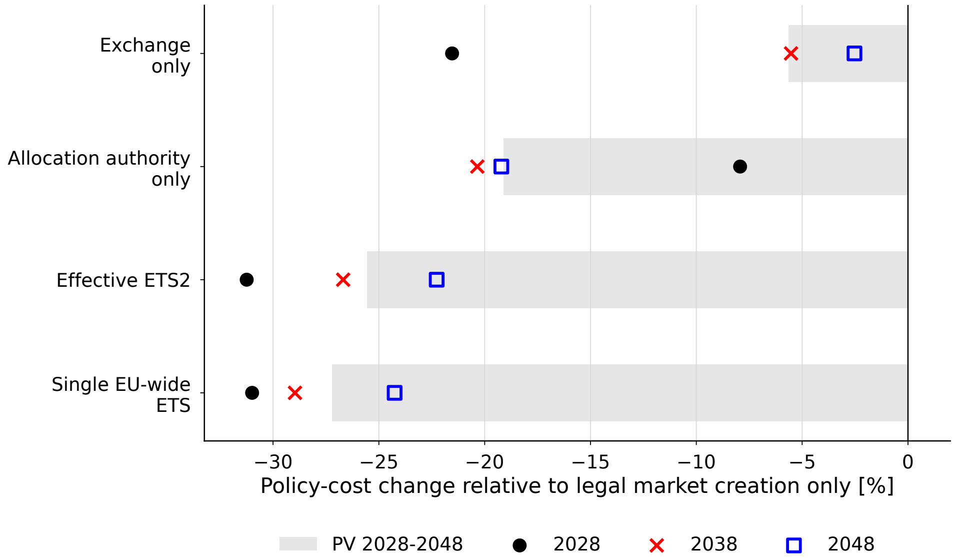
C. *Valuing allocative market functions*

Figure 5 reports Hicksian-equivalent-variation policy costs relative to legal market creation only. The comparisons hold statutory emissions targets fixed and value institutional changes in where and how abatement occurs. The architectures can nevertheless deliver different realized emissions when national fragmentation leaves part of the emissions budget unused in countries with slack constraints while budgets bind elsewhere, or when technology requirements induce abatement beyond that required by the emissions constraints.

Exchange alone lowers present-value policy costs by EUR 293 billion (5.6%); allocation authority alone lowers them by EUR 993 billion (19.1%). Activating both functions reduces costs from EUR 5,199 billion to EUR 3,871 billion, a gain of EUR 1,328 billion (25.5%), including a positive EUR 42 billion interaction. Averaging each function's marginal contribution over the two possible activation orders yields an order-invariant Shapley attribution.[10] Exchange accounts for EUR 314 billion (24% of the total gain) and allocation authority for EUR 1,014 billion (76%). Allocation

[10]A Shapley attribution is a symmetric accounting rule, not an additional counterfactual. It assigns each function the average of its marginal contribution when introduced first and when introduced after the other

Figure 5. **Policy-cost effects of exchange and allocation authority**



Notes: Grey bars report present-value percentage changes in policy costs relative to legal market creation only, using a 1.5% annual discount rate. Markers report annual changes in selected years; negative values denote policy-cost savings. Exchange only replaces national ESR anchors with an EU-wide ETS2 cap while the technology requirements remain. Allocation authority only removes those requirements while national ESR anchors remain. Effective ETS2 activates both functions. The single EU-wide ETS additionally merges the ETS1 and ETS2 scopes. All cases impose the same target trajectories, although realized emissions may fall below the available budgets.

authority is therefore about 3.2 times as valuable as exchange. The two margins also differ in where reform authority resides. Exchange requires an EU-level or intergovernmental compliance arrangement, whereas the country-specific requirements underlying the allocation-authority margin can be restructured through national policy design.

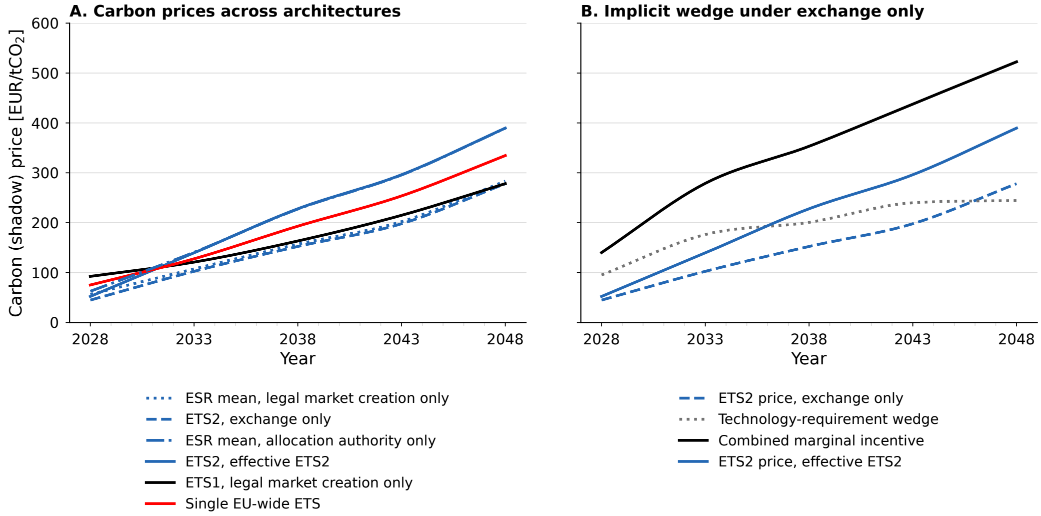
Legal market creation produces emissions below the aggregate statutory budget in early years.[11] Such underuse can arise through two distinct binding margins. National fragmentation prevents unused budget in countries with slack ESR constraints from relieving scarcity elsewhere; binding technology requirements can also induce additional abatement even where an ESR budget is slack. The zero shadow value of a slack budget does not itself generate a welfare gain. Exchange creates value when it reallocates unused budget to margins with positive scarcity values, while allocation authority creates value by relaxing technology requirements with positive quota shadow values.[12]

function. With two functions, this is equivalent to assigning one-half of the interaction gain to each, and the two contributions sum exactly to the total gain.

[11]This pattern is consistent with the historical AEA surpluses documented in Section I.B, although those data do not identify either its mechanism or its welfare consequences.

[12]The difference in realized emissions does not drive the aggregate result: when the effective-ETS2 cap is tightened in each model year to reproduce emissions under legal market creation, 97% of the present-value

Figure 6. **Carbon prices and implicit national-policy wedges**



Notes: Panel A reports common allowance prices and, for architectures retaining national ESR budgets, the ETS2-emissions-weighted mean of country ESR shadow prices. The ESR means are comparative summaries, not common market prices. Panel B decomposes the marginal incentive on household heating and mobility under exchange only. The technology-requirement wedge is the shadow value of the national clean-technology requirements, converted to EUR per ton using benchmark fossil-emissions intensities and aggregated using benchmark household-service emissions. The combined marginal incentive is the sum of this wedge and the ETS2 allowance price. It applies to the constrained household margins and is not an economy-wide carbon price.

The annual effects distinguish the two margins further. In 2028, exchange lowers policy costs by 21.5%, substantially more than the 7.9% gain from allocation authority. Exchange at that date both reallocates emissions across countries and makes unused portions of national emissions budgets available where scarcity values are positive. By 2038 and 2048, all architectures are close to the same aggregate emissions quantity and the ordering reverses: allocation authority lowers annual costs by 20.3% and 19.2%, compared with 5.5% and 2.5% from exchange. As the national requirements tighten, they increasingly determine the composition of abatement and limit what cross-country exchange alone can accomplish. Integrating ETS1 and ETS2 produces a further EUR 87 billion beyond effective ETS2. Most of the available gain therefore comes from making ETS2 effective within its own scope, not from merging the two allowance markets ETS1 and ETS2.

D. Carbon prices and adjustment margins

ALLOWANCE PRICES AND POLICY WEDGES.—Panel A of Figure 6 shows how the two market functions alter observed carbon prices. Exchange replaces dispersed national ESR values with a common ETS2 price. In 2028, the common price is EUR 45

policy-cost saving remains. The quantity-matched effective ETS2 lowers present-value policy costs by EUR 1,290 billion (24.8%). The remaining EUR 38 billion is the additional cost of requiring the effective architecture to reproduce the lower emissions under legal market creation.

Table 3. **Quantity effects of exchange and allocation authority**

	Exchange		Allocation authority		Effective-market total	
Quantity margin	2028	2048	2028	2048	2028	2048
Cross-country reallocation (% of ETS2 emissions)	10	11	1	1	10	12
Change by ETS2-covered use (% of effective-market ETS2 emissions)						
Household direct fuel use	+2	0	+1	+18	+3	+18
Other ETS2-covered uses	+2	0	-1	-18	0	-18
Aggregate realized emissions	+3	0	0	0	+3	0

Notes: Exchange and allocation authority average each function's effect over its two possible activation orders; the effective-market total compares effective ETS2 with legal market creation only. Cross-country reallocation is the total variation between country shares of realized ETS2 emissions, in percent. It is a spatial measure and is not additive across functions. Household direct fuel use comprises covered household combustion for heating and private mobility. Other covered uses comprise services, commercial road transport, and small industrial sources. These two rows partition the aggregate emissions change exactly. Positive entries indicate higher emissions after the market function is activated. Entries are rounded to the nearest percentage point. Appendix E provides the formal definitions.

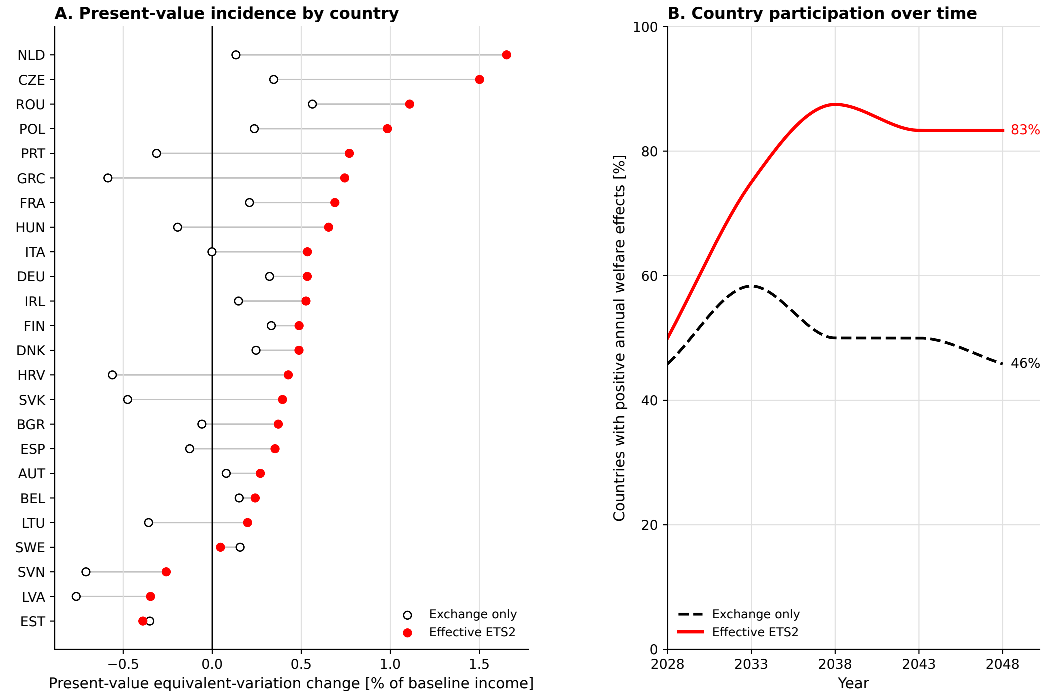
per ton, below the EUR 57 emissions-weighted ESR mean; by 2048 the two values are nearly equal. The allocation-authority-only architecture instead retains national ESR budgets and therefore has no common ETS2 price. Removing the national technology requirements raises its emissions-weighted mean ESR shadow value from EUR 57 to EUR 63 per ton in 2028 and from EUR 283 to EUR 389 in 2048. From 2033 onward, this mean nearly coincides with the common price under effective ETS2, although national ESR shadow values remain dispersed. Allocation authority therefore largely determines the average level of carbon scarcity values, whereas exchange determines whether those values are equalized across countries. Conditional on exchange, removing the national requirements raises the common ETS2 price by 16–50% across 2028–2048, from EUR 278 to EUR 390 per ton in 2048. Yet Figure 5 shows that policy costs fall. The allowance price is therefore not a sufficient statistic for welfare across institutional designs.

Panel B identifies the missing incentive. Under exchange only, the national requirements add an emissions-equivalent wedge of EUR 95 per ton in 2028 and EUR 244 in 2048 on the constrained household margins. Adding this wedge to the allowance price produces combined marginal incentives of EUR 140 and EUR 522, respectively. These sums are not alternative allowance prices: the underlying wedges differ across countries and technologies. They show why a low common allowance price can coexist with high policy costs when other binding institutions continue to govern marginal adjustment, as in Corollary 2.

EMISSIONS REALLOCATION.—Market completion reallocates emissions across countries and covered uses and can alter use of the aggregate budget. Table 3 reports all three margins from an exact sectoral accounting of ETS2 emissions.

Exchange is the dominant spatial margin. It changes country emissions shares by 9.7% in 2028 and 11.4% in 2048, compared with 0.9% and 1.3% for allocation authority. In 2028, exchange also raises realized emissions by 3.2% of effective-market emissions by reducing overcompliance. By 2048, aggregate emissions are unchanged, so exchange reallocates a fixed quantity across countries.

Figure 7. **Market completion and country participation**



Notes: Panel A reports present-value changes in country equivalent variation over 2028–2048, as a percentage of baseline income, relative to legal market creation only. Exchange only activates EU-wide exchange while national technology-mix requirements remain; effective ETS2 also gives the ETS2 price allocation authority over the covered adjustment margins. Panel B reports the share of individually represented member states with positive annual equivalent-variation effects in each model year. Both comparisons maintain the statutory emissions-target trajectory and the 75% ETS2–25% Social Climate Fund revenue architecture.

Allocation authority operates mainly within the ETS2 scope. Relaxing the national requirements shifts emissions toward household fuel use by 1% of effective-market emissions in 2028 and 18% in 2048. Other covered uses undertake the offsetting abatement, principally services and commercial road transport. The large welfare contribution of allocation authority is therefore consistent with its small effect on country emissions shares: it changes how abatement is produced within and across covered uses rather than where the aggregate cap is located.

V. Who Gains When The Market Becomes Effective?

Does completing the market functions exchange and allocation authority generate a country-level Pareto improvement? If not, under the enacted carbon revenue architecture of the EU[13], how costly is closing that gap compared with preserving inefficient institutional constraints? This section quantifies the country-level incidence of market completion, shows how allocation authority broadens the set of countries

[13]Throughout, we hold the carbon revenue architecture, i.e. the share of carbon revenues which accrue to each country from ETS1, ETS2, and the Social Climate Fund, fixed at their respective legislated design.

that gain, and measures the remaining compensation gap.

A. *Country participation and incidence patterns*

MARKET COMPLETION AND COUNTRY PARTICIPATION.—How broadly are the gains from market completion shared? Figure 7 describes cumulative incidence over 2028–2048 in Panel A and the breadth of annual participation over time in Panel B. We define participation as a positive architecture-to-architecture change in the country equivalent-variation measure in Equation (13), which includes carbon rents and other income effects. The measure is cumulative in Panel A and annual in Panel B.

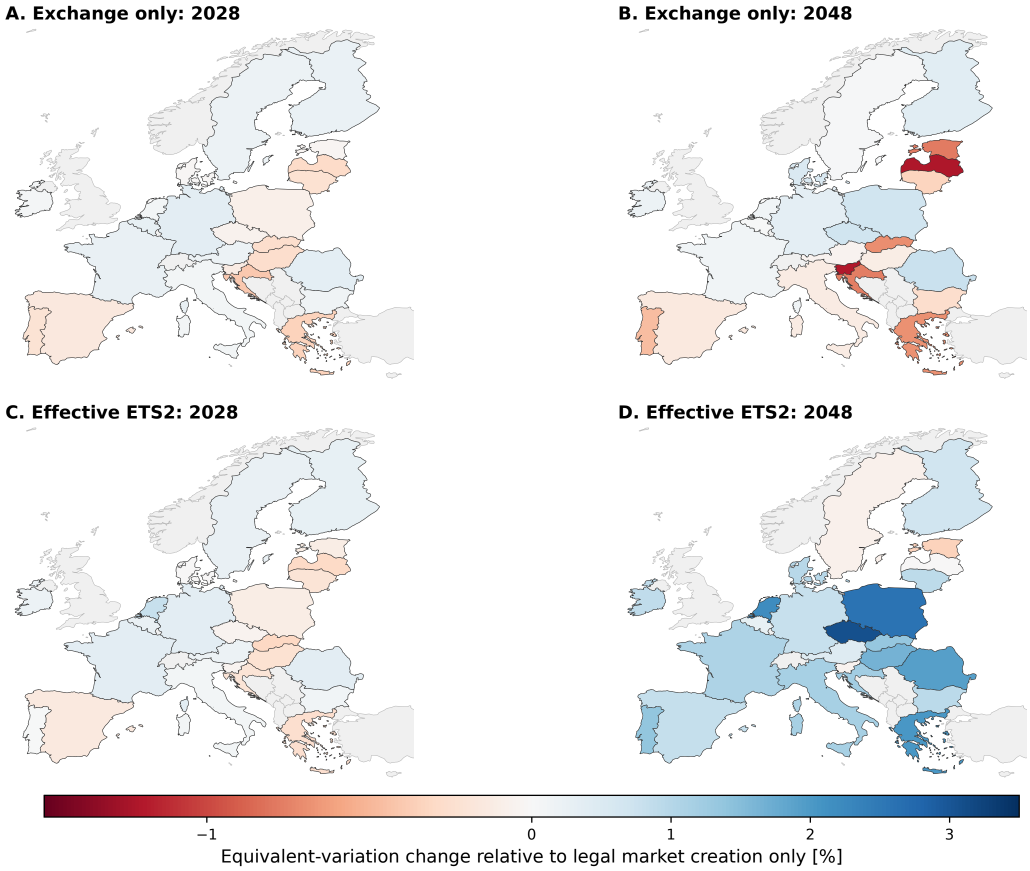
Panel A shows that exchange alone produces mixed present-value effects: 50% of represented countries gain, accounting for 70% of baseline income. Under effective ETS2, the corresponding shares rise to 88% of countries and 99% of baseline income. The annual paths in Panel B diverge as targets tighten. By 2048, the winning-country share is 46% under exchange only and 83% under effective ETS2. Several countries move from annual losses to annual gains, although late gains do not always offset earlier losses over 2028–2048. Along the move from exchange only to effective ETS2, allocation authority therefore raises aggregate welfare and broadens both the number and the economic weight of countries with cumulative gains.

Allocation authority thus does more than create aggregate surplus: it transforms a reform with concentrated incidence into one whose gains reach a broad majority of represented countries. Allocative market completion and broad country participation largely point in the same direction.

PATTERNS OF COUNTRY INCIDENCE.—Which countries account for these participation results, and how do their welfare effects change over time? The broad participation gains from completing the market mask substantial heterogeneity in their timing and magnitude across countries. Country incidence reflects two sets of forces: whether gains arise from exchange or allocation authority, and cross-country differences in inherited ESR scarcity, binding technology-mix constraints, and net carbon-rent positions.

Activating the market functions exchange and allocation authority generates three distinct incidence patterns. First, exchange alone does not progressively broaden participation as targets tighten: the winning-country share is 46% in 2028 and 46% in 2048, with a temporary increase between those dates (Figure 7, Panel B). This stability in the aggregate masks turnover. Czechia, Denmark, and Poland enter the set of winners, whereas Austria, Bulgaria, and Italy move from gains to losses (Figure 8, Panels A and B). Second, allocation authority changes both the breadth and the geography of the gains. By 2048, countries across southern and eastern Europe that still lose under exchange alone—including Bulgaria, Croatia, Greece, Hungary, Italy, Lithuania, Portugal, Slovakia, and Spain—gain under effective ETS2 (Figure 8, Panels B and D). The winning-country share consequently reaches 83% (Figure 7, Panel B). Third, an effective ETS2 does not eliminate country heterogeneity. In 2048, welfare effects under effective ETS2 range from 3.1% in Czechia to -0.3% in Estonia, with losses persisting in Estonia, Latvia, Slovenia, and Sweden (Figure 8, Panel D).

Figure 8. **Country incidence of market completion**

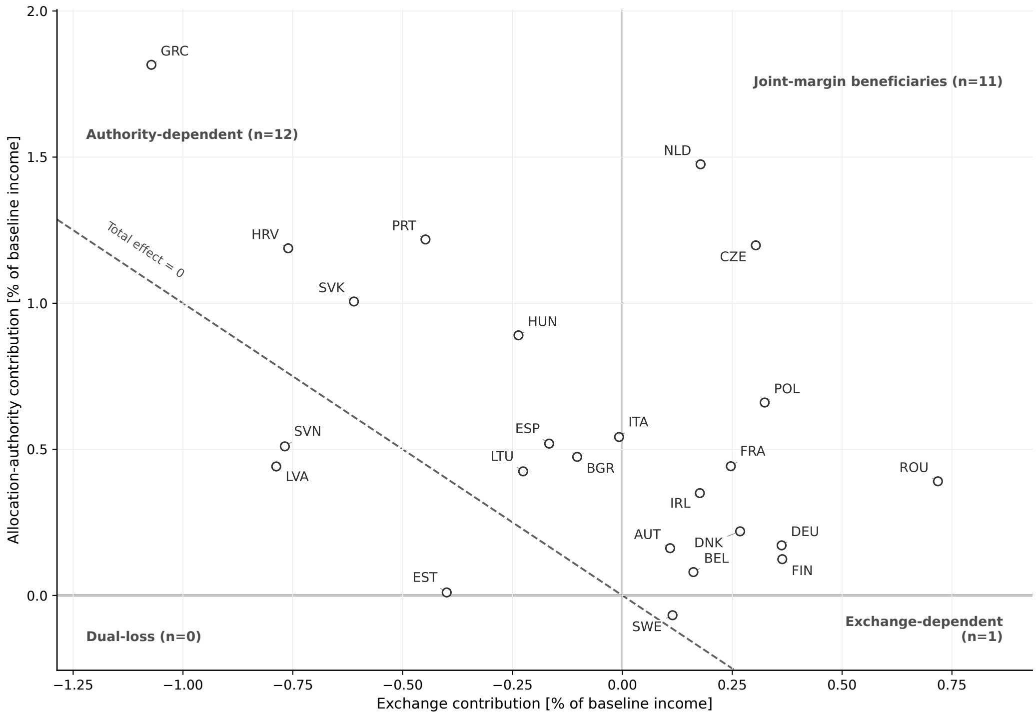


Notes: The figure reports annual country equivalent-variation changes relative to legal market creation only, as a percentage of baseline income. Panels A and B show exchange only, which activates EU-wide exchange while national technology-mix requirements remain. Panels C and D show effective ETS2, which combines exchange with ETS2 price steering over the covered adjustment margins. All comparisons maintain the statutory emissions-target trajectory and the 75% ETS2–25% Social Climate Fund revenue architecture. Member states not represented individually are shown in grey.

B. Institutional attribution of country welfare effects

How should each country's welfare effect be attributed to the two interacting market functions? Figure 9 applies the symmetric Shapley attribution used in Figure 5 at the country level. For each function, it averages the country welfare effect over the two possible activation orders; the two contributions sum to the total present-value effect for every country. Each country's horizontal coordinate is the contribution from exchange, and its vertical coordinate is the contribution from allocation authority. The two zero lines divide the figure into four incidence profiles. Countries in the upper-right quadrant gain from both functions. Those in the upper-left quadrant lose from exchange but gain from allocation authority; the lower-right quadrant reverses this pattern, while countries in the lower-left quadrant lose from both. The

Figure 9. **Institutional attribution and country incidence profiles**



Notes: Each point represents one individually modeled member state, identified by its ISO alpha-3 code. The horizontal coordinate is the Shapley contribution of exchange and the vertical coordinate is the Shapley contribution of allocation authority. Contributions are present-value changes in country equivalent variation over 2028–2048 relative to baseline income. The horizontal and vertical zero lines define the four incidence profiles; labels report the number of represented countries in each profile. The dashed diagonal marks combinations whose two contributions sum to zero, so countries above it gain overall. Present values use a 1.5% annual discount rate. All counterfactuals maintain the statutory emissions-target trajectory and the 75% ETS2–25% Social Climate Fund revenue architecture. Appendix F provides the formal Shapley construction and present-value normalization.

downward-sloping dashed line marks combinations whose two contributions sum to zero, so countries above it have positive total present-value effects.

Figure 9 yields two main results. First, summing the country contributions reproduces the aggregate attribution in Figure 5: allocation authority accounts for approximately 76% of the total gain and exchange for 24%. Second, allocation authority is more broadly beneficial across countries. Its contribution is positive for 96% of represented countries, compared with 50% for exchange.

The country profiles reinforce this difference in breadth. Joint-margin beneficiaries gain from both functions and account for 46% of represented countries. Authority-dependent countries, which account for 50%, lose from exchange but gain from allocation authority; for 75% of this group, the authority contribution is sufficiently large to produce a positive total effect. Sweden is the only exchange-dependent country, and no represented country loses from both functions. The decomposition therefore shows that broad country participation depends primarily on allocation authority, whereas exchange alone generates more heterogeneous incidence. Having attributed the interacting welfare effects symmetrically across the two functions, the next subsection examines the economic margins associated with those contributions.

C. Economic and fiscal incidence channels

Why do these institutional contributions differ across countries? We distinguish two economic channels and one cross-country fiscal channel. Exchange changes where emissions and abatement occur across countries and, when fragmented constraints induce overcompliance, how fully the target budget is used. Allocation authority changes how abatement is delivered within countries by relaxing national technology-mix requirements, while the maintained carbon-revenue architecture redistributes welfare through net ETS2 rents. We examine the first two using model-based mechanism measures and the third through exact fiscal accounting.

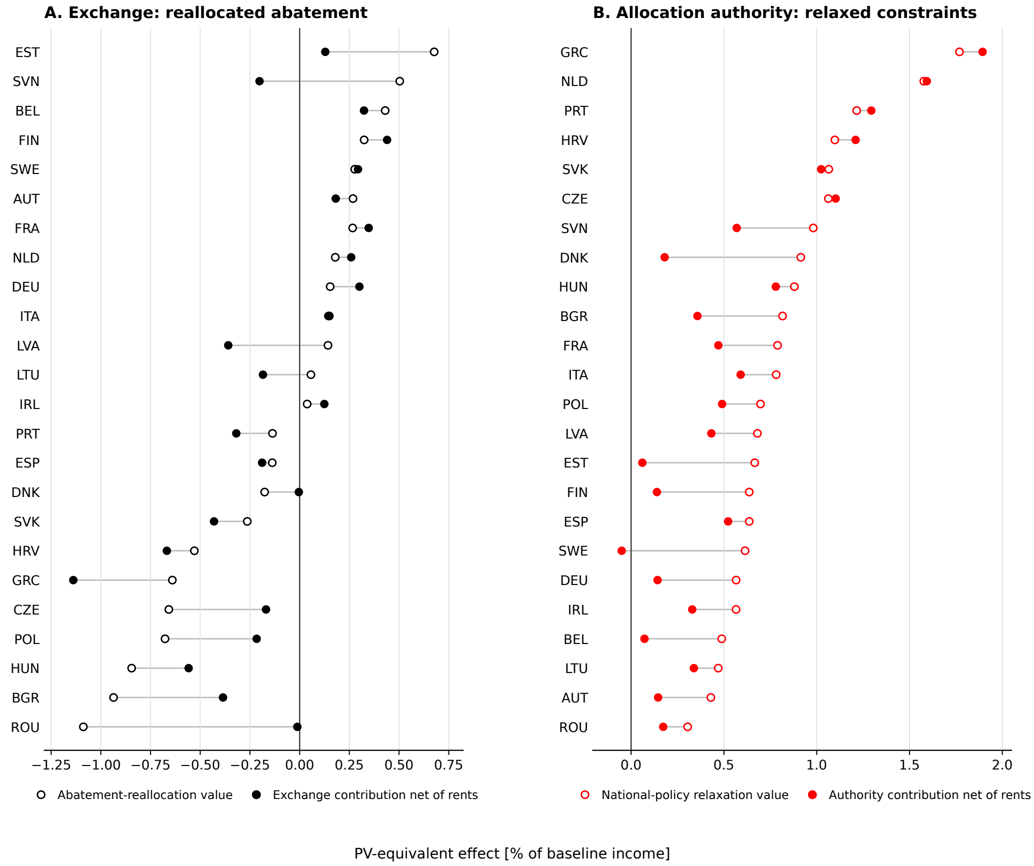
CROSS-COUNTRY REALLOCATION.—When exchange is activated, countries where additional abatement is costly can emit more and avoid some costly abatement, while lower-cost countries emit less and do more. In early years, exchange can also reduce overcompliance and increase aggregate use of the target budget. Figure 10, Panel A, compares each country's exchange contribution with the value of its resulting emissions change, combining these two effects. The open circles value the exchange-induced change in country emissions using the model-implied value of an additional tonne, averaged across both activation orders. Positive values indicate relief from relatively costly abatement; negative values indicate that the country undertakes more. The filled circles report exchange's Shapley contribution after removing the corresponding change in net ETS2 rents.

The measures have the same sign for 88% of countries and a correlation of 0.62. Their alignment shows that exchange incidence is systematically related to real abatement burdens, not only to carbon rents. The distance between a country's two markers records, but does not decompose, the difference between the local mechanism measure and the full-equilibrium welfare contribution, which also incorporates production, consumption, trade, factor-income, and other responses. Once the target binds equally across architectures, country emissions changes sum to zero and exchange creates surplus by shifting abatement from higher- to lower-cost countries; before then, improved budget utilization provides an additional channel.

TECHNOLOGY-MIX CONSTRAINTS.— Allocation authority relaxes national technology-mix requirements, allowing the ETS2 price to steer technology, fuel, and service-demand choices. Figure 10, Panel B, compares each country's welfare contribution net of ETS2 rents with the economic importance of these requirements. The open circles scale the marginal gain from loosening each heating and mobility requirement by the clean-technology activity governed, then sum across services and average across activation orders. Larger values indicate requirements that are more costly at the margin, apply to larger adjustment margins, or both; values near zero indicate requirements that are slack, weak, or narrow. The filled circles report the allocation-authority Shapley contribution net of the corresponding change in rents.

The correlation is 0.91, considerably higher than in Panel A. Greece, the Netherlands, and Portugal lie near the upper end of both measures, while countries with less

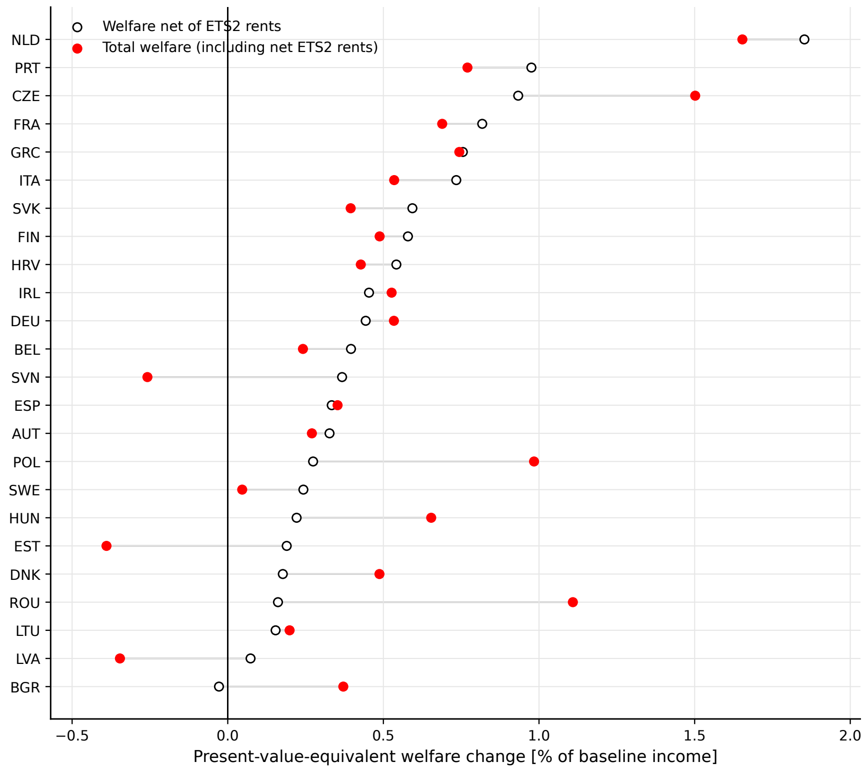
Figure 10. **Allocative channels of country incidence**



Notes: Each row represents an individually modeled member state. Open circles report the function-specific mechanism measure; filled circles report the corresponding Shapley welfare contribution after subtracting its contribution to net ETS2 rents. In Panel A, the mechanism measure values the exchange-induced change in country ETS2 emissions at the mean marginal real-surplus value of an additional emissions unit across the two endpoints. In Panel B, it values national heating and mobility technology-mix requirements using each requirement's shadow value and the targeted clean-technology quantity. Each measure averages over the function's two activation orders. Horizontal segments show the numerical difference between the mechanism measure and the full-equilibrium welfare contribution; they are not exact welfare decompositions. Countries are ordered separately within each panel by the mechanism measure and identified by ISO alpha-3 codes. All comparisons maintain the EU-wide ETS2 target trajectory, although realized emissions can differ when constraints induce overcompliance. All measures are present-value-equivalent percentages of baseline income over 2028–2048. Appendix F provides the formal construction.

consequential requirements generally gain less. Sweden is the only country with a negative net-of-rent contribution, and its mechanism measure lies well below the upper end of the distribution. Because the open-circle indicator is first-order and the filled-circle contribution includes full-equilibrium responses, their comparison identifies a mechanism association rather than an exact welfare decomposition. The close alignment supports the importance of the reach and stringency of national technology-mix requirements for cross-country incidence.

Figure 11. **Net ETS2 rents and country incidence**



Notes: The figure compares effective ETS2 with legal market creation only. Countries are ordered by welfare net of the architecture-to-architecture change in net ETS2 rents. Open black circles report total equivalent variation after subtracting that rent change; filled red circles report total equivalent variation including it. The black circles are an accounting residual, not outcomes from a separately simulated architecture. Each horizontal segment therefore equals the change in the country's net ETS2 rent position, defined as its revenue entitlement under the maintained 75% ETS2–25% Social Climate Fund rule minus the allowance value of emissions originating within the country. Segments that cross zero identify represented countries whose participation status changes. All measures are present-value percentages of baseline income over 2028–2048, using a 1.5% annual discount rate. Appendix F provides further detail on the formal accounting.

Net carbon rents.—Figure 11 accounts for how the maintained carbon revenue architecture modifies country incidence when moving from legal market creation only to effective ETS2. A country's net ETS2 rent is the auction revenue it receives under the maintained carbon revenue rule minus the allowance value of emissions originating within the country. For each country, the horizontal distance between the black and red circles measures the fiscal redistribution induced by the reform; a red circle to the right of its black counterpart indicates that the rent change raises country welfare, whereas a red circle to the left indicates that it lowers welfare. The black circles are obtained by subtracting this rent change from total welfare rather than by simulating a separate no-rent architecture. Segments that cross zero change whether the country gains from market completion.

The rent shifts are substantial: the sum of their absolute country-level present values is EUR 382 billion. Yet they move only 4 countries across the zero-welfare line. They turn losses into gains for Bulgaria and gains into losses for Estonia, Latvia, and Slovenia. By construction, these rent changes cancel in aggregate monetary levels. The net-of-ETS2-rent component is positive for 96% of represented countries; including the rent changes reduces this share to 88%. Net ETS2 rents therefore alter the composition and modestly narrow the breadth of the winning coalition, but do not account for the broad participation gains from allocative market completion.

Taken together, the mechanism measures and fiscal carbon-rent accounting clarify what lies behind the institutional attribution. Exchange incidence is closely, though incompletely, aligned with the value of changing country abatement burdens, while allocation-authority incidence is largest where national requirements restrict economically important adjustment margins. The net-of-ETS2-rent component already yields broad country participation; the rent changes cancel in aggregate monetary levels, rearrange the coalition, and narrow its breadth modestly. Completing the ETS2 market therefore creates surplus mainly by making the common carbon price economically effective, while distributional governance determines which marginal countries share in those gains.

D. Market completion and country compensation

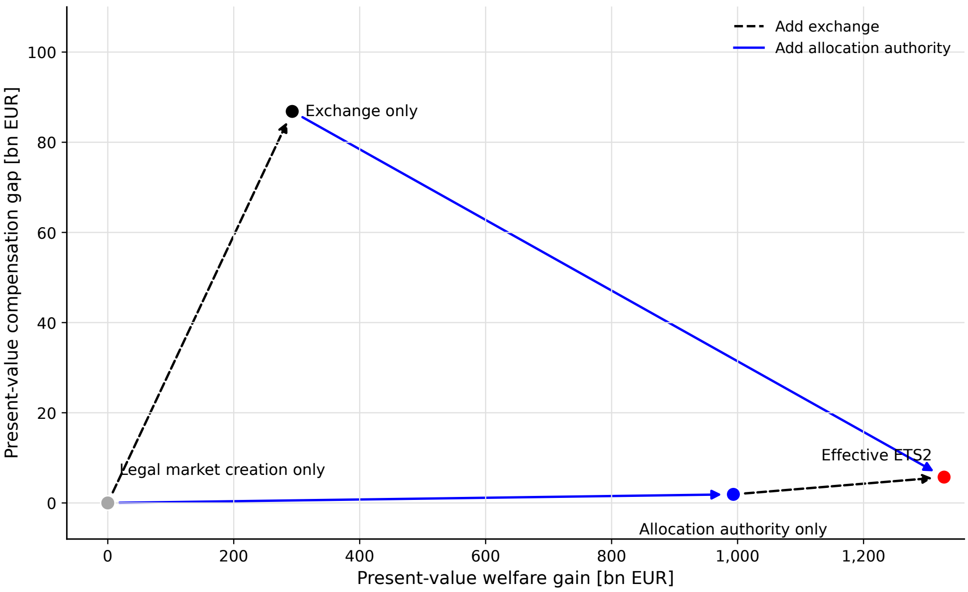
Allocative market completion generates broad country participation but not a country-level Pareto improvement under the maintained revenue architecture. How much redistribution would be needed to make every country weakly better off, rather than preserve inefficient constraints on exchange or allocation authority?

COMPENSATION GAP.—We measure this requirement by the compensation gap: the sum of the absolute present-value welfare losses among countries that are worse off relative to legal market creation only. This gap equals the minimum compensation pool needed to make every country weakly better off using targeted transfers that preserve marginal incentives.[14] The gap is an accounting benchmark of potential compensability.

Figure 12 places each market architecture on an efficiency–compensation plane. An arrow pointing right creates additional aggregate surplus; an arrow pointing down reduces the redistribution needed to eliminate remaining country losses. The direction of each arrow therefore shows whether adding a market function reinforces broad participation or creates an efficiency–compensation tradeoff. Starting from legal market creation only, exchange creates EUR 293 billion in present-value welfare but leaves a compensation gap of EUR 87 billion. Allocation authority alone creates a larger welfare gain of EUR 993 billion and a smaller gap of EUR 2 billion. Adding allocation authority after exchange then creates another EUR 1,035 billion in welfare while reducing the compensation gap by EUR 81 billion. Along this path, allocation authority moves the outcome both toward greater aggregate efficiency and closer to a country-level Pareto improvement.

[14] Formally, let ΔV_r^s denote country r's present-value money-metric welfare change under architecture s. A balanced transfer vector Z_r satisfies $\Delta V_r^s + Z_r \geq 0$ for every country and $\sum_r Z_r = 0$. Such a vector exists whenever $\sum_r \Delta V_r^s \geq 0$, and the minimum compensation paid to losing countries is $C^s = \sum_r \max\{-\Delta V_r^s, 0\}$.

Figure 12. **Aggregate welfare gains and the compensation requirement**



Notes: The horizontal axis reports aggregate present-value welfare gains, and the vertical axis reports the compensation gap, both relative to legal market creation only. The four points represent legal market creation only, exchange only, allocation authority only, and effective ETS2. Arrows show the effect of adding exchange or allocation authority while holding the other function fixed. Moving right indicates a larger aggregate welfare gain; moving down indicates a smaller transfer requirement. The compensation gap is the sum of the absolute present-value welfare losses among individually represented member states that lose; its zero value under legal market creation holds by construction because that architecture is the reference. The gap is calculated under the maintained 75% ETS2–25% Social Climate Fund revenue architecture and is an accounting measure, not a simulated compensation scheme. Present values cover 2028–2048 and assume a 1.5% annual discount rate.

Adding exchange after allocation authority presents a different pattern: it raises present-value welfare by EUR 335 billion while increasing the compensation gap by only EUR 4 billion. Withholding exchange would therefore sacrifice a large aggregate gain to avoid a small additional transfer requirement. Under effective ETS2, the remaining EUR 6 billion gap amounts to 0.4% of the total welfare gains accruing to countries that benefit from the reform. Effective ETS2 is therefore not a Pareto improvement under the maintained revenue rules, but the gross gains are large relative to the losses that remain to be compensated.

SCALE OF CARBON REVENUES.—Carbon revenues provide a second benchmark for the scale of the required compensation. Under effective ETS2, present-value ETS2 revenues are EUR 2,545 billion, so the compensation gap is equivalent to 0.2% of that revenue stream. As a share of annual ETS2 revenues, the requirement declines from 5.6% in 2028 to 0.2% in 2048. This comparison establishes fiscal scale, not an available funding pool: revenues are already assigned under the maintained architecture, and we do not simulate a targeted-transfer reform. It nevertheless shows that the compensation pool is small relative to ETS2 fiscal flows. Addressing the remaining losses is therefore a question for distributional governance, not a reason to weaken market exchange or allocation authority.

VI. Conclusion and Policy Implications

This paper asks when legal market creation produces an effective market-based policy. Completing exchange and allocation authority in ETS2 lowers present-value aggregate EU policy costs over 2028–2048 by EUR 1.33 trillion, or 25.5%, relative to legal market creation only. 76% of this gain is attributed to market allocation authority. Exchange reallocates emissions across countries, whereas allocation authority lets the common price govern technology, fuel, and demand choices. Removing national-policy wedges can therefore raise the allowance price while lowering policy costs as the marginal incentive embodied in their shadow values shifts into the common price. The allowance price is not a sufficient statistic for cost-effectiveness across institutional designs.

Three implications follow for EU carbon pricing. First, common ETS2 allowances are insufficient if national ESR accounting continues to determine where abatement occurs. Completing exchange requires operational AEA trading or an equivalent compliance arrangement that decouples ETS2 emissions from national ESR anchors. Second, the largest efficiency margin lies substantially within member-state policy design. National governments can restructure binding technology-mix requirements so that they preserve independent policy benefits without pre-empting the ETS2 price in governing marginal adjustment. The estimates identify the opportunity cost of failing to do so, not a case for withdrawing policies with independent rationales. Such alignment becomes more important as targets tighten. Third, the larger priority is to make ETS2 effective within its own scope. Once exchange and allocation authority are active, merging ETS1 and ETS2 reduces present-value policy costs by only a further 2.2%.

Market completion also changes country incidence. Under the maintained revenue architecture, effective ETS2 benefits 88% of represented member states, accounting for 99% of aggregate baseline income. The remaining compensation gap is EUR 6 billion, or 0.2% of present-value ETS2 revenues. No compensation scheme is simulated, so these comparisons establish fiscal scale rather than administrative or political feasibility. The gap is small relative to both the gains and the associated revenue stream, pointing to distributional governance rather than weaker exchange or price steering.

The analysis quantifies the cost-effectiveness opportunity cost of the national measures considered here, the efficiency benchmark against which any benefits from addressing other market failures must be assessed. Because those benefits are not valued in the model, the resulting policy comparison is conditional, but the institutional lesson is broader. Effective market creation requires exchangeable scarcity and price-governed marginal allocation; how the resulting gains are shared is a separate question of distributional governance. In the ETS2 context, completing these functions generates large gains and thereby widens the scope for addressing that question.

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Market Creation without Market Authority: Ex-Ante Evidence from European Emissions Trading

Supplementary material (for online publication)

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Appendix A. Observed AEA Transfers

Table A.1 reports the bilateral transactions underlying the summary of observed AEA exchange in Section I. Reporting transfers in levels and relative to national and EU-wide allocations distinguishes transactions that are material for individual countries from aggregate market depth.

Table A.1. **Observed bilateral AEA transfers, 2013–2023**

				Transfer as % of annual allocation		
Transfer year	Acquiring country	Transferring country	Quantity [AEAs]	Acquiring country	Transferring country	EU-27 aggregate
2013	Malta	Bulgaria	82,266	7.0	0.3	0.0
2014	Malta	Bulgaria	124,604	10.7	0.5	0.0
2015	Malta	Bulgaria	135,679	11.6	0.5	0.0
2016	Malta	Bulgaria	166,661	14.3	0.6	0.0
2017	Malta	Bulgaria	253,956	21.6	1.0	0.0
2018	Malta	Bulgaria	209,708	17.9	0.8	0.0
2019	Malta	Bulgaria	254,453	21.7	1.0	0.0
2020	Malta	Bulgaria	139,283	11.9	0.5	0.0
2021	Malta	Bulgaria	508,906	43.4	1.9	0.0
2022	Malta	Bulgaria	278,566	23.8	1.0	0.0
2022	Germany	Bulgaria	3,789,668	0.9	14.3	0.1
2022	Germany	Czechia	3,789,668	0.9	5.6	0.1
2022	Germany	Hungary	3,789,668	0.9	7.2	0.1
2023	Ireland	Slovakia	4,149,944	11.0	16.0	0.2

Notes: The table reports bilateral transfers recorded in the European Union Transaction Log. Quantity is the number of AEAs transferred. The percentage columns scale each transaction by the corresponding annual allocation of the acquiring country, the transferring country, and the EU-27 aggregate. Repeated country pairs in different years are separate records. Sources: own calculations based on European Union Transaction Log data (European Commission, 2024), accessed through EUETS.info (Abrell, 2026).

Appendix B. Proofs

Appendix B1: Proof of proposition 1

Under the maintained assumptions $\mathcal{B} = \mathcal{N}$ and equal aggregate ESR and ETS2 caps, summing the country-level ESR constraints (3) across countries and using $\sum_r \phi_r = 1$ gives

$$\sum_r \sum_{i \in \mathcal{N}} e_{ir} \leq (1-\lambda)\overline{E},$$

which is exactly the ETS2 constraint (4). Introducing ETS2 therefore leaves both the feasible set and the allocative-surplus objective unchanged relative to the ESR-only regime with the same national technology-mix constraints. Because equilibrium allocations maximize this objective over the feasible set, the two regimes have the same set of equilibrium allocations. It remains to characterize the multipliers that support them.

Let $\{q^0_{ir}, e^0_{ir}\}$ denote any ESR-only equilibrium allocation, with national technology-mix multipliers μ^0_{ir} and ESR shadow prices $\tau_r^{ESR,0}$. If every national ESR constraint binds, choose any $k \in [0, \min_r \tau_r^{ESR,0}]$. If at least one national ESR constraint is slack, set $k = 0$. Define the post-ETS2 multipliers by

$$\tau^{ETS2} = k, \qquad \tau_r^{ESR} = \tau_r^{ESR,0} - k, \qquad \mu_{ir} = \mu^0_{ir}.$$

The multipliers are nonnegative. For each overlapping sector $i \in \mathcal{B} = \mathcal{N}$, they preserve the total marginal incentive because

$$\tau_r^{ESR} + \tau^{ETS2} + \mu_{ir} = \tau_r^{ESR,0} + \mu^0_{ir}.$$

All other stationarity conditions are unchanged. Complementary slackness also holds. If every national ESR constraint binds, the duplicate aggregate ETS2 constraint binds as well. If at least one national constraint is slack, aggregate emissions are strictly below the sum of national budgets, so the ETS2 constraint is slack and $k = 0$. The ESR-only allocation is therefore supported as a post-ETS2 equilibrium.

Conversely, take any post-ETS2 equilibrium and define ESR-only multipliers by

$$\tau_r^{ESR,0} = \tau_r^{ESR} + \tau^{ETS2}, \qquad \mu^0_{ir} = \mu_{ir}.$$

Removing the duplicate ETS2 constraint then leaves the stationarity conditions unchanged. If a national ESR constraint is slack, the aggregate ETS2 constraint is also slack and $\tau^{ETS2} = 0$, so complementary slackness is preserved; if all national constraints bind, it holds immediately. Hence every post-ETS2 equilibrium allocation is also an ESR-only equilibrium allocation.

The supporting multipliers thus satisfy

$$\tau_r^{ESR} + \tau^{ETS2} = \tau_r^{ESR,0}.$$

Their nonnegativity implies $0 \leq \tau^{ETS2} \leq \min_r \tau_r^{ESR,0}$. When every national ESR constraint binds, every k in this interval supports the same allocation, so only the sums of the national and common scarcity components are pinned down. □

Appendix B2: Proof of corollary 1

This follows directly from Proposition 1. If at least one country-level ESR constraint is non-binding, aggregate emissions lie strictly below the sum of national budgets. Under exact nesting and equal caps, the ETS2 constraint is therefore also non-binding, so complementary slackness implies $\tau^{ETS2} = 0$. □

Appendix B3: Proof of proposition 2

Fix the ETS1 and ETS2 caps and the national technology-mix constraints. It suffices to compare the ESR architecture without AEA trading with the otherwise identical architecture in which AEA trading is operational.

Without AEA trading, ESR compliance is enforced through country-specific constraints:

$$\sum_{i\in\mathcal{N}} e_{ir} \leq \phi_r(1-\lambda)\overline{E}, \qquad \forall r.$$

With AEA trading, the country-level constraints are pooled into the EU-wide ESR constraint:

$$\sum_r \sum_{i\in\mathcal{N}} e_{ir} \leq (1-\lambda)\overline{E}.$$

Let $\mathcal{F}^{NT}$ denote the feasible set under country-level ESR constraints, ETS1, ETS2, and national technology-mix constraints. Let $\mathcal{F}^{T}$ denote the analogous feasible set when the country-level ESR constraints are replaced by the pooled constraint. The ETS1, ETS2, and technology-mix constraints are identical in the two sets. Because any allocation satisfying all country-level ESR constraints also satisfies the pooled EU-wide ESR constraint, $\mathcal{F}^{NT} \subseteq \mathcal{F}^{T}$.

Equilibrium allocations maximize allocative surplus over the relevant feasible set. Since AEA trading weakly expands the feasible set, the optimum over $\mathcal{F}^{T}$ weakly dominates the optimum over $\mathcal{F}^{NT}$. AEA trading therefore weakly increases cost-effectiveness, holding fixed the ETS1 budget, the aggregate ESR budget, and national technology-mix constraints. Strict gains obtain whenever country-level ESR constraints bind with different shadow values and there is residual flexibility to reallocate emissions across countries without violating those constraints. □.

Appendix B4: Proof of proposition 3

Fix any carbon-budget architecture built from ETS1, ESR, and ETS2 constraints, and fix the AEA trading rule and equilibrium concept. Let $\mathcal{K}$ denote this collection of regime-specific constraints. For a given profile of national technology-mix constraints $\bar{\gamma} := \{\bar{\gamma}_{ir}\}$, define the feasible set

$$\mathcal{F}(\bar{\gamma}) := \Big\{(q,e) : (q,e) \text{ satisfies } \mathcal{K},\ q_{ir} \geq 0,\ e_{ir} \geq 0, e_{ir} \leq \bar{\gamma}_{ir} q_{ir}\ \forall (i,r)\Big\}.$$

Let

$$W(\bar{\gamma}) := \max_{(q,e)\in\mathcal{F}(\bar{\gamma})} \sum_{r\in\mathcal{R}} \sum_{i\in\mathcal{I}} \left[U_{ir}(q_{ir}) - C_{ir}(q_{ir}, e_{ir})\right].$$

If $\bar{\gamma}'_{ir} \geq \bar{\gamma}_{ir}$ for all (i, r), then every allocation feasible under $\bar{\gamma}$ is also feasible under $\bar{\gamma}'$. Hence $\mathcal{F}(\bar{\gamma}) \subseteq \mathcal{F}(\bar{\gamma}')$, and

$$W(\bar{\gamma}') \geq W(\bar{\gamma}).$$

For strict inequality, suppose that $\bar{\gamma}'_{ir} > \bar{\gamma}_{ir}$ for at least one constraint that binds at the optimum under $\bar{\gamma}$ with multiplier $\mu_{ir} > 0$ and positive activity $q_{ir} > 0$. A relaxation expands the feasible set in a direction with positive shadow value. By the envelope theorem, the directional derivative of the value function with respect to $\bar{\gamma}_{ir}$ is $\mu_{ir} q_{ir} > 0$. The relaxation therefore yields a strict welfare gain. □.

Appendix B5: Proof of corollary 2

For an ETS2-covered activity, firm optimality requires

$$MAC_{ir}(q_{ir}, e_{ir}) = \tau_r^{ESR} + \tau^{ETS2} + \mu_{ir}, \qquad p_{ir}^{Y} = MC_{ir}(q_{ir}, e_{ir}) - \mu_{ir}\bar{\gamma}_{ir}.$$

The allowance price τ^{ETS2} therefore identifies neither the total marginal emissions incentive nor the output wedge when $\mu_{ir} > 0$. Architectures with different technology-mix constraints can have different feasible sets, shadow values, and welfare while sharing the same ETS2 allowance price. Proposition 3 establishes that welfare depends on those constraints even at a fixed carbon-budget architecture. The ETS2 price alone therefore cannot rank welfare across architectures that differ in their binding technology-mix constraints. □

Appendix C. Quantitative Model

This appendix provides the full algebraic specification of the WEDGE (Welfare, Energy and Decarbonization in General Equilibrium) model, the quantitative model summarized in Section III. It describes technologies and household behavior, international trade, market clearing and pricing, climate-policy constraints, recursive dynamics, and the competitive equilibrium used for the counterfactual analysis.

1. Sets

We study a discrete-time economy where time is indexed by t. Sectoral goods are indexed by $i, j \in \mathcal{I}$, where $\mathcal{I} = \mathcal{E} \cup \mathcal{N}$ comprises disjoints subsets of energy $\mathcal{E}$ and non-energy $\mathcal{N}$ goods. Energy goods $\mathcal{E} = \mathcal{F} \cup \mathcal{C}$, indexed by $e \in \mathcal{E}$, include the fossil fuels coal, natural gas, and oil, indexed by $f \in \mathcal{F}$, and electricity, indexed by $\tilde{e} \in \mathcal{C}$. Technologies to produce electricity from fossil fuels, nuclear, and various renewable (hydro, solar, and wind) resources are indexed by $s \in \mathcal{S}$. Natural resources are indexed by $z \in \mathcal{Z}$, where $\mathcal{Z} = \mathcal{F} \cup \mathcal{T}$ comprises resources used in the extraction of fossil fuels and non-fossil electricity generation. Energy services are indexed by $x \in \mathcal{X} = \mathcal{X}_h \cup \mathcal{X}_i$, where $\mathcal{X}_h$ and $\mathcal{X}_i$ denote household and production energy services, respectively. Labor is indexed by $l \in \mathcal{L}$. Regions are indexed by $r, s \in \mathcal{R}$. Households in the population of region r are indexed by $h_{(r)} \in \mathcal{H}_r$.

Appendix C2: Energy services and directed technical change

MODELLING ENERGY SERVICES: RATIONALE AND APPROACH.—Energy services are the appropriate level at which to model decarbonization because households and firms ultimately value the useful outputs produced with energy rather than energy itself—for example, process heat, a heated home, or mobility. Representing these services explicitly allows the model to distinguish between reductions in the demand for the underlying service and changes in how that service is produced through fuel switching, electrification, energy-efficiency improvements, and substitution between energy and service-specific equipment. Representing household energy services is particularly important for studying the ETS2, as the costs and emissions reductions associated with carbon pricing depend on how households adjust their demand for residential heating and mobility and on the technologies and energy carriers they use to provide these services.

We differentiate energy services along two dimensions: whether they are demanded by production sectors or households, and whether they are supplied using fossil fuels or electricity. Each energy-service type is produced by combining the relevant energy input with a corresponding machine input. This structure explicitly represents electrification as substitution from fossil-based toward electricity-based energy services, which reduces emissions as electricity generation shifts toward carbon-neutral sources. Machine inputs convert energy into useful energy services and embody knowledge capital, which captures the best available technology and determines how much energy service can be produced from a given amount of energy. Knowledge capital accumulates through a DTC mechanism (Acemoglu et al., 2012) in which successful innovations build on the existing stock of knowledge—scientists "stand on the shoulders of giants"—thereby improving the future efficiency with which energy services are produced.

ENERGY SERVICES IN PRODUCTION AND HOUSEHOLD SECTORS.—Energy services $\hat{Q}_{xirt}$, $x \in \mathcal{X}_i = \{fossil, electricity\}$, for use in production sector i in region r at time t are produced from fossil- or electricity-based energy according to the following constant-elasticity-of-substitution (CES) form:

$$\hat{Q}_{xirt} = \Big(\eta_{xir} \underbrace{\big[\sum_{e \in \mathcal{E}} \zeta_{xeir} E_{xeirt}^{\frac{\rho-1}{\rho}}\big]^{\frac{\rho}{\rho-1}}}_{\text{Electricity or fossil energy inputs}}{}^{\frac{\chi-1}{\chi}} + (1-\eta_{xir}) \underbrace{X_{xirt}}_{\text{Machine inputs}}{}^{\frac{\chi-1}{\chi}}\Big)^{\frac{\chi}{\chi-1}} \tag{C.1}$$

where E_{xeirt} is the input of energy type e (i.e., coal, natural gas, oil, or electricity). $\eta_{xir} \in (0,1)$ and $\zeta_{xeir} \in (0,1)$, with $\sum_e \zeta_{xeir} = 1$, are distribution parameters. ρ is the elasticity of substitution between different types of energy inputs. In the case of an electricity-based energy service, the energy sub-nest contains only electricity. The lower part of Figure C.1 summarizes the nested production structure for fossil and electric energy services in production. χ is the elasticity of substitution between energy and machine inputs X_{xirt}.

Household energy services x comprise heating and mobility. Heating services can be provided from fossil- or electric heating (e.g., heat pumps), while mobility services can be provided from by fossil-run internal-combustion engine (ICE) vehicles or electric vehicles (EV):

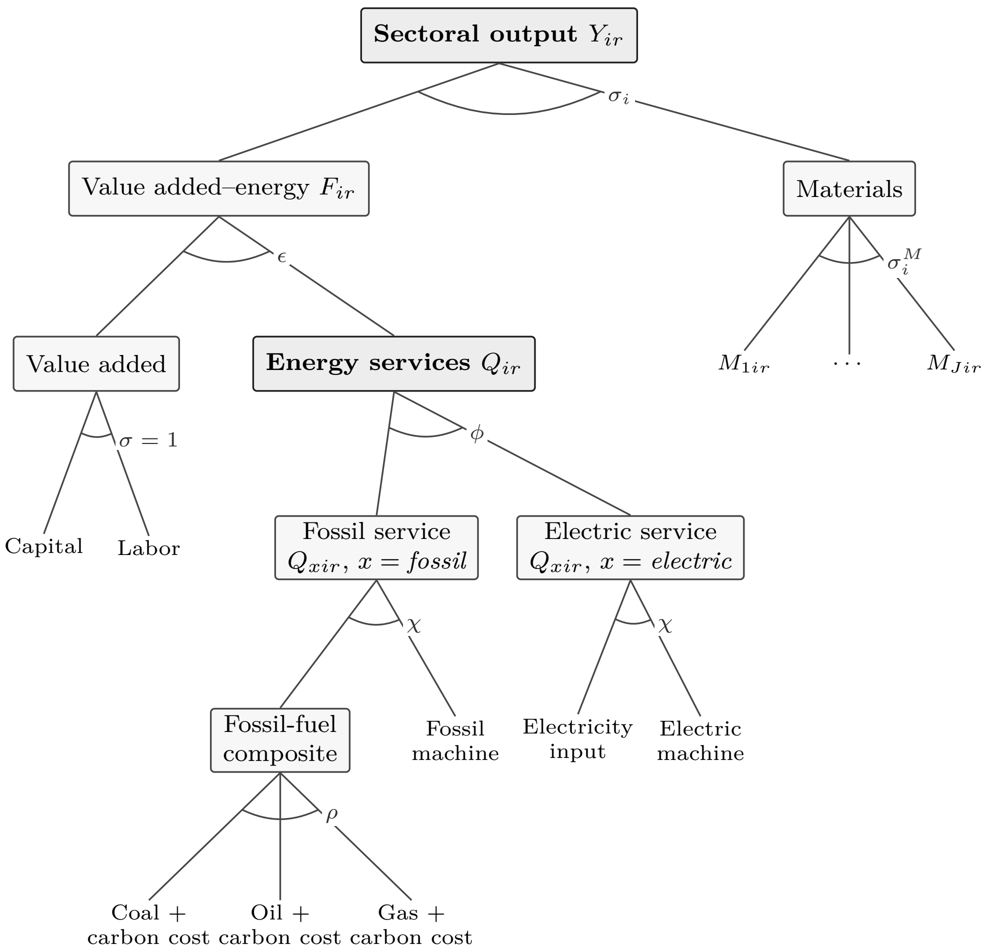
$$x \in \mathcal{X}_h = \{\underbrace{fossil\ heating, heat\ pumps}_{\text{Heating } h(x)}, \underbrace{ICE\ vehicles, EV}_{\text{Mobility } m(x)}\}.$$

Composite household energy services H_r are produced from heating and mobility services according to a two-level CES function:

$$H_{rt} = \Big(\theta_r \underbrace{\big[\sum_{x \in h(x)} \vartheta_{xr} \hat{H}_{xrt}^{\frac{\sigma_h-1}{\sigma_h}}\big]^{\frac{\sigma_h}{\sigma_h-1}}}_{\text{Heating energy services}}{}^{\frac{\sigma-1}{\sigma}} + (1-\theta_r) \underbrace{\sum_{x \in m(x)} \vartheta_{xr} \hat{H}_{xrt}^{\frac{\sigma_m-1}{\sigma_m}}\big]^{\frac{\sigma_m}{\sigma_m-1}}}_{\text{Mobility energy services}}{}^{\frac{\sigma-1}{\sigma}}\Big)^{\frac{\sigma}{\sigma-1}}, \tag{C.2}$$

where $\hat{H}_{xrt}$ is the energy service of type x produced by households in region r at time t combining fuel- and service-type specific equipment according to a CES function similar to (C.1). σ_h and σ_m are the elasticities of substitution between different types of heating and mobility energy services, respectively. θ_r is the distribution parameter between heating and mobility energy services, and ϑ_{xr}, with $\sum_{x \in h(x)} \vartheta_{xr} = \sum_{x \in m(x)} \vartheta_{xr} = 1$, is the distribution parameter between different types of energy services within each end use. θ_r and ϑ_{xr} are used to calibrate the model to observed mix of heating and mobility technologies (energy-service shares) in each region. The different sub-nests for heating and mobility energy services in (C.2) enable representing

Figure C.1. **Nested production technologies**



Notes: The diagram shows the bested structure for a production sector. Sectoral output combines the value-added–energy aggregate on the left with the materials aggregate on the right. Within value added, capital combines with labor; energy services combine fossil- and electricity-based technologies. Each energy-service technology combines an energy input with a technology-specific machine. Fossil fuels, inclusive of the cost from carbon pricing, enter a lower fuel composite. Curved connectors report the elasticity of substitution at the corresponding CES nest. Time indices are omitted for clarity.

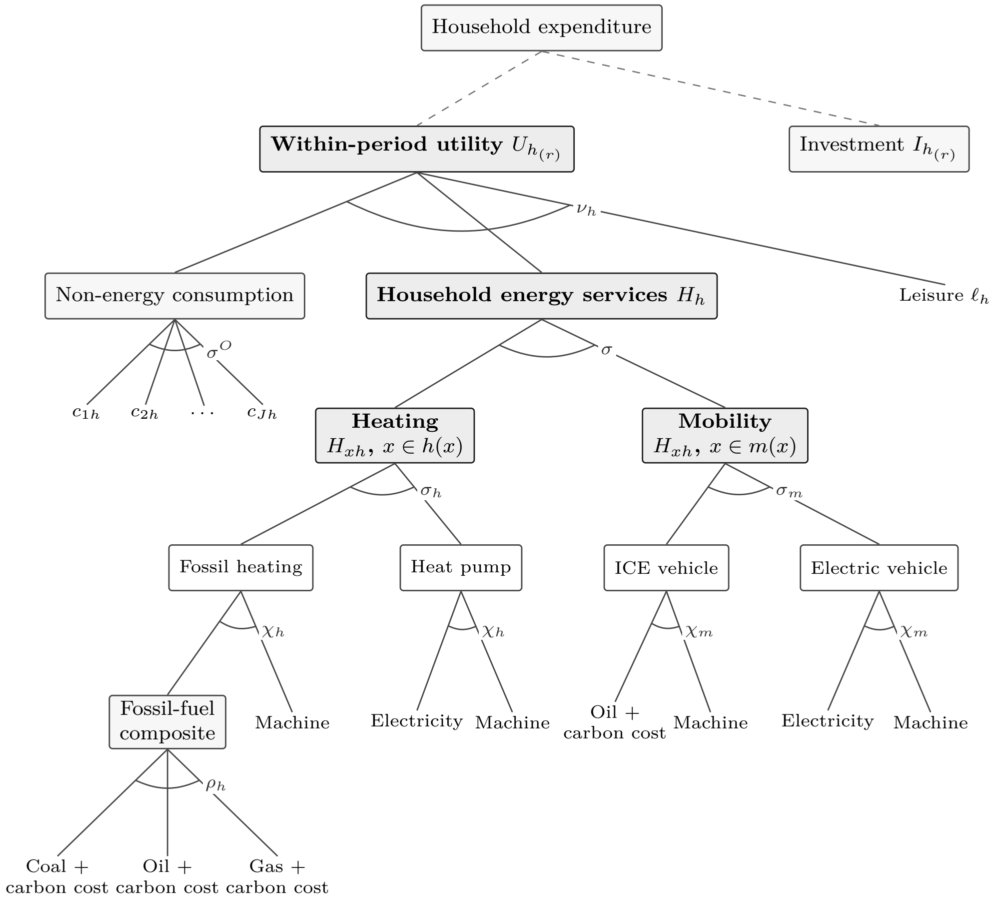
different behavioral responses. The lower part of Figure C.2 summarizes the nested structure for heating and mobility household energy services.

DIRECTED TECHNICAL CHANGE IN ENERGY SERVICES.—Machine services X_{xart} used to generate energy services in production sectors and households are produced in a Dixit-Stiglitz environment of monopolistic competition from machines of varying quality:

$$X_{xart} = \int_0^1 (A_{vxart})^{1-\lambda}(x_{vxart})^{\lambda}dv \tag{C.3}$$

where $\lambda \in (0,1)$. a indexes the user of an energy-service technology: $a = i$ for a

Figure C.2. **Nested household utilities**



Notes: The solid tree shows within-period household demand. Other consumption, household energy services, and leisure enter the upper CES nest. Other consumption includes household appliance electricity, which enters utility directly without a machine input. Heating and mobility each combine a fossil and an electric technology. Fossil heating combines a coal–oil–gas composite with a technology-specific machine; the other technologies combine their energy input directly with a technology-specific machine. The dashed top branch shows the recursive saving closure: within-period utility and investment enter the household expenditure activity in fixed proportions. Time indices are omitted for clarity.

production sector and $a = h$ for a household. The machines x_{vxart} that work with energy service type x to produce energy services $\hat{Q}_{xirt}$ or $\hat{H}_{xrt}$ at time t are divided into a continuum of types, indexed by v. The quality (or efficiency) of machine x_{vxart} is given by A_{vxart}. Machines of type v are produced by monopolists who each take the price of machine services as given (each is sufficiently small) but recognize their ability to influence the price of machines of type v. The cost of producing a machine is in units of the investment good.

Scientists choose which energy service x in which sector i they want to study and are then randomly allocated to a machine type v. Scientists in region r at time t working on energy services of type qi are of measure s_{xart}. Each scientist succeeds in innovating with probability $\eta \in (0, 1]$. If they fail, scientists earn nothing and the quality of that type of machine is unchanged. As in Acemoglu et al. (2012) and Hart (2019), among others, successful scientists receive a one-period patent to produce their type of machine. Successful scientists improve the quality of their machine type to:

$$A_{vxart} = A_{vxar(t-1)} + \gamma A_{vxar(t-1)} \tag{C.4}$$

where $\gamma > 0$ is a parameter measuring productivity in quality improvement.

If a number of s_{xart} scientists research machines used for energy services xi, the average quality of these machines evolves according to:

$$\begin{aligned} \overline{A}_{xart} &= \int_0^1 \left[\eta s_{xart}(1+\gamma)A_{vxar(t-1)} + (1-\eta s_{xart})A_{vxar(t-1)}\right] dv \\ &= (1+\eta\gamma s_{xart})\overline{A}_{xar(t-1)} \, . \end{aligned} \tag{C.5}$$

A scientist who succeeds in innovating exercises her patent to obtain the monopoly profit Π_{xart} for the researched energy service. The allocation of scientists is based on relative profits created by the payoffs from doing successfully researching different types of energy services. The first-order condition for a producer of machine services yields demand for machines of type v related to energy services $xart$:

$$x_{vxart} = \left(\frac{p^X_{xart}}{p^x_{vxart}}\right)^{\frac{1}{1-\lambda}} A_{vxart} \, . \tag{C.6}$$

The monopolistic producer of x_{vxart} thus faces an isoelastic demand curve and accordingly marks up its price. In equilibrium, the produce of machine type v used to produce energy services xa earns profits:

$$\pi_{vxart} = \lambda(1-\lambda)(p^x_{vxart})^{\frac{1}{1-\lambda}} A_{vxart} \, . \tag{C.7}$$

The expected profits of scientists choosing to research machines that work to produce energy services of type xi in region r at time t is therefore:

$$\Pi_{xart} = \eta\lambda(1-\lambda)(p^x_{vxart})^{\frac{1}{1-\lambda}}(1+\gamma)\overline{A}_{xar(t-1)} \, . \tag{C.8}$$

Households in region r at time t supply a fixed measure of research effort in aggregate $\overline{S}_{rt}$ which is allocated to research on energy services of type xi:

$$\overline{S}_{rt} = \sum_x \sum_a s_{xart} \, . \tag{C.9}$$

Appendix C3: Technologies and production

Figure C.1 summarizes the nested production technology. Sectoral output combines a value-added–energy aggregate with a materials aggregate. Within the former, value added combines with fossil- and electricity-based energy services.

NON-ENERGY GOODS AND ENERGY SERVICES.—The output Y_{irt}, $i \in \mathcal{N}$, of non-energy good i in region r at time t is produced competitively from K_{irt} units of capital, L_{irt} units of labor, aggregate energy services Q_{irt}, and intermediate non-energy inputs M_{jirt} from other sectors j. The representative firm's production function is a nested CES:

$$(C.10) \qquad Y_{irt} = \Big(\alpha_{ir} F_{irt}^{\frac{\sigma_i - 1}{\sigma_i}} + (1-\alpha_{ir}) \underbrace{\Big[\sum_{j \in \mathcal{M}} \beta_{jir} M_{jirt}^{\frac{\mu-1}{\mu}}\Big]^{\frac{\mu}{\mu-1}}}_{\text{Composite of non-energy intermediate inputs}}{}^{\frac{\sigma_i - 1}{\sigma_i}}\Big)^{\frac{\sigma_i}{\sigma_i - 1}}$$

which, at the top-level, trades off a capital-labor-energy services composite given by:

$$(C.11) \qquad F_{irt} = \Big(\gamma_{ir} \big[\underbrace{K_{irt}^{\delta_{ir}} L_{irt}^{(1-\delta_{ir})}}_{\text{Value-added}}\big]^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma_{ir}) \underbrace{Q_{irt}}_{\text{Aggregate energy services}}{}^{\frac{\epsilon-1}{\epsilon}}\Big)^{\frac{\epsilon}{\epsilon-1}}$$

with a composite of non-energy intermediate inputs. Capital and labor are nested with a Cobb-Douglas function. $\alpha_{ir} \in (0,1)$, $\beta_{jir} \in (0,1)$, with $\sum_j \beta_{jir} = 1$, $\gamma_{ir} \in (0,1)$, and $\delta_{ir} \in (0,1)$ are distribution (or share) parameters. σ_i, μ, and ϵ is the elasticity of substitution between F_{ir} and the intermediate-input composite, between intermediate inputs, and between value-added and energy services, respectively.

Energy services from electricity and fossil fuels are imperfect substitutes:

$$(C.12) \qquad Q_{irt} = \Big(\sum_{x \in \mathcal{X}_i} \kappa_{xir} \hat{Q}_{xirt}{}^{\frac{\phi-1}{\phi}}\Big)^{\frac{\phi}{\phi-1}},$$

where $\kappa_{xir} \in (0,1)$, with $\sum_q \kappa_{xir} = 1$, are distribution parameters and $\phi < \infty$ is the elasticity of substitution between different types of energy services.

ELECTRICITY AND FOSSIL ENERGY PRODUCTION.—To capture cross-country differences in the electricity generation mix, and the resulting heterogeneity in the carbon intensity and cost of electricity, electricity is produced from fossil-based (natural gas, oil, coal), renewable (wind, solar, hydro) and other carbon-neutral (nuclear) energy sources.

Electricity output Y_{srt} from technology $s \in \mathcal{S} = \{\textit{fossil}, \textit{nuclear}, \textit{hydro}, \textit{wind \& solar}\}$ is produced competitively combining a technology-specific factor R_{srt} with inputs of capital, labor and materials:

$$(C.13) \qquad Y_{srt} = \Big(\underbrace{\theta_{sr} R_{srt}^{\frac{\lambda_{sr}-1}{\lambda_{sr}}}}_{\text{Natural resource factor}} + \underbrace{(1-\theta_{sr}) \hat{Y}_{srt}^{\frac{\lambda_{sr}-1}{\lambda_{sr}}}}_{\text{Non-resource inputs of capital, labor, materials}}\Big)^{\frac{\lambda_{sr}}{\lambda_{sr}-1}}$$

where $\hat{Y}_{srt}$ represents non-resource inputs with a similar nested structure as in (C.10)–(C.1). With the resource factor being in fixed supply at any point in time, the price elasticity of electricity supply from technology s is related to the share parameter $\theta_{sr} \in (0,1)$ and the elasticity of substitution λ_{sr} according to:

$$\lambda_{sr} = \eta_{sr} \frac{\theta_{sr}}{1-\theta_{sr}}\,. \tag{C.14}$$

For example, by appropriately choosing θ_{sr} and λ_{sr} based on data, it is possible to calibrate a supply curve for renewable electricity from wind and solar which approximates the empirical distribution of size and quality of wind and solar sites (i.e., resources) in a specific region.[b]

While electricity output generated from different technologies is constrained by the availability and costs of resource factors, electricity is a perfectly homogeneous good. Hence, the total electricity output $Y_{\tilde{e}rt}$ in region r at time t is given by the sum of electricity produced from all technologies:

$$\sum_{s\in\mathcal{N}} Y_{srt} = Y_{\tilde{e}rt}\,. \tag{C.15}$$

Domestically produced fossil energy Y_{frt} of $f = \{\textit{coal}, \textit{natural gas}, \textit{crude oil}\}$ follows a similar CES structure as (C.13).

Appendix C4: Households

PREFERENCES AND ENDOWMENTS.—Each region is inhabited by a household population $\mathcal{H}_r$ comprising workers, entrepreneurs, and scientists. The composition of household populations differs among regions. $h_{(r)} \subset \mathcal{H}_r$ indexes an individual household in region r. Households have heterogeneous preferences over final consumption goods c_{iht}, comprising non-durable consumption and energy services related to mobility and housing, and leisure time ℓ_{ht}. The instantaneous utility function for household $h_{(r)}$ is given by:

$$U_{h_{(r)}t}\left(c_{iht}, l_{ht}\right) = \Bigg(\underbrace{\omega_h \Big[\sum_{j\in\mathcal{M}} \xi_{ih} c_{iht}^{\frac{\vartheta_h-1}{\vartheta_h}}\Big]^{\frac{\vartheta_h}{\vartheta_h-1}\,\frac{\nu_h-1}{\nu_h}}}_{\substack{\text{Non-durable goods}\\ \text{and energy services}}} + (1-\omega_h) \underbrace{\ell_{ht}}_{\substack{\text{Leisure}\\ \text{consumption}}}^{\frac{\nu_h-1}{\nu_h}}\Bigg)^{\frac{\nu_h}{\nu_h-1}} \tag{C.16}$$

where $\omega_h \in (0,1)$ and $\xi_{ih} \in (0,1)$, with $\sum_i \xi_{ih} = 1$, $\forall h$, are distribution parameters. ϑ_h and ν_h is the elasticity of substitution between consumptions goods, and between material and leisure consumption, respectively.

Figure C.2 summarizes the nested structure underlying household demand. It makes explicit the two adjustment margins most relevant to ETS2: substitution between clean and fossil technologies within heating and mobility, and adjustment in aggregate demand for these energy services.

Households maximize utility (C.16) subject to income (C.17) derived from supplying

[b] See Appendix D for the derivation of (C.14).

labor, shares of profits from physical, knowledge, and natural resource capital, shares of profits accruing to scientists, and transfers from the government, including potential rebates from carbon pricing.

Income of household $h_{(r)}$ at time t is given by:

$$(\text{C.17}) \quad M_{h_{(r)}t} = \underbrace{p^{\ell}_{ht}\overline{L}_{ht}}_{\substack{\text{Value of time}\\ \text{endowment}}} + \underbrace{\Theta^{l}_{h}\sum_{i}\sum_{q}\Pi_{qirt}}_{\substack{\text{Share in}\\ \text{scientists' profits}}} + \underbrace{\Theta^{k}_{h}\Omega_{rt}}_{\substack{\text{Share in aggregate}\\ \text{capital income}}} + \underbrace{T_{ht}}_{\substack{\text{Transfers and}\\ \text{carbon rebates}}}$$

where $\overline{L}_{ht}$ is the household's time endowment at time t, and p^{ℓ}_{ht} the household-specific value of time at t. Θ^{l}_{h} is the share of scientists' profits in region r accruing to household h. Θ^{k}_{h} represents the household's claim on the aggregate payments to the different types of capital in region r, with $\sum_{h(r)}\Theta^{k}_{h(r)} = 1$, $\forall r$. With a single, representative household per region, the respective shares are equal to one. Aggregate capital income in region r at time t

$$\Omega_{rt} = \underbrace{p^{k}_{rt}K_{rt}}_{\substack{\text{Physical}\\ \text{capital}}} + \underbrace{\sum_{z}p^{r}_{zrt}R_{zrt}}_{\substack{\text{Natural}\\ \text{resource capital}}} + \underbrace{\sum_{x}\sum_{a}p^{a}_{xart}\overline{A}_{xart}}_{\substack{\text{Knowledge}\\ \text{capital}}},$$

comprises income from physical capital K_{rt}, natural resource z, and knowledge capital of type d. p^{k}_{rt}, p^{r}_{zrt}, and p^{a}_{xart} denote the respective prices for each type of capital. T_{ht} denotes income from government transfers, including revenues collected from carbon pricing (depending on climate policy).

ENDOGENOUS LABOR SUPPLY.—Solving a household's utility maximization problem and applying the envelope theorem (i.e., Shephard's Lemma) yields the optimal demand for leisure at the household level ℓ_{ht}. ℓ_{ht} represents voluntary unemployment. Given the household's time endowment, the total time allocated to supplying labor to firms is given by:

$$(\text{C.18}) \quad \hat{n}_{ht} = \overline{L}_{ht} - \underbrace{\frac{\partial p^{u}_{ht}}{\partial p^{\ell}_{ht}}U_{ht}}_{\substack{\text{Leisure}\\ \text{consumption}}}$$

where $p^{u}_{ht}(\mathbf{p}^{c}_{t}, p^{\ell}_{ht})$ is the unit expenditure function of household h given a vector of prices $\mathbf{p}^{c}_{t}$ for non-durable goods and energy services and the household-specific valuation of time (i.e., the price of leisure).

SAVINGS.—Each period, households save a share of their current income with savings rate $s_{h(r)}$. The savings rate is exogenous, constant over time, and invariant to climate policy. Savings of household h at time t are thus given by $s_{h}M_{ht}$.

ENDOWMENTS OVER TIME.—We assume that the time endowments of households and the number of scientists in a given region grow at rate γ_{rt} over time, implying that the following laws of motions:

$$\overline{L}_{h(t+1)} = (1+\gamma_{rt})\overline{L}_{ht} \quad \text{and} \quad \overline{S}_{r(t+1)} = (1+\gamma_{rt})\overline{S}_{rt}\,. \tag{C.19}$$

Aggregate investment $I_{rt} = \sum_{h \in \mathcal{H}_r} s_h M_{ht}$ in region r is determined by the sum of household-level savings. Aggregate physical capital in region r increases through investment I_{rt} and depreciates at rate δ_r:

$$K_{r(t+1)} = (1-\delta_r)K_{rt} + I_{rt}\,. \tag{C.20}$$

Appendix C5: International trade and the supply of final goods

All energy and non-energy goods are tradable. Sector-specific bilateral international trade is represented following the standard Armington (1969) approach where goods produced at different locations are treated as imperfect substitutes. The Armington aggregation produces final goods that differ according to their use as intermediate inputs in the production of sectoral output, for household consumption and investment, and for government consumption.

The amount of the Armington composite good i supplied in region r for use category $q = \{\textit{intermediate input in sector j, consumption, investment, government}\}$ at time t, B^q_{irt}, is given by a CES composite of sectoral outputs produced domestically and abroad:

$$B^q_{irt} = \Big[\Theta_{qir} D_{qirt}^{\frac{\tau_{ir}-1}{\tau_{ir}}} + (1-\Theta_{qir}) \underbrace{\{(\sum_{s\neq r} m_{qisr} \hat{M}_{qisrt}^{\frac{\psi_{ir}-1}{\psi_{ir}}})^{\frac{\psi_{ir}}{(\psi_{ir}-1)}}\}}_{=\text{ CES import aggregate}}{}^{\frac{(\kappa_{ir}-1)}{\tau_{ir}}}\Big]^{\frac{\tau_{ir}}{\tau_{ir}-1}} \tag{C.21}$$

where D_{qirt} denotes domestic supply and $\hat{M}_{qisrt}$ represents imports of sectoral good i from region s to region r for use final use category q. τ_{ir} and ψ_{ir} are elasticity of substitution parameters as observed from national accounts data.

Θ^q_{ir} and m^q_{isr} are distribution parameters which enable incorporating rich bi-lateral, sector- and final use-specific international trade patterns. For example, an energy-intensive manufacturing sector in region r may source an energy good, used as an input in production, differently from domestic and foreign markets than a similar sector in region s or than a household for private consumption in the same or a different region. Final goods for investment are further aggregated in a CES fashion into a composite good; likewise for government consumption goods.

Appendix C6: Markets and pricing

To characterize equilibrium prices, we define additional market clearing and pricing conditions.

GOODS MARKETS.—The market for sectoral output clears if produced output equals domestic and export demand from use of the sectoral good as intermediate inputs in production, for private and government consumption, and for investment:

$$\underbrace{Y_{irt}}_{\substack{\text{Supply of}\\\text{sectoral output}}} = \underbrace{\sum_q D_{qirt}}_{\substack{\text{Domestic demand}\\\text{for final use}}} + \underbrace{\sum_q \sum_{s \neq r} \hat{M}_{qirst}}_{\substack{\text{Export demand}\\\text{for final use}}} . \tag{C.22}$$

Finals good markets determine the price of the Armington goods p^q_{irt}. Aggregate supply of consumer goods of type i must equal the total consumption by households in a given region:

$$H^{consumption}_{irt} = \sum_{h \in \mathcal{B}_r} c_{iht} . \tag{C.23a}$$

Aggregate supply of intermediate input good i for use in sector j:

$$B^{intermediate\ input\ sector\ j}_{irt} = \frac{\partial c^Y_j(\mathbf{p}_{rt})}{\partial p^{intermediate\ input\ sector\ j}_{irt}} Y_{jrt} . \tag{C.23b}$$

The markets for the composite investment and government consumption goods clear if:

$$B^{investment}_{irt} = \frac{\partial c^I(\mathbf{p}_{rt})}{\partial p^{investment}_{irt}} I_{rt} + \sum_x \sum_a \int_0^1 x_{vxart} dv \tag{C.23c}$$

$$B^{government}_{irt} = \frac{\partial c^G(\mathbf{p}_{rt})}{\partial p^{government}_{irt}} G_{rt} \tag{C.23d}$$

where $c^I(\mathbf{p}_{rt})$ and $c^G(\mathbf{p}_{rt})$ denote the unit cost function for the composite investment and government consumption good, respectively.

PHYSICAL AND RESOURCE CAPITAL AND LABOR MARKETS.—The rental markets for physical and for natural resource capital clear if:

$$K_{rt} = \sum_i \frac{\partial c^Y_i(\mathbf{p}_{rt})}{\partial p^k_{rt}} Y_{irt} \quad \text{and} \quad R_{zrt} = \sum_i \frac{\partial c^Y_i(\mathbf{p}_{rt})}{\partial p^r_{zrt}} Y_{irt} . \tag{C.24}$$

Similarly, regional labor markets clear if the total labor supplied by households equals the total labor demanded by firms:

$$\sum_{h_{(r)}} \hat{n}_{h_{(r)}t} = \sum_i \frac{\partial c^Y_i(\mathbf{p}_{rt})}{\partial p^l_{rt}} Y_{irt} . \tag{C.25}$$

Appendix C7: Climate policies

CARBON PRICING.—The carbon-market architecture enters where fossil fuels are used. To map the notation of Section II into the production and household blocks above, let $\mathcal{D} = \{heating, mobility\}$ denote household energy-service end uses and let

$u \in \mathcal{U} \equiv \mathcal{I} \cup \mathcal{D}$ index a direct-emissions use. Thus, $u = i$ denotes a production sector and $u = d$ a household end use. Let E_{furt} be the direct input of fossil fuel $f \in \mathcal{F}$ into use u in country r at time t. For production, this quantity aggregates the technology-specific fuel inputs E_{xfirt} in (C.1). For households, it comprises fuel used by fossil heating and ICE vehicles; heat pumps and EVs have no direct fossil-fuel input. Combustion emissions are

$$e_{urt} := \sum_{f \in \mathcal{F}} \beta_f E_{furt}, \tag{C.26}$$

where β_f is the CO_2 content of fuel f. Fossil fuels used to generate electricity are charged at the generating activity. Electricity subsequently used by firms or households therefore carries the upstream carbon cost in its equilibrium price and receives no second direct charge.

As in Section II, $\mathcal{T}$ denotes ETS1-covered uses, $\mathcal{A}$ ESR-only uses, and $\mathcal{B}$ uses covered jointly by the ESR and ETS2. Household heating and mobility and the ETS2-covered production activities belong to $\mathcal{B}$. The carbon-scarcity component applying to use u is the time-indexed counterpart of (7):

$$P_{urt} = \begin{cases} \tau_t^{ETS1}, & u \in \mathcal{T}, \\ \tau_{rt}^{ESR}, & u \in \mathcal{A}, \\ \tau_{rt}^{ESR} + \tau_t^{ETS2}, & u \in \mathcal{B}. \end{cases} \tag{C.27}$$

It raises the user price of fossil fuel according to

$$\tilde{p}^E_{furt} = p^E_{furt} + \beta_f P_{urt}. \tag{C.28}$$

The activity-specific prices in (C.28) enter the fuel nests in (C.1) and the corresponding household energy-service technologies underlying (C.2). Carbon pricing thereby affects fuel use, substitution between energy and machines, the choice between fossil and electric technologies, and energy-service demand. Through goods and factor markets, investment, and directed technical change, these responses also alter economy-wide prices, income, and future production possibilities.

Let $\overline{E}_t^{ETS1}$, $\overline{E}_{rt}^{ESR}$, and $\overline{E}_t^{ETS2}$ denote the time-varying emissions budgets. The associated scarcity prices satisfy

$$0 \le \tau_t^{ETS1} \perp \overline{E}_t^{ETS1} - \sum_{r \in \mathcal{R}} \sum_{u \in \mathcal{T}} e_{urt} \ge 0, \tag{C.29a}$$

$$0 \le \tau_{rt}^{ESR} \perp \overline{E}_{rt}^{ESR} - \sum_{u \in \mathcal{A} \cup \mathcal{B}} e_{urt} \ge 0, \tag{C.29b}$$

$$0 \le \tau_t^{ETS2} \perp \overline{E}_t^{ETS2} - \sum_{r \in \mathcal{R}} \sum_{u \in \mathcal{B}} e_{urt} \ge 0. \tag{C.29c}$$

ETS2-covered emissions enter both (C.29b) and (C.29c), reproducing the institutional overlap in Section II. In the exact-overlap benchmark used for the quantitative counterfactuals, the aggregate ETS2 budget equals the sum of the national budgets over the modeled ETS2 scope. The legal-market-only case therefore implements the national ESR constraints and normalizes the redundant ETS2 price component to zero, selecting one of the allocation-equivalent price decompositions in Proposition 1. Activating exchange replaces these national constraints over ETS2-covered emissions with the common condition (C.29c); this is the model's implementation of operational AEA flexibility or an equivalent common compliance arrangement. The single-EU-ETS benchmark instead pools the ETS1 and ETS2 budgets and covered emissions under one condition. Across these cases, the constraint architecture changes while preferences and technologies remain fixed.

ETS1 and ETS2 rents accrue according to the maintained country revenue shares, whereas the value of a national ESR budget accrues to the household endowed with those emissions rights. These receipts are the dynamic counterparts of Ψ_r in (12) and enter the transfer term T_{ht} in (C.17). They affect household income and country equivalent variation but not the marginal fossil-fuel charge in (C.28). The model therefore separates the allocation of emissions from the distribution of carbon rents.

NATIONAL CAC POLICIES.—National command-and-control (CaC) policies are implemented as minimum clean-technology shares in household heating and mobility. For end use $d \in \mathcal{D}$, let $\mathcal{X}_d \subset \mathcal{X}_h$ contain the technologies that supply that service and let $\mathcal{X}_d^C \subset \mathcal{X}_d$ contain its clean technology: heat pumps for heating and EVs for mobility. Using the household technology outputs $\hat{H}_{xrt}$ in (C.2), total and clean service output are

$$q_{drt} := \sum_{x \in \mathcal{X}_d} \hat{H}_{xrt}, \qquad q_{drt}^C := \sum_{x \in \mathcal{X}_d^C} \hat{H}_{xrt}. \tag{C.30}$$

Let $s_{drt}^C \in [0,1]$ denote the policy-imposed minimum clean share. The requirement and its shadow value satisfy

$$0 \le \varpi_{drt} \ \perp \ q_{drt}^C - s_{drt}^C q_{drt} \ge 0, \tag{C.31}$$

where ϖ_{drt} is the price of the associated technology certificate. The interpretation of (C.31) is that one certificate for each unit of clean service requires every unit of heating or mobility service to surrender s_{drt}^C certificates. If p_{xrt}^H denotes the unit cost of technology x before the requirement, the certificate system changes its effective unit cost to

$$\widetilde{p}_{xrt}^H = p_{xrt}^H + \begin{cases} -(1 - s_{drt}^C)\varpi_{drt}, & x \in \mathcal{X}_d^C, \\ s_{drt}^C \varpi_{drt}, & x \in \mathcal{X}_d \setminus \mathcal{X}_d^C. \end{cases} \tag{C.32}$$

Clean technologies receive a gross certificate credit ϖ_{drt}, while every unit of service bears the obligation $s_{drt}^C \varpi_{drt}$. Equation (C.32) therefore changes relative technology costs inside the heating and mobility nests. Unlike the carbon charge in (C.28), it does not price an additional unit of aggregate service demand in proportion to the emissions that unit generates.[c]

The paths s^C_{drt} encode the country-specific heating and mobility requirements described in Section III.C. When a requirement binds, $\varpi_{drt} > 0$ and its technology-cost wedge operates alongside the applicable carbon-scarcity component P_{urt}. In the allocation-authority counterfactual, the modeled minimum-share requirements are relaxed while carbon budgets, preferences, and technologies are held fixed. Complementary slackness then gives $\varpi_{drt} = 0$, allowing the common ETS2 price to govern technology, fuel, and service-demand choices. Certificate payments and credits net to zero within each country and end use, so these requirements generate no revenue entitlement analogous to an allowance allocation.

Appendix C8: Competitive recursive-dynamic equilibrium with climate policies

Let $\boldsymbol{m}$ denote a climate-policy architecture. At each date, $\boldsymbol{m}$ specifies the coverage sets $(\mathcal{T}, \mathcal{A}, \mathcal{B})$, the operative carbon constraints and their budget paths $\overline{E}^{ETS1}_t$, $\{\overline{E}^{ESR}_{rt}\}_r$, and $\overline{E}^{ETS2}_t$, the national clean-technology requirements $\{s^C_{drt}\}_{d,r}$, and the rules governing carbon-rent entitlements. Given $\boldsymbol{m}$ and inherited endowments of time, physical capital, natural resources, and knowledge, a recursive competitive equilibrium consists of sequences of quantities

$$\{Y_{irt}, Y_{srt}, Y_{\tilde{e}rt}, F_{irt}, M_{jirt}, K_{irt}, L_{irt}, Q_{irt}, \hat{Q}_{xirt}, E_{xeirt}, X_{xirt}, R_{srt}, H_{rt}, \hat{H}_{xrt},$$

$$x_{vxart}, A_{vxart}, \overline{A}_{xart}, s_{xart}, B^q_{irt}, D_{qirt}, \hat{M}_{qisrt}, c_{iht}, \ell_{ht}, \hat{n}_{ht}, n_{lht}, I_{rt}, K_{rt}, R_{zrt},$$
$$\overline{L}_{ht}, \overline{S}_{rt}, G_{rt}, T^0_{ht}, T_{ht}\},$$

market prices and policy shadow values

$$\{p^Y_{irt}, p^q_{irt}, p^\ell_{ht}, w_{rt}, p^k_{rt}, p^r_{zrt}, p^X_{xart}, p^x_{vxart}, p^a_{xart}, p^E_{furt}, p^H_{xrt},$$

$$\tau^{ETS1}_t, \{\tau^{ESR}_{rt}\}_{r\in\mathcal{R}}, \tau^{ETS2}_t, \{\varpi_{drt}\}_{d\in\mathcal{D}, r\in\mathcal{R}}\},$$

and associated policy and income objects

$$\{e_{urt}, P_{urt}, \tilde{p}^E_{furt}, q_{drt}, q^C_{drt}, \tilde{p}^H_{xrt}, \Omega_{rt}, \Psi_{rt}, M_{ht}\},$$

such that the following conditions hold:

(i) Producers of sectoral goods choose cost-minimizing inputs and earn zero profits

[c]The clean-share implementation is the quantitative counterpart of the emissions-intensity constraint in (5). To see the mapping, suppose locally that the dirty technology emits $e_{drt} = \theta_{drt} q^D_{drt}$, where $q^D_{drt} = q_{drt} - q^C_{drt}$ and θ_{drt} is emissions per unit of dirty service. Equation (C.31) then implies

$$\frac{e_{drt}}{q_{drt}} \le \theta_{drt}(1 - s^C_{drt}) \equiv \overline{\gamma}_{drt}. \tag{C.33}$$

Thus, the certificate price and the conceptual-framework multiplier are related by $\varpi_{drt} = \theta_{drt}\mu_{drt}$. The net credit to clean output in (C.32) is consequently the implementation counterpart of the implicit output subsidy $\mu_{drt}\overline{\gamma}_{drt}$ in (6). The emissions intensity within a technology remains endogenous because energy can substitute with machines and, in fossil heating, across fuels. We therefore impose the observed technology-share requirement directly; Equation (C.33) supplies its economic interpretation rather than replacing the energy-service technologies with fixed emissions coefficients.

subject to (C.10)–(C.12). Electricity generators and fossil-energy producers choose inputs at minimum cost under (C.13) and the analogous fossil-resource technology, and supplies from the electricity technologies satisfy (C.15).

(ii) Production and household energy-service technologies choose energy and machine inputs at minimum cost under (C.1) and the household technologies underlying (C.2). Direct fossil inputs are valued at the carbon-inclusive prices in (C.28); household heating and mobility technologies are valued at the certificate-adjusted costs in (C.32). The resulting technology outputs aggregate into production and household energy services according to (C.12) and (C.2).

(iii) Monopoly machine producers face the demand in (C.6), choose machine supply to maximize the profits in (C.7), and meet the machine demands of energy-service producers. Scientists select research fields to maximize the expected return in (C.8); their allocation exhausts the resource constraint in (C.9); and knowledge evolves according to (C.4) and (C.5).

(iv) Armington suppliers choose domestic and imported varieties at minimum cost under (C.21). Households choose consumption and leisure to maximize (C.16) subject to the income constraint (C.17) and the maintained saving rule. Their allocation of time between leisure and labor satisfies (C.18).

(v) Sectoral-output and use-specific Armington markets clear according to (C.22) and (C.23a)–(C.23d). Regional markets for labor, physical capital, and natural-resource factors satisfy (C.25) and (C.24). Machine, knowledge, and research markets clear at their respective prices.

(vi) Combustion emissions, the applicable carbon-scarcity component, and carbon-inclusive fossil-fuel prices satisfy (C.26)–(C.28). Every operative carbon constraint satisfies the corresponding complementarity condition in (C.29a)–(C.29c); the shadow price of an inactive constraint is zero. In the legal-market-only architecture, the redundant ETS2 price component is normalized to zero. When exchange is activated, the national constraints over ETS2-covered emissions are replaced by the common ETS2 condition. In the single-EU-ETS benchmark, the ETS1 and ETS2 conditions are replaced by their pooled counterpart.

(vii) Household clean-technology outputs and total heating and mobility services satisfy (C.30). Each operative national requirement satisfies (C.31), and its certificate price enters technology costs through (C.32). If a requirement is inactive or slack, $\varpi_{drt} = 0$. Certificate payments and credits balance within each country and end use and therefore create no net household income.

(viii) Under the separate ETS1, ESR, and ETS2 constraints, country r receives carbon rents $\Psi_{rt} = \xi_r \tau_t^{ETS1} \overline{E}_t^{ETS1} + \pi_r \tau_t^{ETS2} \overline{E}_t^{ETS2} + \tau_{rt}^{ESR} \overline{E}_{rt}^{ESR}$, where ξ_r and π_r are the maintained country entitlement shares, with $\sum_r \xi_r = \sum_r \pi_r = 1$. Under the single-EU-ETS benchmark, the rent terms associated with the pooled constraints are replaced by the common allowance price times the pooled emissions budget and the maintained country entitlement share. Carbon rents enter household transfers according to $T_{ht} = T_{ht}^0 + \upsilon_{hr} \Psi_{rt}, \qquad \sum_{h \in \mathcal{H}_r} \upsilon_{hr} = 1$, where T_{ht}^0 denotes non-carbon net transfers and υ_{hr} is household h's share of country carbon-rent income. Thus, carbon prices and emissions budgets determine the endogenous rent component of household income; only T_{ht}^0 follows the common exogenous transfer path.

(ix) Aggregate investment is determined by household saving, physical capital accumulates according to (C.20), and time and scientist endowments evolve according to (C.19). Knowledge follows (C.5); government demand, non-carbon transfers, and natural-resource endowments follow their exogenous paths. The updated state variables become the inherited endowments of the next within-period equilibrium.

Appendix D. Data and Calibration

This appendix documents the empirical mapping of the WEDGE (Welfare, Energy and Decarbonization in General Equilibrium) model. It describes the benchmark accounts and their replication, reports the behavioral and dynamic parameters that govern adjustment away from the benchmark, documents the renewable-electricity supply calibration, and records the emissions targets, national technology-mix requirements, emissions-budget endowments, and carbon-rent entitlements used in the counterfactuals.

Appendix D1: Benchmark data and aggregation

The model is calibrated to a 2017 social accounting matrix constructed from version 11 of the Global Trade Analysis Project database (GTAP, Aguiar et al., 2022). GTAP supplies mutually consistent country accounts for production, intermediate use, consumption, investment, factor income, bilateral trade, energy flows, taxes and subsidies, and fossil-fuel CO_2 emissions. We supplement the electricity accounts with technology-specific input structures from Abrell, Rausch and Streitberger (2019) and country generation by source in 2023 from the Global Change Data Lab's Our World in Data series (Global Change Data Lab, 2024). To match the model aggregation, wind, solar, and other non-bioenergy renewables form one technology; hydro and nuclear remain separate; and coal, gas, oil, and bioenergy enter the residual thermal technology. Household expenditure and income shares draw on Eurostat Household Budget Survey and EU Statistics on Income and Living Conditions data (Eurostat, 2023a,b). The sectoral and regional aggregation is reported in Table 2.

The benchmark construction preserves the identities linking production, domestic and imported intermediate demand, bilateral trade, factor earnings, tax receipts, household income, government demand, investment, and the current account. Fossil-fuel flows are converted into positive combustion CO_2 emissions using the carbon contents embedded in GTAP. Electricity generation is disaggregated into residual thermal, nuclear, hydro, and wind-and-solar technologies while preserving aggregate electricity output and input costs.

Appendix D2: Calibrated shares and benchmark replication

We represent constant-elasticity-of-substitution technologies in calibrated share form (Rutherford, 1995). Consider a constant-returns CES nest combining inputs x_j, with user prices p_j, into output Q. Let bars denote benchmark values. The benchmark unit cost and value shares are

$$\bar{c} = \frac{\sum_j \bar{p}_j \bar{x}_j}{\bar{Q}}, \qquad \theta_j = \frac{\bar{p}_j \bar{x}_j}{\sum_k \bar{p}_k \bar{x}_k}, \tag{D.1}$$

and the normalized unit-cost function is

$$c(\boldsymbol{p}) = \bar{c}\left[\sum_j \theta_j \left(\frac{p_j}{\bar{p}_j}\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}. \tag{D.2}$$

By Shephard's lemma, conditional input demand is

$$x_j = \bar{x}_j \left(\frac{Q}{\bar{Q}}\right)\left(\frac{c(\boldsymbol{p})}{\bar{c}}\right)^{\sigma}\left(\frac{p_j}{\bar{p}_j}\right)^{-\sigma}. \tag{D.3}$$

At benchmark prices and output, Equation (D.3) reproduces each observed input independently of σ. Benchmark value flows therefore identify the share parameters and normalizations; externally specified elasticities determine curvature and adjustment away from the benchmark. We apply this construction recursively to production, electricity, energy-service, trade, and household-demand nests, with observed fiscal wedges included in user prices and government accounts.

Appendix D3: Behavioral and dynamic parameters

Table D.1 summarizes the parameter groups, underlying data sources, and implemented values using the notation of Appendix C. Data-calibrated CES shares vary by country, sector, input, and trade partner and are determined by the benchmark accounts through Equations (D.1)–(D.3).

Substitution between clean and fossil technologies.—The parameters governing substitution between clean and fossil technologies in household energy services and the response of energy-service demand are key model parameter. We next review the empirical evidence and discuss our parametrization. We also present results from sensitivity analysis which varies the ease of substitution between fossil and electric technologies.

In general, elasticities should be interpreted as responses of an evolving durable stock over two decades (i.e., 2028-2048), rather than as fuel-demand elasticities conditional on the installed vehicle and heating stock. In road transport, higher gasoline prices shift new-car purchases and accelerate scrappage: Li, Timmins and von Haefen (2009) estimate a long-run fleet fuel-economy response nearly an order of magnitude larger than the short-run response, while Klier and Linn (2010) and Busse, Knittel and Zettelmeyer (2013) show that vehicle sales and asset prices respond to expected lifetime fuel costs. The emerging electric-vehicle market adds a highly price-responsive adoption margin. Muehlegger and Rapson (2022) estimate a purchase-price elasticity of -2.1, Fridstrøm and Østli (2021) report own-price elasticities of -1.27 for battery-electric and -1.72 for plug-in hybrid vehicles, and Bushnell, Muehlegger and Rapson (2026) find electric-vehicle sales four to six times more responsive to gasoline prices than to equal percentage changes in electricity prices. Charging infrastructure and an improving automobile technology frontier further expand the feasible choice set (Springel, 2021; Knittel, 2011).

Heating studies likewise find stronger responses when equipment choice is modeled

Table D.1. **Implemented parameter values.**

Parameter	Source	Value
Non-energy production		
Output–materials elasticity: σ_i	Calibrated: Chen et al. (2015)	0
Non-energy materials elasticity: μ	Calibrated: Chen et al. (2015)	0
Value-added–energy-services elasticity: ϵ	Calibrated: Chen et al. (2015)	0.35
Output-nest share: α_{ir}	Data: GTAP (Aguiar et al., 2022)	ir-specific
Material-input shares: β_{jir}	Data: GTAP	jir-specific
Value-added share: γ_{ir}	Data: GTAP	ir-specific
Capital share in value added: δ_{ir}	Data: GTAP	ir-specific
Energy services		
Energy-input elasticity: ρ	Calibrated: Chen et al. (2015)	1
Energy–machine elasticity: χ	Calibrated: Lemoine (2024)	2
Production technology elasticity: ϕ	Calibrated	0.5
Heating–mobility elasticity: σ	Calibrated	1
Heating technology elasticity: σ_h	Baseline long-run calibration	8
Mobility technology elasticity: σ_m	Baseline long-run calibration	8
Energy-input shares: η_{xar}	Data: energy-service accounts	xar-specific
Production technology shares: κ_{xir}	Data: GTAP	xir-specific
Heating share in household energy services: θ_r	Data: energy-service accounts	r-specific
Heating technology shares: ϑ_{xr}	Data: energy-service accounts	xr-specific
Mobility technology shares: ϑ_{xr}	Data: energy-service accounts	xr-specific
Energy-input shares within technology: ζ_{xeir}	Data: energy-service accounts	$xeir$-specific
Energy production		
Renewable supply elasticity: η_{sr}	Constructed from JRC	sr-specific
Renewable resource elasticity: λ_{sr}	Calibrated from supply elasticity	sr-specific
Renewable resource share: θ_{sr}	Data: technology cost accounts	sr-specific
International trade		
Domestic–import elasticity: τ_{ir}	Calibrated: Aguiar et al. (2022)	ir-specific
Source-country elasticity: ψ_{ir}	Calibrated: Aguiar et al. (2022)	ir-specific
Domestic shares: Θ_{qir}	Data: GTAP	qir-specific
Bilateral import shares: m_{qisr}	Data: GTAP	$qisr$-specific
Research and innovation		
Innovation success parameter: η	Normalized	1
Quality step: γ	Calibrated: Lemoine (2024)	1
Machine-quality exponent: λ	Calibrated: Lemoine (2024)	0.8
Implied machine-variety elasticity: $1/(1-\lambda)$	Implied by λ	5
Households		
Consumption-goods elasticity: ϑ_h	Calibrated: Chen et al. (2015)	0.3
Consumption–leisure elasticity: $\nu_{h_{(r)}}$	Calibrated to match uncompensated labor supply targets	r-specific
Consumption share in utility: ω_h	Data: Eurostat HBS–SILC (Eurostat, 2023a,b)	r-specific
Consumption-good shares: ξ_{ih}	Data: GTAP	ir-specific
Emissions		
Fuel carbon content: β_f (tCO_2/toe)	Data: GTAP energy and emissions accounts	f-specific
Growth		
Annual effective-labor growth: γ_{rt} (%)	Calibrated	1.5
Annual capital depreciation: δ_r (%)	Exogenous	3

explicitly. Vaage (2000) obtains an energy-price elasticity exceeding one in magnitude in a model with heating-system choice; Sahari (2019) estimates electric-heating technology elasticities of -0.42 to -1.56 and finds that electricity taxes shifted investment toward renewable heating; and Li and Just (2018) jointly models short-run fuel use and long-run appliance adoption. Heat-pump adoption is strongly associated with relative electricity and gas prices (Davis, 2024), while replacing a gas boiler with a heat pump reduces household gas use by about 90 percent in the field evidence of Bernard et al. (2024). Energy prices can also redirect energy-saving innovation (Newell, Jaffe and Stavins, 1999; Popp, 2002).

MODEL-IMPLIED EQUILIBRIUM SENSITIVITY.—None of these estimates identifies the model's primitive CES parameters or validates a particular aggregate arc elasticity. Together, however, they support an upper-end long-run adjustment case in which stock turnover, technology adoption, and an evolving technology set make fossil-fuel demand substantially more responsive than historical regressions that hold those margins largely fixed. Table D.2 reports the model-implied road- and heating-fuel equilibrium elasticities, showing that our baseline parametrization (i.e., the flexible-adjustment baseline) produces equilibrium elasticities which are consistent with the identified range from the literature.

In addition, we conduct a sensitivity analysis to examine the implications of lower household flexibility. The alternative specification reduces the elasticity of substitution between fossil and electric technologies from eight to one and the elasticity between energy and machine services within each technology from 2 to 0.2. This lower-flexibility specification produces aggregate road- and heating-fuel responses that are closer to the range of empirical estimates for price elasticities of fuel demand (but which may be considered as too low as an implied response of an evolving durable stock of electric technologies). This sensitivity exercise disciplines a joint adjustment environment; it does not identify the primitive CES elasticities or define statistical bounds on them.

Lower household flexibility raises policy costs under both market architectures, but more strongly when national requirements continue to govern technology choice. Present-value costs rise from EUR 5,199 billion to EUR 7,896 billion under legal market creation and from EUR 3,871 billion to EUR 5,312 billion under effective ETS2. The Shapley contribution from exchange increases from EUR 314 billion to EUR 495 billion, whereas the contribution from allocation authority rises from EUR 1,014 billion to EUR 2,088 billion. Allocation authority therefore remains the dominant source of the effective-market gain and becomes more important when household adjustment is less elastic. The larger aggregate gain also broadens country participation: all represented countries gain from market completion in the low-flexibility specification.

The alternative also raises the 2048 ETS2 price under effective market creation from EUR 891 to EUR 1,305 per ton. This is a terminal shadow price under a stringent fixed emissions path in which the ETS2 price must govern the constrained adjustment margins, not a forecast of the politically observed allowance price. Its magnitude reinforces the interpretation of low flexibility as a stress test. The smaller proportional change in present-value effective-market costs again shows that a terminal marginal price and cumulative welfare costs need not move proportionately.

The national clean-share requirements have allocative content in both specifications. In the baseline, positive certificate prices occur for 42–71% of country-service requirements under legal market creation only and 44–69% under exchange with

Table D.2. **Behavioral flexibility, market effectiveness, and country participation**

Object	Flexible-adjustment baseline	Low-flexibility specification
Panel A. Household adjustment		
Clean–fossil elasticity: mobility σ_m (heating σ_h)	8 (8)	1 (1)
Energy–machine elasticity within technologies	2	0.2
Road-fuel equilibrium arc elasticity, 2028 (2048)	-1.62 (-1.63)	-0.72 (-0.79)
Heating-fuel equilibrium arc elasticity, 2028 (2048)	-2.23 (-2.45)	-0.70 (-0.75)
Panel B. Aggregate welfare and country participation		
PV policy cost: legal market only (EUR billion)	5,199	7,896
PV policy cost: effective ETS2 (EUR billion)	3,871	5,312
Policy-cost reduction (%)	25.5	32.7
Exchange contribution (EUR billion)	314	495
Allocation-authority contribution (EUR billion)	1,014	2,088
Allocation-authority share (%)	76.4	80.8
Countries gaining (%)	87.5	100.0
Compensation gap (EUR billion)	5.7	0.0
ETS2 price in 2048 (EUR/tCO_2)	891	1,305

Notes: Panel A reports EU aggregate finite-change elasticities along each no-policy path following a revenue-recycled 10 percent increase in the user price of fossil inputs to the indicated household service. EU fuel quantities are summed across countries, and country user-price changes are aggregated with baseline fuel-expenditure shares. The reduced-form responses combine technology switching, substitution between energy and machine services, service conservation, income effects, and equilibrium price adjustment. The low-flexibility specification changes only the three household elasticities reported in Panel A. The model-implied equilibrium elasticities can be compared to external estimates from meta-analyses of long-run road-fuel and natural-gas price elasticities of fuel demand (Brons et al., 2008; Havranek, Irsova and Janda, 2012; Labandeira, Labeaga and López-Otero, 2017). The meta-analyses yield ranges of $[-0.81, -0.31]$ and $[-0.85, -0.57]$ for road-fuel and natural-gas price elasticities, respectively. Panel B reports present values over 2028–2048. Function-specific contributions use the Shapley attribution of the exchange–allocation-authority interaction. Countries gain when their present-value equivalent-variation change from legal market creation to an effective ETS2 is positive; the compensation gap sums losses among the remaining countries. Both specifications hold emissions targets and the carbon-revenue architecture fixed.

national requirements. In the low-flexibility specification, the corresponding ranges are 35–79% and 44–79%. The requirements therefore constrain technology choice rather than merely restating the clean shares households would choose at prevailing prices.

Appendix D4: Renewable electricity supply

Renewable expansion is limited by heterogeneous site quality rather than by a single engineering potential available at one cost. We construct country-specific long-run supply schedules for the model's wind-and-solar aggregate and summarize the slope of each schedule by a price elasticity η_r^{ren}. The calibration proceeds in four steps: regional technical potentials are converted into cost segments, the country cost-supply curve is summarized by a local elasticity, that elasticity is mapped into the CES curvature in Equation (C.14), and country-specific projection ratios shift effective renewable generation capacity over time.

Data and cost segments.—The underlying resource data are the European Commission Joint Research Centre's integrated ENSPRESO data for 2030, which provide potential capacity and annual generation at the NUTS 2 level (European Commission, Joint Research Centre, 2021; Ruiz et al., 2019). We retain onshore and offshore wind, ground-mounted solar PV, and rooftop solar PV. For technology k in regional segment

a of country r, let $\overline{K}_{ark}$ denote potential capacity in GW and $\overline{G}_{ark}$ potential annual generation in TWh. The implied capacity factor is

$$\text{(D.4)} \qquad \mathrm{CF}_{ark} = \frac{\overline{G}_{ark}}{8.76\,\overline{K}_{ark}}.$$

The factor 8.76 converts one GW operated for one year into TWh. We translate resource quality into a levelized-cost proxy using technology-specific investment cost I_k, annual fixed operating cost F_k, real discount rate d_k, and lifetime N_k. With

$$\text{(D.5)} \qquad \mathrm{CRF}_k = \frac{d_k(1+d_k)^{N_k}}{(1+d_k)^{N_k}-1}, \qquad c_{ark} = \frac{I_k\,\mathrm{CRF}_k + F_k}{8.76\ \mathrm{CF}_{ark}},$$

c_{ark} is measured in EUR per MWh when investment and operating costs are expressed per kW. The workbook uses $(I_k, F_k, d_k, N_k) = (1600, 35, 0.04, 30)$ for onshore wind, $(800, 13.3, 0.035, 30)$ for ground-mounted PV, and $(1250, 21.5, 0.035, 30)$ for rooftop PV. These choices lie within the technology-cost ranges reported by Kost et al. (2024) and Lazard (2024). Holding technology costs common across countries makes spatial cost differences reflect ENSPRESO's variation in resource quality rather than country-specific financing or permitting conditions.

COST-SUPPLY ELASTICITY.—Ordering the segments by c_{ark} produces the cumulative country supply schedule

$$\text{(D.6)} \qquad Q_r(p) = \sum_{a,k} \overline{G}_{ark}\,\mathbf{1}\{c_{ark} \le p\}\,, \qquad \overline{Q}_r = \sum_{a,k} \overline{G}_{ark},$$

where p is the electricity price required to cover a segment's levelized cost. Let p_r^{25}, p_r^{50}, and p_r^{75} be the generation-weighted cost quartiles, so that the corresponding cumulative quantities equal 25, 50, and 75 percent of $\overline{Q}_r$. Because the empirical schedule is stepwise, we approximate its central portion by

$$\text{(D.7)} \qquad \widetilde{Q}_r(p) = \frac{\overline{Q}_r}{1+\exp[-\kappa_r(p-p_r^{50})]}.$$

Matching the first and third quartiles gives $\kappa_r = 2\ln(3)/(p_r^{75} - p_r^{25})$. The price elasticity at the midpoint is therefore

$$\text{(D.8)} \qquad \eta_r^{\text{ren}} \equiv \left.\frac{\partial \ln \widetilde{Q}_r(p)}{\partial \ln p}\right|_{p=p_r^{50}} = \frac{p_r^{50}\ln(3)}{p_r^{75} - p_r^{25}}.$$

This object is a parsimonious long-run slope of the country cost-supply curve around its median potential, not an econometric short-run response of observed generation. Large values arise when substantial potential is concentrated in a narrow cost interval. The estimates should therefore be interpreted as calibration moments for resource availability; they abstract from grid expansion, system-balancing costs, permitting delays, and endogenous changes in technology costs.

For the model's wind-and-solar technology, this construction supplies the country-specific moment $\eta_{sr} = \eta_r^{\text{ren}}$. It does not by itself determine the CES elasticity: the mapping also requires the benchmark value share of the fixed renewable resource.

MAPPING INTO THE CES TECHNOLOGY.—To derive Equation (C.14), suppress time indices and write the technology-specific production function in Equation (C.13) as

$$Y_{sr} = [\theta_{sr} R_{sr}^{\rho_{sr}} + (1-\theta_{sr}) X_{sr}^{\rho_{sr}}]^{1/\rho_{sr}}, \qquad \rho_{sr} = \frac{\lambda_{sr}-1}{\lambda_{sr}}, \tag{D.9}$$

where R_{sr} is the technology-specific resource in fixed supply and X_{sr} is the variable non-resource input composite. A competitive producer chooses X_{sr} given output price p_{sr}^Y and input price p_{sr}^X. Its first-order condition is

$$p_{sr}^X = p_{sr}^Y (1-\theta_{sr}) X_{sr}^{\rho_{sr}-1} Y_{sr}^{1-\rho_{sr}}. \tag{D.10}$$

The non-resource revenue share is $s_{sr}^X = p_{sr}^X X_{sr}/(p_{sr}^Y Y_{sr}) = \partial \ln Y_{sr}/\partial \ln X_{sr}$ and, under the benchmark normalization, equals $1-\theta_{sr}$. Differentiating (D.10) with respect to $\ln p_{sr}^Y$ while holding p_{sr}^X and R_{sr} fixed gives

$$0 = 1 + (\rho_{sr}-1)\frac{\partial \ln X_{sr}}{\partial \ln p_{sr}^Y} + (1-\rho_{sr})\eta_{sr}. \tag{D.11}$$

Because $\eta_{sr} = s_{sr}^X \, \partial \ln X_{sr}/\partial \ln p_{sr}^Y$ and $1-\rho_{sr} = 1/\lambda_{sr}$, Equation (D.11) implies

$$\eta_{sr} = \lambda_{sr}\frac{s_{sr}^X}{1-s_{sr}^X} = \lambda_{sr}\frac{1-\theta_{sr}}{\theta_{sr}}, \qquad \Longleftrightarrow \qquad \lambda_{sr} = \eta_{sr}\frac{\theta_{sr}}{1-\theta_{sr}}, \tag{D.12}$$

which is Equation (C.14). The fixed resource is essential: if both inputs could expand freely under constant returns, competitive supply would be perfectly elastic at unit cost and no finite supply elasticity could discipline λ_{sr}. With R_{sr} fixed within a model period, production has decreasing returns in the variable composite and the constructed η_r^{ren} identifies the local CES curvature conditional on the benchmark resource value share θ_{sr}. The mapping is local because that value share changes as the economy moves away from the benchmark.

PROJECTED CAPACITY PATH.—We allow wind-and-solar generation capacity to expand over time using country-specific projection ratios normalized to one in 2025. The paths are a synthetic calibration rather than a forecast taken from a single source. We construct them to lie within central ranges from the European Commission's PRIMES-based EU Reference and Fit for 55 scenarios and its REPowerEU update, the national deployment envelopes in ENTSO-E and ENTSOG's Ten-Year Network Development Plan scenarios, and the International Energy Agency's Net Zero Emissions pathway (European Commission, 2021a,b, 2022; European Network of Transmission System Operators for Electricity and European Network of Transmission System Operators for Gas, 2025; International Energy Agency, 2021). The aggregate EU path reaches approximately 1.6 times its 2025 level in 2030, 2.3 times in 2040, and 2.7–3.0 times in 2050. Country paths reflect initial renewable penetration, coal-phaseout pressure, and access to offshore wind resources.

Let g_{rt}^{ren} denote the resulting projection ratio for country r in period t, with $g_{r,2025}^{\text{ren}} = 1$. Under approximately stable average capacity factors, projected generation growth provides a proportional measure of growth in effective generation capacity. We represent this expansion by

$$\overline{R}_{srt} = g_{rt}^{\text{ren}} \overline{R}_{sr,2025}, \qquad s = \textit{wind \& solar}. \tag{D.13}$$

The projection path therefore shifts each country's renewable supply schedule between periods, while η_r^{ren} and the corresponding λ_{sr} determine endogenous movement along that schedule as electricity prices change. We impose the same capacity path across all market architectures; renewable generation remains endogenous and can depart from the projected path in response to policy and general-equilibrium adjustment.

Figure D.1 places the observed 2023 generation mix alongside the model-simulated 2048 mixes without climate policy and under effective ETS2. The no-policy outcome shows the transition generated by the common capacity and economic reference paths, while effective ETS2 adds the response to carbon constraints. The 2048 mix is broadly similar across the four policy architectures studied in Section IV; we therefore report only effective ETS2 rather than add four largely repetitive policy columns. Wind and solar provide the majority of aggregate EU generation by 2048, but country mixes remain markedly heterogeneous. The capacity path thus shifts renewable supply opportunities without imposing either a common country mix or a fixed generation outcome.

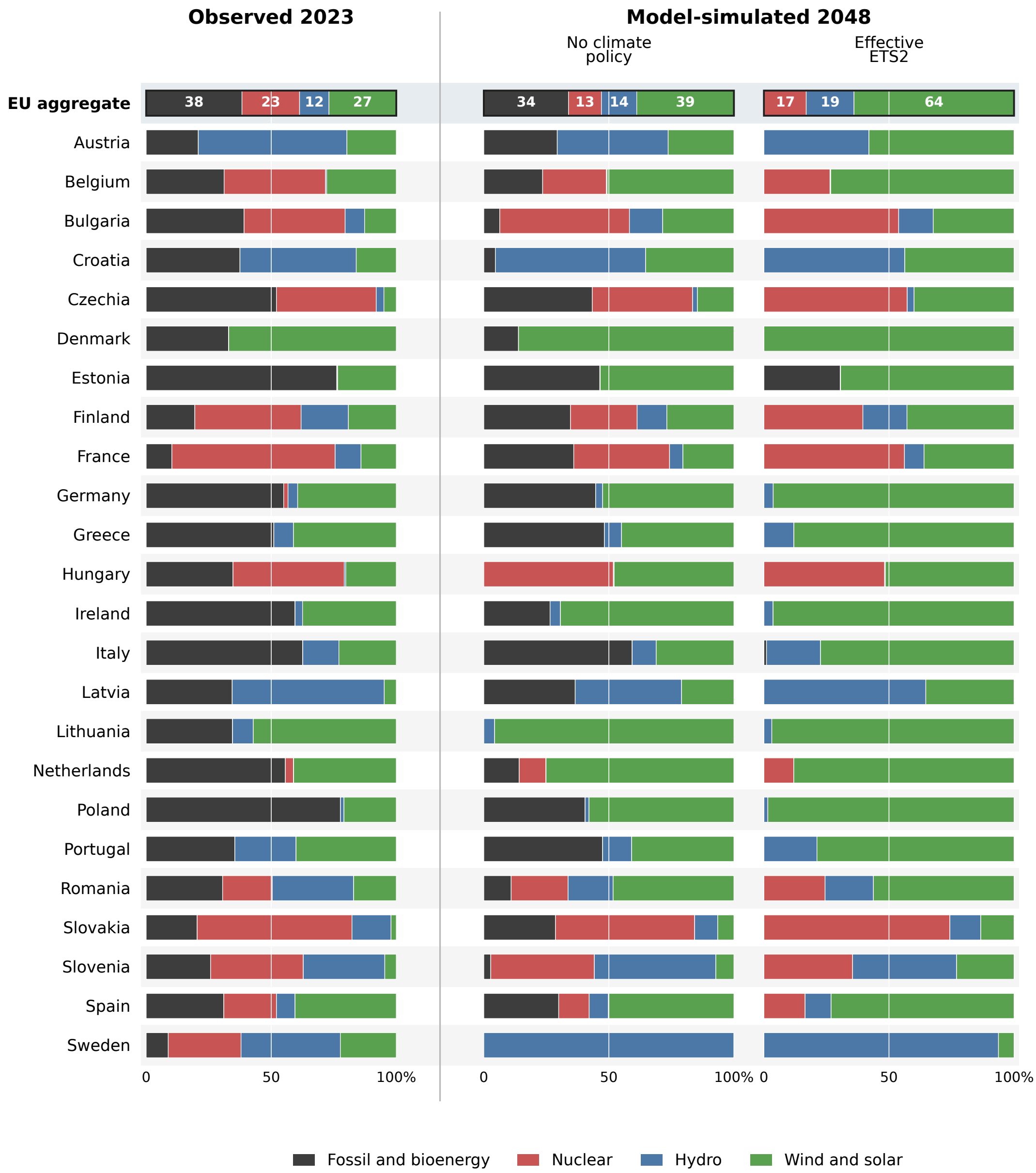
Appendix D5: Household heating and mobility technology shares

The GTAP household energy accounts do not identify the four technologies in equation (C.2). We therefore draw on additional data to allocate benchmark household expenditure on gas, coal, oil, and electricity to fossil heating, electric heating, ICE mobility, and EV mobility.

The country oil allocations combine Eurostat household end-use and energy-balance data, updated National Energy and Climate Plans (European Commission, 2024c), and ODYSSEE-MURE indicators (Eurostat, 2025, 2026; ODYSSEE-MURE, 2026). The electricity allocations combine Eurostat end-use data with information on electric mobility from the European Alternative Fuels Observatory, heat-pump markets from the European Heat Pump Association (European Heat Pump Association, 2024), and the technology-level energy accounts in JRC-IDEES (Eurostat, 2025; European Commission, 2026; European Commission, Joint Research Centre, 2026). These sources are harmonized into country-specific end-use allocation shares rather than treated as a single directly observed equipment-stock dataset. In particular, the electric-heating branch is represented by the model's heat-pump technology, but its benchmark energy value measures electricity-based heating services; the EV branch likewise measures electricity allocated to electric mobility rather than the number of vehicles.

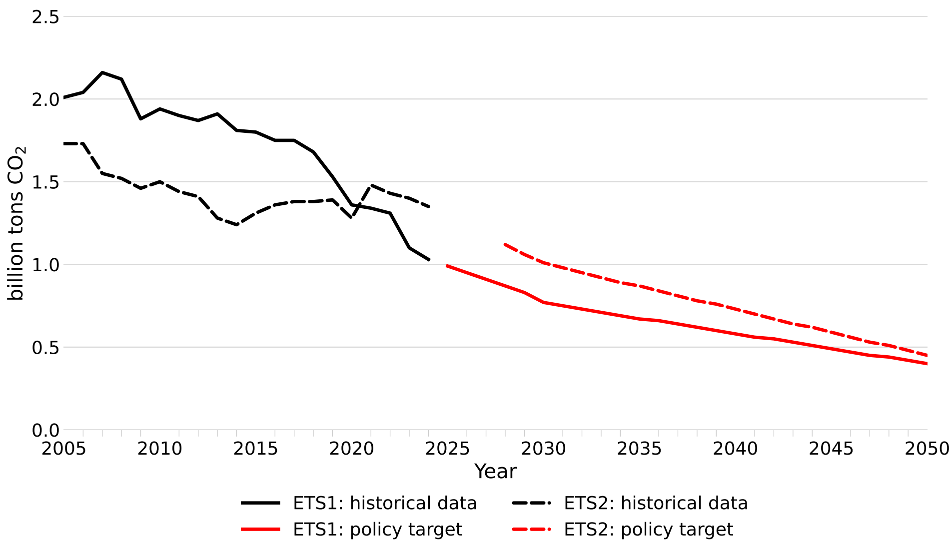
At the benchmark, these parameters make household demand reproduce the constructed country-specific fossil–electric heating and ICE–EV output-value shares

Figure D.1. **Observed and model-simulated electricity-generation mix**



Notes: Each bar decomposes domestic electricity generation into four technology shares and sums to 100 percent. The first column reports observed generation in 2023 from the Our World in Data electricity-production-by-source series (Global Change Data Lab, 2024). Wind and solar includes wind, solar, and other renewables excluding bioenergy; fossil and bioenergy corresponds to the model's residual thermal technology. The 2048 columns report WEDGE simulations. The no-policy scenario omits carbon constraints; effective ETS2 activates cross-country exchange and allowance-price steering for ETS2 emissions. Effective ETS2 is shown as representative because the 2048 electricity mix is broadly similar across the four policy architectures analyzed in the paper. The EU aggregate is calculated from total generation across the represented countries.

Figure D.2. **Historical emissions and policy-target paths for ETS1 and ETS2**



Notes: Historical annual CO_2 emissions are from the European Environment Agency (Agency, 2024). Target paths through 2030 draw on member-state projections with existing and additional measures reported under the EU Governance Regulation (European Parliament and Council of the European Union, 2018; European Environment Agency, 2025b; European Commission, Directorate-General for Climate Action, 2025). Post-2030 paths are consistent with the EU climate-neutrality trajectory and 2040 intermediate target (European Parliament and Council of the European Union, 2026).

exactly. Table D.1 reports their cross-country ranges. The substitution elasticities σ_h and σ_m then govern movement away from those benchmark shares.

Appendix D6: Reference path and emissions targets

The 2017 accounts provide the structural benchmark. We forward-calibrate each country to 2028 using observed real-GDP growth through 2025 and the 2025 growth rate for 2026–27 (Eurostat, 2026c). From 2028 onward, WEDGE is solved recursively at five-year intervals through 2048. Effective-labor growth combines country-specific population projections from Eurostat (2024) with annual labor-productivity growth of 1.07 percent based on European Central Bank (2024). This yields average EU real-GDP growth of approximately 1.6 percent per year in the no-policy path, close to the 1996–2024 historical average (Eurostat, 2026c). Investment updates physical capital, and directed research updates knowledge embodied in household mobility and heating technologies. Exogenous demographic and productivity paths are common across market architectures; investment, technology, and trade respond endogenously.

Figure D.2 reports the climate-policy paths. Historical emissions and adopted 2030 targets anchor ETS1 and ESR–ETS2 scarcity through 2030. The later path is consistent with the EU climate-neutrality trajectory and 2040 intermediate target. All institutional counterfactuals use the same partition-specific target path, so welfare comparisons vary market architecture rather than climate ambition.

Appendix D7: National technology-mix requirements

We represent the modeled national measures as country- and time-specific minimum clean-technology shares in household heating and mobility. The mobility path combines Eurostat passenger-car-stock data with member states' updated National Energy and Climate Plans and the Commission reference-scenario update. The heating path combines Eurostat renewable-energy indicators for heating and cooling with national plans and European Heat Pump Association market reports (Eurostat, 2026b,a; European Commission, 2024c,a; European Heat Pump Association, 2024). Electric-vehicle stock shares are mapped into mobility-service shares under equal utilization across drivetrains; heat-pump shares are expressed as shares of heating services.

Figure D.3 shows the resulting inputs. In 2028, mobility requirements range from 4.8 to 35.7 percent and heating requirements from 8.3 to 67.3 percent across represented member states. By 2048, the corresponding ranges are 80.0–98.4 percent and 73.0–98.4 percent. The common upward movement captures the tightening of national policy portfolios, while the cross-country variation determines where the requirements bind and how strongly they displace adjustment directed by the ETS2 price.

The model implements each requirement through a certificate market. Clean heating and mobility technologies produce one certificate per unit of service output, while total service output must surrender certificates at the prescribed country-year rate. Market clearing imposes that rate as a minimum clean share, and the certificate price is the shadow value of the requirement. This representation summarizes the direction and stringency of the modeled policy portfolio; it neither reproduces each underlying instrument nor values benefits from correcting market failures outside the model.

Appendix D8: Emissions budgets and carbon-rent entitlements

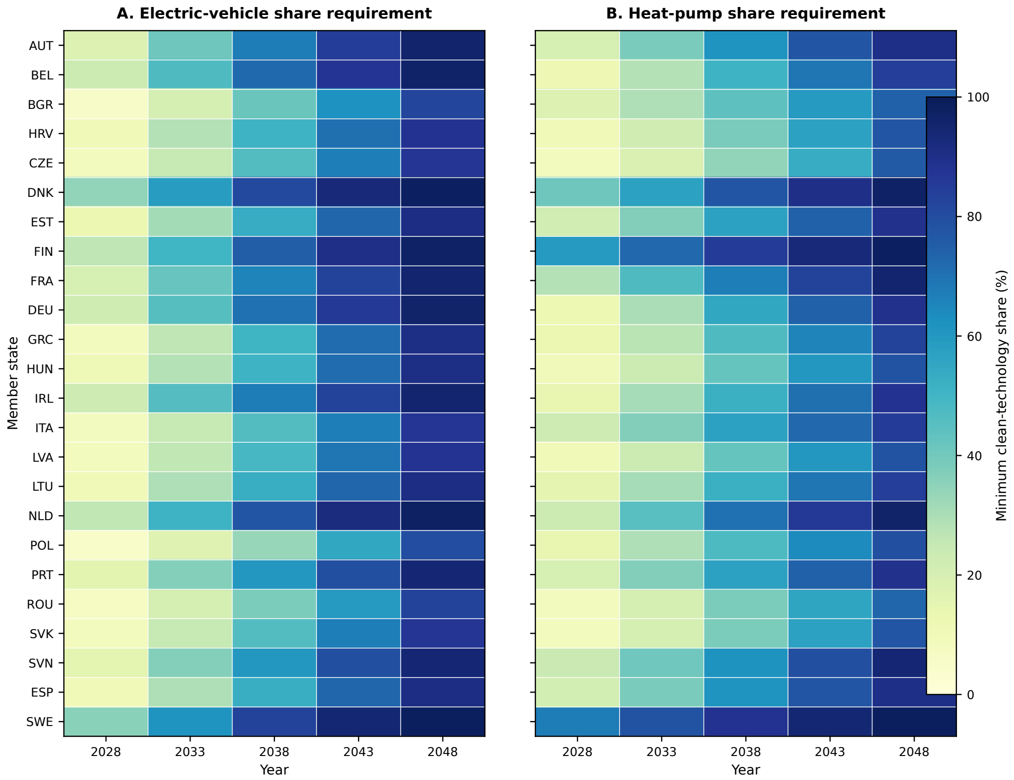
Carbon budgets and rent entitlements are distinct calibration objects. Legally adopted 2030 reductions anchor country ESR targets, while national ESR budget endowments determine the fragmented scarcity positions represented by ϕ_r in Equation (12). ETS1 and ETS2 revenue shares determine ξ_r and π_r, respectively, and allocate auction receipts independently of where emissions occur. Table D.3 reports these objects. The ETS2 entitlement combines the maintained 75 percent ETS2 allocation with the 25 percent Social Climate Fund component used throughout the counterfactuals.

This separation is material for the incidence analysis. National budget shares govern scarcity and the location of abatement when ESR compliance is fragmented; revenue shares govern who receives the value created by the allowance markets. The counterfactuals vary exchange and allocation authority while keeping the aggregate emissions trajectory and these revenue rules fixed.

Appendix D9: Equilibrium computation

WEDGE is formulated as a mixed complementarity problem in which activity levels satisfy zero-profit conditions, prices clear commodity and factor markets, and carbon

Figure D.3. **National clean-technology share requirements**



Notes: Panel A reports the minimum share of electric vehicles in household mobility-service output; Panel B reports the minimum heat-pump share in household heating-service output. Rows are individually represented EU member states. The paths combine Eurostat observations with updated National Energy and Climate Plans, the European Commission reference-scenario update, and European Heat Pump Association market information (Eurostat, 2026b,a; European Commission, 2024c,a; European Heat Pump Association, 2024). The requirements apply in architectures with national measures and are relaxed in the allocation-authority counterfactuals.

prices and certificate values satisfy the relevant policy constraints and complementary slackness (Mathiesen, 1985); see also Rutherford (1995). This formulation permits carbon prices to equal zero when national budgets or aggregate caps are slack. We implement the model in the General Algebraic Modeling System using MPSGE (Rutherford, 1999) and compute equilibria with the PATH solver (Dirkse and Ferris, 1995).

Table D.3. **National ESR targets, budget endowments, and carbon-revenue shares**

Member state	2030 ESR target reduction from 2005 (%)	ESR budget endowment share (%)	ETS1 revenue entitlement (%)	ETS2–SCF revenue entitlement (%)
Austria	48	2.0	1.6	1.9
Belgium	47	2.9	2.6	3.1
Bulgaria	10	1.6	2.7	1.9
Croatia	17	1.0	0.5	1.0
Czechia	26	3.2	5.1	2.7
Denmark	50	1.4	1.4	1.2
Estonia	24	0.3	0.9	0.3
Finland	50	1.2	1.9	1.2
France	48	14.1	6.2	14.6
Germany	50	16.1	22.6	17.3
Greece	23	3.3	3.9	2.9
Hungary	19	2.5	1.5	2.5
Ireland	42	1.8	1.1	1.8
Italy	44	12.8	10.7	12.0
Latvia	17	0.5	0.2	0.5
Lithuania	21	0.6	0.4	0.7
Netherlands	48	4.3	3.8	3.7
Poland	18	10.2	13.2	11.4
Portugal	29	2.3	2.0	1.9
Romania	13	4.7	4.8	4.9
Slovakia	23	1.2	1.6	1.3
Slovenia	27	0.6	0.5	0.5
Spain	38	10.1	9.7	9.4
Sweden	50	1.4	0.9	1.2
EU aggregate	40	100.0	100.0	100.0

Notes: The first numeric column reports legally adopted 2030 ESR reductions relative to 2005; the EU aggregate target is 40 percent (European Commission, 2023a). The next column reports each represented member state's share of the aggregate national emissions-budget endowment used in the model. The ETS1 column reports auction-revenue entitlements. The final column is the maintained ETS2 revenue architecture used in the counterfactuals: 75 percent of receipts follow the ETS2 allocation shares and 25 percent follow Social Climate Fund shares. Budget endowments govern national scarcity under fragmented ESR compliance; revenue entitlements govern the distribution of carbon rents.

Appendix E. Emissions Reallocation Accounting

Appendix E1: Quantity accounting

This appendix defines the quantity measures in Table 3. Let E^c_{krt} denote realized ETS2 emissions from covered use k, country r, year t, and counterfactual cell $c \in \{00, 10, 01, 11\}$. The first digit indicates exchange and the second allocation authority. Covered uses form an exact partition, $k \in \{H, O\}$, where H is household direct fuel use for heating and private mobility and O comprises all other ETS2-covered uses. Hence

$$E^c_{rt} = \sum_k E^c_{krt}, \qquad E^c_t = \sum_r E^c_{rt}.$$

Every cell faces the same target trajectory, but realized emissions can fall below the target when fragmented constraints induce overcompliance.

For a comparison from cell c to c', cross-country reallocation is the total variation between the two country emissions-share distributions,

$$D^{c \to c'}_t = 50 \sum_r \left| \frac{E^{c'}_{rt}}{E^{c'}_t} - \frac{E^c_{rt}}{E^c_t} \right|.$$

It is the percentage of realized emissions that would have to be reassigned across countries to transform one normalized distribution into the other. Normalizing each architecture by its own realized total separates spatial reallocation from aggregate budget utilization.

The change for covered use k is

$$Q^{c \to c'}_{kt} = 100 \frac{\sum_r (E^{c'}_{krt} - E^c_{krt})}{E^{11}_t},$$

and the aggregate change satisfies the exact identity

$$G^{c \to c'}_t := 100 \frac{E^{c'}_t - E^c_t}{E^{11}_t} = \sum_k Q^{c \to c'}_{kt}.$$

Positive values indicate higher realized emissions after the market function is activated. Table 3 averages $00 \to 10$ and $01 \to 11$ for exchange and $00 \to 01$ and $10 \to 11$ for allocation authority; the effective-market total is $00 \to 11$. The two averaged function effects add exactly to the effective-market total for each signed quantity change. The spatial measure D is non-additive because it is a distance between normalized distributions.

Appendix F. Country Incidence Accounting

This appendix formalizes the country welfare contributions and mechanism measures used in Figures 9–11. It first defines the institutional attribution of country welfare, then constructs the allocative measures for exchange and allocation authority, and finally records the exact accounting for net ETS2 rents.

Appendix F1: Counterfactual cells and welfare attribution

Let $c \in \{00, 10, 01, 11\}$ index the counterfactual cells. The first digit indicates exchange and the second allocation authority; one denotes an active market function. Let V_{rt}^c be country r's equivalent variation in year t under cell c. The Shapley contributions of exchange and allocation authority are

$$S_{rt}^E = \frac{1}{2}\left[\left(V_{rt}^{10} - V_{rt}^{00}\right) + \left(V_{rt}^{11} - V_{rt}^{01}\right)\right], \tag{F.1}$$

$$S_{rt}^A = \frac{1}{2}\left[\left(V_{rt}^{01} - V_{rt}^{00}\right) + \left(V_{rt}^{11} - V_{rt}^{10}\right)\right]. \tag{F.2}$$

Each contribution averages the function's welfare effect over its two possible activation orders, and $S_{rt}^E + S_{rt}^A = V_{rt}^{11} - V_{rt}^{00}$.

Let R_{rt}^c denote country receipts from ETS2 auctions and the Social Climate Fund under the maintained revenue rule, $\tau_{t,c}^{ETS2}$ the allowance price, and E_{rt}^c ETS2 emissions originating in the country. Net ETS2 rents are

$$N_{rt}^c = R_{rt}^c - \tau_{t,c}^{ETS2} E_{rt}^c. \tag{F.3}$$

Applying Equations (F.1) and (F.2) to N_{rt}^c gives the corresponding rent contributions $S_{N,rt}^E$ and $S_{N,rt}^A$. The filled circles in Figure 10 report $S_{rt}^E - S_{N,rt}^E$ and $S_{rt}^A - S_{N,rt}^A$. Subtracting the exact rent contribution isolates the part of country incidence that can be compared with the allocative mechanism measures below; it does not remove other general-equilibrium responses.

All annual objects are converted to the common present-value scale used in the paper. If $\mathrm{PV}(x_r)$ applies the paper's discount weights to a country sequence and $\mathcal{A} := \mathrm{PV}(1)$ is the corresponding annuity factor, the reported income-equivalent measure is

$$\widetilde{x}_r = 100 \frac{\mathrm{PV}(x_r)}{\bar{Y}_r \mathcal{A}}, \tag{F.4}$$

where $\bar{Y}_r$ is baseline country income.

Appendix F2: Exchange-induced emissions reallocation

The open circles in Figure 10, Panel A, value the country emissions change induced by exchange. Their economic basis follows from the stylized model. Let $\mathcal{E}_r$ be the quantity of ETS2 emissions occurring in country r and define the local allocative-surplus value function

$$\widehat{W}_r(\mathcal{E}_r, \bar{\gamma}_r) := \max_{\{q_{ir}, e_{ir}\}_{i\in\mathcal{I}}} W_r \quad \text{subject to} \quad \sum_{i\in\mathcal{B}} e_{ir} \leq \mathcal{E}_r, \qquad e_{ir} \leq \bar{\gamma}_{ir} q_{ir} \quad \forall i \in \mathcal{B},$$

where W_r is defined in Equation (1). If κ_r is the multiplier on the country emissions quantity, the envelope theorem and firm optimality in Equation (6) imply

$$m_r := \frac{\partial \widehat{W}_r}{\partial \mathcal{E}_r} = \kappa_r = MAC_{ir}(q_{ir}, e_{ir}) - \mu_{ir} = P_{ir}, \qquad i \in \mathcal{B}. \tag{F.5}$$

The residual marginal abatement cost m_r is therefore the marginal real-surplus value of allowing one additional emissions unit after national technology-mix requirements have shaped domestic adjustment. In the quantitative model it is measured by the combined ETS2 and ESR scarcity value applying to ETS2-covered emissions.

For country r and year t, the finite-change measure is

$$X^E_{rt} = \frac{1}{4} \sum_{(c,c')\in\{(00,10),(01,11)\}} \left(m^c_{rt} + m^{c'}_{rt}\right) \left(E^{c'}_{rt} - E^c_{rt}\right). \tag{F.6}$$

Within each activation path, Equation (F.6) values the emissions change at the mean residual marginal abatement cost of the two endpoints; the expression then averages over the two exchange paths. A positive value means that exchange assigns the country more emissions and relieves it of abatement valued highly at the margin. When EU-wide realized emissions are unchanged, the measure captures only spatial reallocation; when exchange reduces overcompliance, it also includes the value of greater budget utilization. Figure 10, Panel A, compares $\widetilde{X}^E_r$ with the net-of-rent welfare contribution $(\widetilde{S^E_r - S^E_{N,r}})$.

Equation (F.6) is a mechanism measure rather than an exact welfare decomposition. The open circle values the direct change in a country's abatement burden, whereas the filled-circle welfare contribution also contains production, consumption, trade, factor-income, and other equilibrium responses. The connecting segment records the numerical gap between these two objects; it is not itself a separate welfare component.

Appendix F3: National technology-mix requirements

The second term in the local envelope condition is

$$\mathrm{d}\widehat{W}_r = m_r \,\mathrm{d}\mathcal{E}_r + \sum_{i\in\mathcal{B}} \mu_{ir} q_{ir} \,\mathrm{d}\bar{\gamma}_{ir}. \tag{F.7}$$

It values a relaxation of a binding technology-mix requirement by the requirement's shadow value and the activity to which it applies. The quantitative model implements these requirements as minimum clean-technology shares for heating and mobility. Let μ^c_{krt} denote the certificate shadow value, Q^c_{krt} energy-service output, and h^c_{krt} the required clean share for service $k \in \{H, M\}$. The first-order value of the requirements at the constrained endpoint is $\mu^c_{krt} Q^c_{krt} h^c_{krt}$.

Panel B uses

$$X^A_{rt} = \frac{1}{2} \sum_{c \in \{00,10\}} \sum_{k \in \{H,M\}} \mu^c_{krt} Q^c_{krt} h^c_{krt}. \tag{F.8}$$

Cells 00 and 10 are the constrained endpoints of the two allocation-authority paths. Equation (F.8) sums the shadow-value-weighted exposure across heating and mobility and averages it over those paths. Larger values indicate requirements that are more costly at the margin, govern larger service quantities, or both. Figure 10, Panel B, compares $\widetilde{X}^A_r$ with $(S^A_r - S^A_{N,r})$.

As in Panel A, the open circle is a first-order mechanism measure. The filled-circle Shapley contribution is a finite, full-equilibrium welfare change, so the comparison tests whether exposure to binding requirements is systematically associated with allocation-authority gains rather than imposing an exact decomposition. The connecting segment again records the gap between the two measures rather than an additional incidence channel.

Appendix F4: Net ETS2 rent accounting

Figure 11 compares effective ETS2 with legal market creation only. Define

$$\Delta N_r = \mathrm{PV}\left(N^{11}_{rt} - N^{00}_{rt}\right), \qquad \Delta V^{\mathrm{net}}_r = \mathrm{PV}\left(V^{11}_{rt} - V^{00}_{rt}\right) - \Delta N_r. \tag{F.9}$$

The figure plots the income-equivalent versions of total welfare and $\Delta V^{\mathrm{net}}_r$ on a common scale. Their signed distance is the architecture-to-architecture change in the country's net ETS2 rent position. The net-of-rent point is an accounting residual, not the outcome of a separately simulated revenue architecture.

Country entitlements exhaust ETS2 auction revenues and the allowance market clears, so $\sum_r N^c_{rt} = 0$ in every cell and year. Consequently, $\sum_r \Delta N_r = 0$: changes in net ETS2 rents redistribute the country welfare effects of market completion but do not alter aggregate welfare.

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