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Beyond Recycling Volumes: A Life-Cycle Material-Flow Model of Circular Economy Policy Mixes

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Abstract

Circular economy policies increasingly seek to coordinate upstream product design with downstream recycling, yet most assessments treat life-cycle material flows and macroeconomic adjustment separately. This paper develops a stylized life-cycle-oriented dynamic general-equilibrium model to examine how extended producer responsibility (EPR), recycling subsidies, and their combination affect material circularity, waste accumulation, and welfare. Life-cycle design quality is modeled as an endogenous decision that simultaneously reduces waste intensity and increases effective recyclability. Post-consumer material flows enter a recycling sector through a transaction-price rule and are converted into recycled material output under a bounded material-conversion technology. The framework is parameterized using plastic-packaging material-flow evidence and evaluated through policy shocks, permanent policy-regime comparisons, policy-region diagrams, and consumption-equivalent welfare analysis.

The results show that the two instruments operate through different life-cycle channels. Recycling subsidies mainly expand downstream recycling activity and recycled material output, whereas producer responsibility strengthens upstream design incentives and reduces unrecycled waste flows and the accumulated waste stock. The policy mix is not superadditive in recycled material output, but it generates positive design-quality interactions and additional waste-stock reductions mainly in source-reduction-oriented and balanced systems. Welfare results depend on waste-stock damage valuation. Under a conservative damage weight, the mix exhibits positive welfare interaction but negative absolute welfare; under a higher damage weight, the absolute welfare effect becomes positive throughout the grid. The contribution is to link life-cycle design incentives, material-flow constraints, circular economy policy mixes, and welfare evaluation in a common macro-dynamic framework.

Keywords: circular economy; industrial ecology; life-cycle management; extended producer responsibility; recycling subsidy; dynamic macroeconomic model

JEL classification: C61; C63; E32; Q53; Q56; Q58

1 Introduction

Circular economy policy is increasingly concerned with how product design, post-consumer material recovery, recycled material use, and residual waste accumulation interact across the product life cycle. From an industrial ecology perspective, this is a question about the stocks and flows of materials in production and consumption systems and about how policy instruments alter these flows over time. Plastic packaging, textiles, electronics, and other short-lived material systems illustrate this challenge. They generate large post-consumer waste flows, depend on both virgin and secondary materials, and are increasingly governed through combinations of eco-design requirements, extended producer responsibility, recycling subsidies, recycled-content rules, and waste-management policies (European Commission, 2025; OECD, 2022a, 2022b, 2024).

Life-cycle assessment, material-flow analysis, and circular economy studies have provided detailed evidence on material throughput, recycling losses, product design, and environmental burdens. These approaches are essential for identifying where circularity is technically feasible and where material losses occur. However, many policy questions also involve economy-wide feedbacks. Policies that affect design quality and recycling returns can change material substitution, sectoral resource allocation, investment, consumption, and welfare. A life-cycle policy that improves waste outcomes may therefore have different implications for recycled material output, macroeconomic adjustment, and social welfare. This paper addresses this gap by developing a stylized dynamic macroeconomic framework grounded in life-cycle material-flow logic rather than a process-based life-cycle assessment.

The research question is: how do extended producer responsibility, recycling subsidies, and their combination transmit through upstream life-cycle design and downstream recycling channels to affect recycled material output, waste accumulation, and welfare? This question matters for industrial ecology because circular economy performance cannot be inferred from a single recycling indicator. A policy may increase recycled output without improving design quality or reducing waste stocks. Conversely, source-reduction-oriented design may lower waste accumulation while shrinking the material base available for recycling. The model therefore evaluates multiple outcomes jointly: design quality, effective recycling flows, recycled material output, unrecycled waste flows, waste stocks, and consumption-equivalent welfare.

To address this question, the paper develops a life-cycle-oriented dynamic general-equilibrium framework. Final-goods firms endogenously choose life-cycle design quality q_t , which increases effective recyclability $\theta(q_t)$ and reduces unit waste intensity $\phi(q_t)$. A share $\theta_t W_t$ of gross waste flow W_t becomes a tradable effective recycling flow X_t , while the residual becomes the unrecycled waste flow N_t^w and accumulates into a waste stock

Z_t . The recycling sector purchases X_t at a transaction price linked to the marginal value of the flow and converts it into recycled material output according to $R_t = \rho_t X_t$, where $0 < \rho_t < \bar{\rho} < 1$. This structure closes upstream design, downstream recycling, and environmental stocks within a single dynamic system.

The contribution is fourfold. First, the paper embeds life-cycle material-flow relationships into a dynamic general-equilibrium framework. Product design quality is modeled as an endogenous decision that affects both waste intensity and effective recyclability, thereby linking upstream life-cycle management to downstream material recovery. Second, the model represents two policy instruments that operate at different stages of the product life cycle: recycling subsidies raise downstream recycling returns, while extended producer responsibility changes the private value of reducing unrecycled waste. Third, the paper introduces a bounded recycling-conversion technology and a reduced-form transaction-price link for effective recycling flows, which help maintain material-flow consistency while allowing recycling value to feed back to producers. Fourth, the analysis decomposes policy interaction across recycled material output, design quality, waste stock, and welfare. This decomposition shows why policy complementarity in circular economy systems is indicator-dependent and why recycling volumes alone are insufficient for evaluating life-cycle policy mixes.

The main results identify a division of policy roles rather than a universal policy ranking. Recycling subsidies primarily stimulate downstream recycled material output. Extended producer responsibility more directly improves design quality and reduces unrecycled waste flows and the waste stock. Their combination is not superadditive in recycled material output, but it can generate positive interactions in design quality and additional waste-stock reductions in source-reduction-oriented and balanced systems. Welfare results are conditional on the valuation of waste-stock damage. Under a conservative damage weight, the policy mix has positive welfare interaction but negative absolute consumption-equivalent welfare relative to no new policy. Under a higher damage weight, the absolute welfare effect becomes positive throughout the evaluated grid. These findings position the model as a macro-dynamic complement to industrial ecology tools, not as a replacement for detailed LCA or MFA.

The rest of the paper proceeds as follows. Section 2 reviews the related literature and clarifies the paper’s position. Section 3.1 presents the model. Section 3.2 summarizes the theoretical mechanisms and propositions. Section 3.3 discusses calibration. Section 4 reports the policy experiments and quantitative results. Section 5 discusses broader implications. Section 6 concludes.

2 Literature review

The analysis connects industrial ecology and life-cycle material-flow analysis with circular economy policy and environmental macroeconomics. To clarify the incremental contribution, the review is organized around four connections: industrial ecology and circular economy, policy instruments and life-cycle design incentives, environmental macroeconomic models, and the remaining bridge between these literatures.

2.1 Industrial ecology, life-cycle thinking, and circular economy

Industrial ecology and life-cycle research provide the main systems perspective for the paper. This literature examines material and energy flows across production and consumption systems, the environmental consequences of product systems, and the physical limits of closing material loops. Circular economy studies emphasize that resource use should move beyond a linear production-to-consumption-to-disposal model toward reduced throughput through reduction, reuse, repair, remanufacturing, recycling, and systemic design (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017; Lieder & Rashid, 2016; Stahel, 2016). Work on circular economy definitions and barriers also shows that policy and business practice can overemphasize recycling while neglecting reduction, product-life extension, and system-level change (Kirchherr et al., 2018; Vidal et al., 2024).

Life-cycle assessment, material-flow analysis, and recycling-technology studies discipline the material constraints in the model. Evidence for EU plastic packaging shows significant losses during collection, sorting, reprocessing, and export treatment, implying a gap between reported recycling rates and actual recycled material output (Antonopoulos et al., 2021). Assessments of closed-loop plastic recycling show that mechanical and solvent-based recycling are constrained by contamination, degradation, sorting, and reprocessing losses (Uekert et al., 2023). These findings motivate the model’s distinction between effective recycling flows and recycled material output, and they justify imposing a bounded conversion condition rather than treating post-consumer materials as losslessly transformed into secondary materials.

2.2 Circular economy policy instruments and life-cycle design incentives

Producer responsibility and eco-design studies show that crucial circular economy incentives often arise upstream in the product life cycle. Fullerton and Wu (1998) and Calcott and Walls (2005) demonstrate that deposit-refund systems, disposal taxes, re-

cycling subsidies, and producer responsibility can affect producers’ design choices. EPR shifts post-consumer disposal responsibility upstream, inducing firms to consider recycling, sorting, and disposal costs at the design and material-selection stages (European Commission, 2025; Lorang et al., 2022; OECD, 2024). Plastic-packaging policy increasingly combines recyclability design, recycled-content requirements, packaging reduction, and recycling-system development (Brown & Börkey, 2024; Ellen MacArthur Foundation, 2016, 2017).

This policy literature motivates the distinction between downstream recycling incentives and upstream design responsibility. Recycling subsidies raise the return to recycled material output and primarily target recovery and reprocessing conditions. EPR changes the private value of reducing unrecycled waste and therefore acts closer to the design stage. Partial-equilibrium studies can analyze marginal incentives and policy interactions, such as the complementarity between plastic-packaging recycling policies and EPR (Larrain et al., 2022). They generally offer less scope for aggregate price feedbacks, capital accumulation, material substitution, and welfare costs. The present paper keeps the life-cycle policy logic while embedding it in a dynamic macroeconomic setting.

2.3 Environmental macroeconomic and circular economy DSGE models

Environmental DSGE models provide tools for evaluating how environmental policy affects intertemporal resource allocation, capital accumulation, labor supply, prices, and welfare. This literature examines environmental taxes, emissions targets, emissions trading, carbon cycles, nominal rigidities, and policy mixes (Annicchiarico & Di Dio, 2015; Annicchiarico & Diluiso, 2019; Bovenberg & de Mooij, 1994; Fischer & Springborn, 2011; Golosov et al., 2014; Heutel, 2012; Roach, 2021). Recent E-DSGE applications also evaluate environmental taxes, carbon trading, renewable portfolio standards, industrial subsidies, and sectoral sustainability policies (Fan et al., 2023; Liu et al., 2024; Xiao et al., 2024).

A growing body of work introduces circular economy mechanisms into macroeconomic general-equilibrium and DSGE models. Examples include computable general-equilibrium analyses of circular economy innovation policy (Boonman et al., 2023), DSGE approaches to resource decoupling (Antosiewicz et al., 2016), regional waste-to-resource transitions (Zajac & Avdiushchenko, 2020), waste-recycling policies in an E-DSGE setting (Argentiero et al., 2022), and circularity in food-production DSGE models (Moustabchir et al., 2024). These studies show that circular economy mechanisms are entering macroeconomic modelling, but many models treat recycling rates, circular-technology adoption, or waste-to-resource conversion as exogenous or semi-exogenous processes rather than as

outcomes of endogenous life-cycle design choices.

2.4 Research gap and contribution to industrial ecology

Existing research therefore leaves an important connection underdeveloped. Industrial ecology and life-cycle studies provide detailed tools for measuring material flows, recycling losses, product design options, and environmental impacts, while environmental macroeconomic models provide tools for evaluating dynamic resource allocation, policy shocks, and welfare. The present paper connects these perspectives by embedding a stylized life-cycle material-flow structure into a dynamic general-equilibrium model. The purpose is not to replace process-based LCA, material-flow analysis, or sector-specific policy evaluation. Rather, the model provides a complementary framework for asking how life-cycle design incentives and recycling policies propagate through material flows, macroeconomic allocation, waste-stock accumulation, and welfare.

3 Methods

3.1 Model framework

This subsection presents a stylized life-cycle-oriented dynamic general-equilibrium model for circular economy policy analysis. The framework does not conduct a process-based life-cycle assessment. Instead, it translates core life-cycle management mechanisms into a macro-dynamic setting: design quality affects waste generation and recyclability, recyclable flows enter a recycling sector, recycled material re-enters production, and unrecycled residuals accumulate as an environmental stock. The design variable q_t is interpreted as a reduced-form index of upstream life-cycle design decisions, including lightweighting, material simplification, source reduction, recyclability-oriented design, and ease of sorting.

Time is discrete, $t = 0, 1, 2, \dots$. Unless otherwise stated, all variables are real. The baseline is a real dynamic general-equilibrium model that is closed in household, final-goods, and factor markets, while virgin material enters at an exogenous real resource cost. Exchange rates, monetary policy, and international trade are not modeled explicitly. The recycling subsidy is denoted by τ_t^R , while EPR or the liability cost on the unrecycled waste flow is denoted by τ_t^Z . The notation uses Λ_t for the final-goods firm's net private marginal value of one unit of output and Ω for lifetime welfare.

3.1.1 Agents and life-cycle structure

There are five core components. First, the representative household consumes the final good, supplies labor, and accumulates capital. Second, final-goods firms use capital, labor, and a material composite to produce final output and generate a tradable effective recycling flow X_t after consumption. Third, the material composite combines virgin material input V_t and recycled material output R_t . Fourth, the recycling sector pays price P_t^X for effective recycling flows and uses recycling capital K_t^R and recycling labor L_t^R to convert them into recycled material output. Fifth, the government uses recycling subsidies and EPR to affect downstream recycling returns, recycling-flow prices, and upstream design incentives. Institutionally, this formulation can be interpreted as a reduced-form EPR environment in which producers internalize, or are assigned residual claims over, post-consumer recycling flows.

Figure 1 illustrates the life-cycle transmission mechanism. Final output generates gross waste flow W_t . Life-cycle design quality q_t affects material circularity through two channels. It reduces waste intensity $\phi(q_t)$, lowering waste generation at the source, and raises effective recyclability $\theta(q_t)$, allowing a larger share of gross waste to become the tradable effective recycling flow X_t . The recycling sector purchases X_t and converts it into recycled material output R_t at the bounded conversion rate ρ_t . Its marginal value $\mathcal{M}_t$ determines the transaction price $P_t^X = \lambda_X \mathcal{M}_t$, which transmits downstream recycling value back to upstream design decisions. Recycled material output re-enters the material composite Mat_t and thereby supports final output. The unrecycled waste flow N_t^w accumulates into the waste stock Z_t . Social welfare depends on the macroeconomic allocation through consumption and labor and on environmental damage through Z_t . EPR liability τ_t^Z charges the unrecycled waste flow and thereby strengthens upstream design incentives, whereas the recycling subsidy τ_t^R raises downstream recycling returns.

The life-cycle material chain is summarized as follows. Final output Y_t generates gross waste flow W_t . Life-cycle design quality q_t raises the effective recyclability ratio θ_t and lowers waste intensity ϕ_t . A share $X_t = \theta_t W_t$ becomes the tradable effective recycling flow, while the remainder $N_t^w = (1 - \theta_t)W_t$ becomes the unrecycled waste flow and accumulates into Z_t . The recycling sector purchases X_t at the transaction price P_t^X and converts it into recycled material output under the material-conservation condition $R_t = \rho_t X_t < X_t$. Virgin material input and recycled material output jointly form Mat_t .

Throughout the paper, θ_t should be interpreted as an effective recyclability ratio. It maps gross waste flows into effective recycling flows that can enter the recycling sector rather than an official reported recycling rate.

Core variable definitions and code-level notation are reported in Supplementary Table S1.

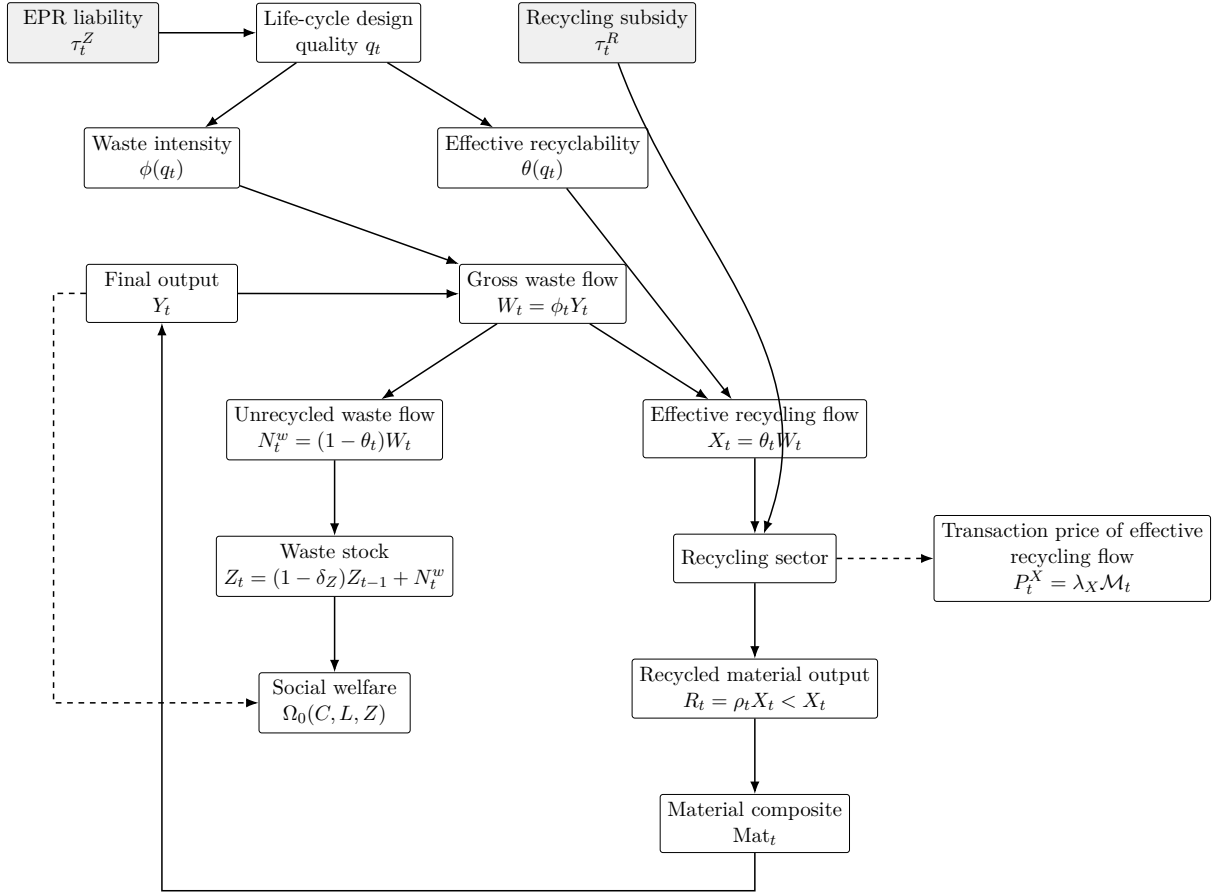


Figure 1: Life-cycle transmission mechanism linking upstream design, post-consumer material flows, recycled material output, waste accumulation, macroeconomic allocation, and welfare

3.1.2 Households

The representative household chooses consumption C_t , labor supply L_t , investment I_t , and the capital stock K_t . Period utility is separable in consumption, labor, and the environmental damage from the waste stock.

$$U(C_t, L_t, Z_t) = \log C_t - \chi \frac{L_t^{1+\nu}}{1+\nu} - \xi_Z Z_t, \quad (1)$$

where $\chi > 0$ is the weight on labor disutility, $\nu > 0$ governs labor-supply curvature, and $\xi_Z \geq 0$ measures the welfare damage of the waste stock. Because Z_t is an aggregate environmental state, households take it as given in the decentralized equilibrium. It affects welfare evaluation but not the private Euler or labor-supply conditions.

Capital evolves according to

$$K_t = (1 - \delta_K)K_{t-1} + I_t, \quad (2)$$

where $\delta_K \in (0, 1)$ is the capital depreciation rate. Combining the household budget constraint, firm profit rebates, and aggregate resource constraints yields the standard conditions

$$\frac{1}{C_t} = \beta E_t \left[\frac{1}{C_{t+1}} (r_{t+1} + 1 - \delta_K) \right], \quad (3)$$

$$\chi L_t^\nu = \frac{w_t}{C_t}. \quad (4)$$

Total capital and labor are allocated between final-goods production and recycling as follows.

$$K_{t-1} = K_t^Y + K_t^R, \quad (5)$$

$$L_t = L_t^Y + L_t^R. \quad (6)$$

3.1.3 Final-goods production and material inputs

Final-goods firms produce with capital, labor, and a material composite.

$$Y_t = A_t (K_t^Y)^\alpha (L_t^Y)^{1-\alpha-\mu} (\text{Mat}_t)^\mu, \quad (7)$$

where α is the capital share, μ is the material-input share, and $1 - \alpha - \mu$ is the labor share. The quantitative experiments set $A_t = A = 1$ and use policy shocks as the relevant disturbances.

The effective recycling flow X_t is treated as a tradable post-consumer material flow. After producing and selling final goods, final-goods firms generate gross waste flow W_t . A

share $\theta_t W_t$ enters the recycling system and is sold to recyclers as X_t . Let P_t^X denote the transaction price. In the baseline, this price is linked to the recycling sector's marginal value of the flow.

$$P_t^X = \lambda_X \mathcal{M}_t, \quad 0 \leq \lambda_X \leq 1, \quad (8)$$

where $\mathcal{M}_t$ is the marginal value of X_t in recycling and λ_X captures the share of this value transmitted to upstream firms. $\lambda_X = 1$ corresponds to frictionless value transmission. $0 < \lambda_X < 1$ captures sorting, quality certification, transportation, bargaining, and contractual frictions. $\lambda_X = 0$ is an extreme sensitivity case with no pass-through. Because X_t is generated by the life-cycle material-flow identity and is taken as available by the recycling sector, equation (8) is a reduced-form pricing rule rather than a Walrasian demand condition for X_t .

The net private marginal value of one unit of final output is

$$\Lambda_t = 1 - \tau_t^Z (1 - \theta_t) \phi_t + P_t^X \theta_t \phi_t. \quad (9)$$

The second term is the liability cost associated with the unrecycled waste flow, and the third term is revenue from selling the induced effective recycling flow. Given Λ_t , the firm's first-order conditions are

$$r_t = \Lambda_t \alpha \frac{Y_t}{K_t^\gamma}, \quad (10)$$

$$w_t = \Lambda_t (1 - \alpha - \mu) \frac{Y_t}{L_t^\gamma}, \quad (11)$$

$$P_t^M = \Lambda_t \mu \frac{Y_t}{\text{Mat}_t}. \quad (12)$$

The material composite is a CES aggregate of virgin and recycled materials.

$$\text{Mat}_t = \left[(1 - \omega) V_t^{\frac{\sigma-1}{\sigma}} + \omega R_t^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}}, \quad (13)$$

where $\omega \in (0, 1)$ is the recycled-material weight and $\sigma > 0$ is the elasticity of substitution. The material-demand conditions are

$$P^V = P_t^M (1 - \omega) \left(\frac{\text{Mat}_t}{V_t} \right)^{1/\sigma}, \quad (14)$$

$$P_t^R = P_t^M \omega \left(\frac{\text{Mat}_t}{R_t} \right)^{1/\sigma}. \quad (15)$$

3.1.4 Life-cycle design quality and life-cycle material flows

Life-cycle design quality is the central contemporaneous endogenous choice in the model. It affects two stages of the product life cycle by raising recyclability and lowering unit waste intensity. Since Y_t is measured in real final-goods units whereas W_t is a physical waste flow, the model introduces a conversion factor $\varpi_W > 0$ from real output to standardized material-service units. Waste intensity is

$$\phi_t \equiv \phi(q_t) = \varpi_W \phi_0 q_t^{-b}, \quad (16)$$

where $\phi_0 > 0$ is baseline waste intensity and $b > 0$ measures the source-reduction effect of design quality. Gross waste flow is

$$W_t = \phi_t Y_t. \quad (17)$$

In the baseline, ϖ_W is normalized to one and $\varpi_W \phi_0$ jointly matches the standardized material-flow moment $W/Y \simeq 0.30$.

Recyclability is bounded above according to

$$\theta_t \equiv \theta(q_t) = \bar{\theta} \frac{\kappa q_t^a}{1 + \kappa q_t^a}, \quad 0 < \theta_t < \bar{\theta} \leq 1, \quad (18)$$

where $\bar{\theta}$ is the technological upper bound, $a > 0$ measures the effect of design quality on recyclability, and $\kappa > 0$ is a scale parameter. To ensure $\theta(1) = \theta_0$,

$$\kappa = \frac{\theta_0}{\bar{\theta} - \theta_0}. \quad (19)$$

Effective recyclable and unrecycled waste flows are

$$X_t = \theta_t W_t, \quad (20)$$

$$N_t^w = (1 - \theta_t) W_t. \quad (21)$$

The elasticity of recyclability with respect to design quality is

$$\varepsilon_{q,t}^\theta = a \left(1 - \frac{\theta_t}{\bar{\theta}} \right). \quad (22)$$

Holding current output fixed, the marginal effect of design quality on effective recycling flows is

$$\frac{\partial X_t}{\partial q_t} = \frac{X_t}{q_t} [\varepsilon_{q,t}^\theta - b]. \quad (23)$$

Thus design improvements increase X_t only when the recyclability effect dominates the

source-reduction effect.

3.1.5 The recycling sector and recycled material production

The recycling sector purchases X_t and uses recycling capital and labor to improve the conversion rate. Material conservation is imposed through

$$R_t = \rho_t X_t, \quad 0 < \rho_t < \bar{\rho} < 1, \quad (24)$$

where $\bar{\rho}$ is the physical upper bound. This specification captures sorting, contamination, reprocessing, and quality-loss constraints and prevents capital and labor from amplifying material input without bound.

The conversion rate is determined by

$$\rho_t = \bar{\rho} \frac{S_t}{1 + S_t}, \quad S_t = A_R (K_t^R)^{\alpha_R} (L_t^R)^{\beta_R} X_t^{\eta-1}. \quad (25)$$

When $\alpha_R + \beta_R + \eta = 1$, S_t is homogeneous of degree zero in (K_t^R, L_t^R, X_t) , so the conversion rate depends on relative recycling-system intensity rather than scale alone.

The recycling subsidy enters as an increase in the effective sales revenue of recycled materials. $\tau_t^R = 1$ denotes no subsidy. $\tau_t^R > 1$ denotes an equivalent output subsidy. Recycling-sector profits are

$$\Pi_t^R = \tau_t^R P_t^R R_t - r_t K_t^R - w_t L_t^R - P_t^X X_t. \quad (26)$$

Given X_t , the recycling sector chooses K_t^R and L_t^R . The first-order conditions are

$$r_t = \tau_t^R P_t^R \bar{\rho} X_t \frac{\alpha_R S_t}{K_t^R (1 + S_t)^2}, \quad (27)$$

$$w_t = \tau_t^R P_t^R \bar{\rho} X_t \frac{\beta_R S_t}{L_t^R (1 + S_t)^2}. \quad (28)$$

The marginal value of effective recycling flows is

$$\mathcal{M}_t = \tau_t^R P_t^R \bar{\rho} \frac{S_t (S_t + \eta)}{(1 + S_t)^2}. \quad (29)$$

The parameter η is the recycling-flow elasticity parameter in the conversion index. It is not itself the unconditional elasticity of recycled material output with respect to X_t . Holding recycling capital and labor fixed, the corresponding local elasticity is

$$\frac{\partial \log R_t}{\partial \log X_t} = \frac{S_t + \eta}{1 + S_t}. \quad (30)$$

The transaction price is $P_t^X = \lambda_X \mathcal{M}_t$. This completes the pricing link between upstream producers and the recycling sector. The separate material-conservation condition $R_t = \rho_t X_t$ with $\rho_t < 1$ ensures that $R_t < X_t$.

3.1.6 Waste stock and environmental damage

The unrecycled waste flow accumulates into the waste stock according to

$$Z_t = (1 - \delta_Z)Z_{t-1} + N_t^w, \quad (31)$$

where $\delta_Z \in (0, 1)$ captures natural decay, treatment, or stock depreciation. Since Z_t enters utility, the unrecycled waste flow affects not only current environmental pressure but also long-run welfare. This distinction allows the model to separate recycled material output from environmental improvement. Source reduction may lower W_t , N_t^w , and Z_t while also reducing X_t and R_t .

3.1.7 Endogenous life-cycle design quality

Firms choose life-cycle design quality and incur the cost

$$\Gamma_t = \frac{\psi_q}{2}(q_t - q_0)^2, \quad (32)$$

where $\psi_q > 0$ is the design-cost parameter and q_0 is the reference level in the design-cost function rather than a policy-regime steady state. Define the marginal contribution of design quality to reducing the unrecycled waste flow as

$$D_t^q = \frac{Y_t \phi_t}{q_t} \left[\varepsilon_{q,t}^\theta \theta_t + b(1 - \theta_t) \right], \quad (33)$$

where $D_t^q = -\partial N_t^w / \partial q_t > 0$. The first-order condition for design quality is

$$\psi_q(q_t - q_0) = \tau_t^Z D_t^q + P_t^X \frac{X_t}{q_t} \left[\varepsilon_{q,t}^\theta - b \right]. \quad (34)$$

The left-hand side is the marginal cost of design improvement. The first term on the right-hand side is the benefit from lowering liability on the unrecycled waste flow. The second term is the marginal change in revenue from the effective recycling flow. Its sign depends on whether recyclability improvement dominates source reduction. This condition is the core of the model's complementarity mechanism.

3.1.8 Government policy instruments and shocks

The government uses two policy instruments. The recycling subsidy τ_t^R raises the effective revenue from recycled material output. EPR τ_t^Z raises the private liability cost of the unrecycled waste flow. Both instruments follow the following AR(1) processes around their steady-state values.

$$\ell_t^R = \rho_R \ell_{t-1}^R + \varepsilon_t^R, \quad \tau_t^R = \bar{\tau}^R \exp(\ell_t^R), \quad (35)$$

$$\ell_t^Z = \rho_Z \ell_{t-1}^Z + \varepsilon_t^Z, \quad \tau_t^Z = \bar{\tau}^Z \exp(\ell_t^Z). \quad (36)$$

The government budget is balanced through lump-sum taxes or transfers. Net taxes are

$$\text{Tax}_t = (\tau_t^R - 1)P_t^R R_t - \tau_t^Z N_t^w. \quad (37)$$

If $\text{Tax}_t > 0$, subsidy expenditures exceed EPR revenues and are financed through lump-sum taxation. If $\text{Tax}_t < 0$, EPR revenues exceed subsidies and are rebated lump-sum. Since this is a pure fiscal redistribution, it is not a direct resource cost in the aggregate resource constraint.

3.1.9 Resource constraint and decentralized equilibrium

The aggregate resource constraint is

$$Y_t = C_t + I_t + \Gamma_t + P^V V_t. \quad (38)$$

Payments for effective recycling flows are internal transactions between final-goods firms and recyclers and cancel in the aggregate. Subsidies, EPR revenues, and lump-sum taxes or transfers are fiscal redistributions.

Given initial K_{-1} and Z_{-1} and policy processes $\{\tau_t^R, \tau_t^Z\}$, a decentralized equilibrium with the reduced-form pass-through rule is a set of price sequences $\{w_t, r_t, P_t^M, P_t^R, P_t^X\}_{t=0}^\infty$ and quantity sequences for household choices, sectoral allocations, material flows, recycling, design quality, and waste stocks such that the household conditions, factor-market clearing, firm first-order conditions, material-flow equations, recycling-sector conditions, waste-stock dynamics, design condition, policy processes, and resource constraint all hold. Local stochastic dynamics are solved in Dynare using a second-order approximation with pruning, while permanent policy-regime comparisons are computed as deterministic steady states. The full equilibrium system, complementarity indicators, and welfare calculations are reported in Supplementary Section S1.

3.2 Theoretical mechanisms and propositions

This subsection summarizes the key mechanisms. The full system and derivations are in Supplementary Section S1. The propositions below summarize sign conditions and transmission channels; they are not global rankings of policy strength. The mechanism operates through design quality q_t , design orientation $d = a - b$, and policy complementarity. Design quality simultaneously affects recyclability $\theta(q_t)$ and waste intensity $\phi(q_t)$. Consequently, the same design improvement may increase effective recycling flows or reduce the material base available to recyclers through source reduction.

3.2.1 Life-cycle material flows and life-cycle design quality

Gross waste flow is $W_t = \varpi_W \phi_0 q_t^{-b} Y_t$ and effective recycling flow is $X_t = \theta(q_t) W_t$. Holding output fixed,

$$\frac{\partial \log X_t}{\partial \log q_t} = \varepsilon_{q,t}^{\theta} - b. \quad (39)$$

When $\varepsilon_{q,t}^{\theta} > b$, design improvement expands effective recycling flows. When $\varepsilon_{q,t}^{\theta} < b$, design improvement mainly reduces waste at the source and may shrink the material base for recycling.

Proposition 1. Design quality affects effective recycling flows through the life-cycle design orientation. If design improvements mainly raise recyclability, a higher q_t tends to increase X_t and downstream recycling activity. If design improvements mainly reduce waste intensity, a higher q_t lowers W_t , N_t^w , and Z_t , but may reduce X_t and R_t . Circular-economy policy therefore cannot be evaluated only by recycling volumes. It must also consider the life-cycle direction of design quality.

3.2.2 Division of transmission across policy instruments

The recycling subsidy raises downstream returns from recycled material output and feeds back to upstream firms through P_t^X . EPR raises the liability cost of the unrecycled waste flow and directly enters the design condition, encouraging firms to improve design quality and reduce the unrecycled waste flow.

Proposition 2. Recycling subsidies enter directly through downstream recycling returns, while EPR enters directly through the upstream design condition. The recycling subsidy affects R_t through the recycling sector and can influence q_t only through the transaction-price pass-through channel. EPR enters the design first-order condition through the liability value of reducing N_t^w . A higher λ_X strengthens the transmission of recycling value to upstream design, but the sign and magnitude of that response remain conditional on design orientation and material flows. These channel

differences do not provide an absolute ranking of the two instruments because their policy units and steady-state reference points differ.

3.2.3 Multi-dimensional policy complementarity

For any steady-state variable $A \in \{R, q, Z\}$, define

$$Comp_A = A^{mix} - A^{Ronly} - A^{Zonly} + A^{base}. \quad (40)$$

$Comp_R > 0$ denotes superadditivity in recycled material output, $Comp_q > 0$ denotes superadditivity in design quality, and $Comp_Z < 0$ denotes additional reduction in waste stock. Because $R_t = \rho_t X_t$ and X_t depends on both recyclability and source reduction, $Comp_R$ and $Comp_Z$ can have different signs.

Proposition 3. Policy complementarity is indicator-dependent. Recycling subsidies and EPR may be complementary in design quality or waste-stock reduction while being substitutive in recycled material output. This arises from the life-cycle material-flow constraint. Source reduction can reduce waste stocks while shrinking the effective material base entering the recycling sector.

3.2.4 Welfare evaluation and recycling-technology constraints

Social welfare includes consumption, labor disutility, and waste-stock damage. The quantitative welfare comparison is conducted across deterministic steady states. For policy regime $j \in \{base, Ronly, Zonly, mix\}$, define steady-state period utility as

$$u^j = \log C^j - \chi \frac{(L^j)^{1+\nu}}{1+\nu} - \xi_Z Z^j. \quad (41)$$

With log consumption, the consumption-equivalent welfare change relative to the no-new-policy benchmark is

$$CEV_j = \exp(u^j - u^{base}) - 1. \quad (42)$$

The code measures welfare interaction in utility space,

$$Comp_u = u^{mix} - u^{Ronly} - u^{Zonly} + u^{base}, \quad (43)$$

and reports its exact consumption-equivalent transformation,

$$Comp_{CEV} = \exp(Comp_u) - 1 = \frac{1 + CEV_{mix}}{(1 + CEV_{Ronly})(1 + CEV_{Zonly})} - 1. \quad (44)$$

Thus, $Comp_{CEV} > 0$ indicates a positive interaction relative to the multiplicative benchmark implied by the two single-policy welfare changes, whereas $CEV_{mix} > 0$ indicates an absolute welfare improvement relative to the benchmark. For small welfare changes, this exact measure is close to, but not identical to, $CEV_{mix} - CEV_{Ronly} - CEV_{Zonly}$.

Proposition 4. Welfare complementarity is not the same as absolute welfare improvement. A positive $Comp_{CEV}$ states that the joint policy has a positive utility-space interaction relative to the multiplicative benchmark implied by the two single-policy welfare changes. It does not imply that CEV_{mix} is positive relative to the no-new-policy benchmark. The absolute welfare sign depends on the modeled consumption, labor, design-cost, and waste-stock effects.

3.3 Calibration and parameterization

The calibration is mechanism-oriented rather than intended to estimate a specific jurisdictional plastic-packaging system. Its purpose is to construct a plausible material-flow-consistent baseline in which the dynamic policy channels can be evaluated. The main text therefore focuses on the material-flow anchors and life-cycle design-orientation parameters that are most relevant to the industrial ecology interpretation. Standard macroeconomic parameters, scale normalizations, recycling-sector parameters, welfare scenarios, and steady-state checks are reported in Supplementary Tables S3–S8.

Plastic packaging is used as the main material-flow reference because it is short-lived, waste-intensive, design-sensitive, and widely governed through EPR and recycling policies. The baseline effective recyclability ratio $\theta_0 = 0.25$ is not an official reported recycling rate. It represents the share of gross waste that becomes an effective recycling flow in the model. The upper bound $\bar{\theta} = 0.85$ captures technological and system-level limits to recyclability. The waste-intensity anchor $W/Y \simeq 0.30$ standardizes physical waste flows relative to model output. The recycled-material share is treated as a model-generated check rather than a direct calibration target.

Life-cycle design quality affects recyclability through a and source reduction through b . Because actual eco-design pathways differ across products and sectors, a and b are treated as life-cycle design-orientation parameters rather than directly estimated structural parameters. The main grid fixes total design intensity at $s = a + b = 0.80$ and varies $d = a - b$ over $[-0.60, 0.60]$. This changes the direction of design improvements while holding total design intensity fixed. Table 2 defines the three representative design paths used in the results.

The recycling-value pass-through parameter λ_X measures how much of the recycling sector’s marginal value of effective recycling flows is transmitted to upstream produc-

Table 1: Material-flow target moments and plastic-packaging anchors

Moment or parameter	Baseline	Robustness range	Interpretation
$\theta_0 = X/W \mid_{q=1}$	0.25	0.15 to 0.50	Effective recycling ratio at baseline design
$\bar{\theta}$	0.85	0.75 to 0.90	Upper bound on design recyclability
R/Mat	Model-generated	About 0.04 to 0.06	Non-targeted recycled-material input share
W/Y	0.30	0.20 to 0.40	Standardized waste intensity
N^w/W	$1 - X/W$	Endogenous	Share of unrecycled waste flow

Table 2: Life-cycle design-orientation parameters

Design path	(a, b)	Mechanism	Interpretation
Source-reduction-oriented	(0.20, 0.60)	Lower waste intensity dominates	Lightweighting, packaging reduction, and reuse-oriented design
Balanced	(0.40, 0.40)	Recyclability and source reduction move jointly	Joint improvement in recyclability and source reduction
Recyclability-oriented	(0.60, 0.20)	Effective recyclability dominates	Mono-material design, easier sorting, and easier reprocessing
Design-cost parameter	$\psi_q = 0.10$	Baseline design cost	Sensitivity values are 0.05 and 0.20

ers. The baseline is $\lambda_X = 0.25$, with sensitivity values from no pass-through to full pass-through. Dynamic impulse-response experiments use $\bar{\tau}^R = 1.00$, $\bar{\tau}^Z = 0.05$, and $\rho_R = \rho_Z = 0.90$ to study marginal policy shocks around an existing EPR regime. Permanent policy-regime comparisons use four regimes: no new policy (1.00, 0.00), recycling-subsidy-only (1.05, 0.00), EPR-only (1.00, 0.05), and the policy mix (1.05, 0.05). These magnitudes are designed for relative mechanism comparison rather than structural estimates of real-world tax or subsidy rates.

3.4 Policy experiments and evaluation metrics

Unless otherwise stated, the baseline calibration uses $\lambda_X = 0.25$, $\psi_q = 0.10$, $\eta = 0.30$, $\bar{\rho} = 0.90$, and $\xi_Z = 0.010$. The representative steady-state and complementarity paths are source-reduction-oriented $(a, b) = (0.20, 0.60)$, balanced $(0.40, 0.40)$, and recyclability-oriented $(0.60, 0.20)$. The two-dimensional diagrams hold $a + b = 0.80$ fixed and vary $d = a - b$ over $[-0.60, 0.60]$. The analysis distinguishes between two types of experiments. Local dynamic shock experiments study a recycling-subsidy shock, an EPR-liability shock, and a common joint shock around an existing EPR steady state with $\bar{\tau}^Z = 0.05$ and $\bar{\tau}^R = 1.00$. In the complementarity scripts, the common innovation enters both policy equations. Each innovation has a standard deviation of 0.01, so the two single-policy shocks represent the same one-percent log innovation relative to their own steady states rather than the same absolute policy-point change. Because the no-subsidy point is $\tau^R = 1$ whereas the no-EPR point is $\tau^Z = 0$, there is no unique natural definition of equal policy intensity. The local impulse responses are therefore used to compare transmission channels and dynamic shapes, not to rank the two instruments by absolute strength. Steady-state institutional comparisons, phase diagrams, and welfare analysis compare four permanent regimes, namely no new policy (1.00, 0.00), recycling-subsidy-only (1.05, 0.00), EPR-only (1.00, 0.05), and the policy mix (1.05, 0.05). The first experiment answers how marginal policy innovations transmit around the existing EPR regime. The second compares long-run allocations and welfare across institutions.

For any steady-state variable A , complementarity is

$$Comp_A = A^{mix} - A^{Ronly} - A^{Zonly} + A^{base}. \quad (45)$$

For R and q , a positive value denotes superadditivity. For Z , a negative value denotes additional waste reduction. Welfare analysis reports both the absolute CEV of the policy mix relative to the no-new-policy benchmark and the welfare-complementarity term $Comp_{CEV}$.

4 Results

4.1 Dynamic transmission of the two circular economy policies

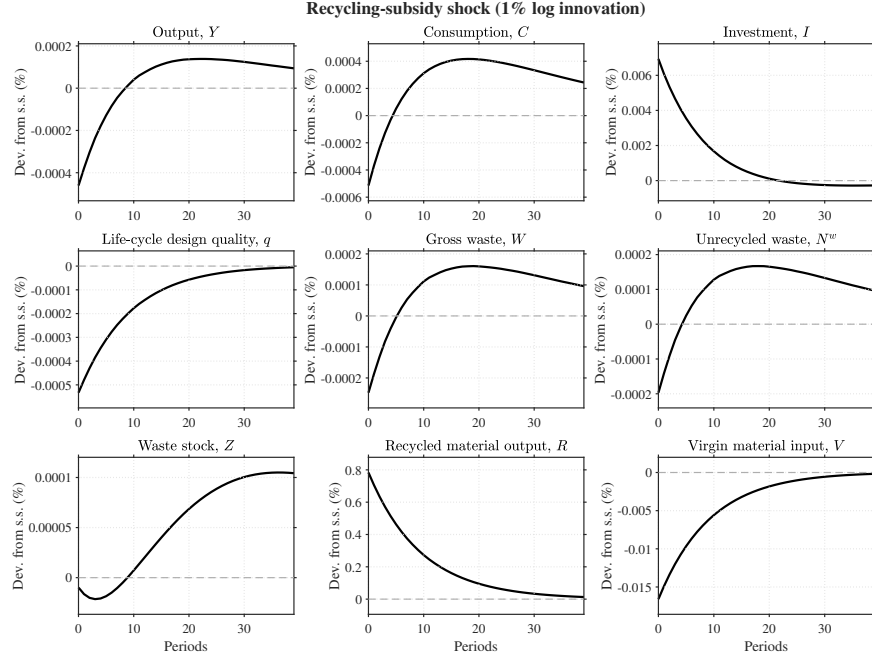
Figure 2 compares the core responses to a recycling-subsidy shock and an EPR-liability shock. The responses are quantitatively small because the shocks are one-percent log innovations around the steady state. Their purpose is not to claim large short-run macroeconomic effects, but to identify how life-cycle policy instruments transmit through material flows and waste accumulation.

The recycling-subsidy shock identifies a downstream circularity channel. By raising the effective return to recycled material output, the subsidy expands recycling-sector activity and increases R_t on impact. Virgin material input falls as recycled output substitutes for virgin input. However, the policy does not directly price unrecycled waste at the design stage, so the response of life-cycle design quality is weak. This distinction is important for industrial ecology assessment: a policy can improve one circularity indicator, recycled output, without necessarily improving upstream design or long-run waste-stock outcomes.

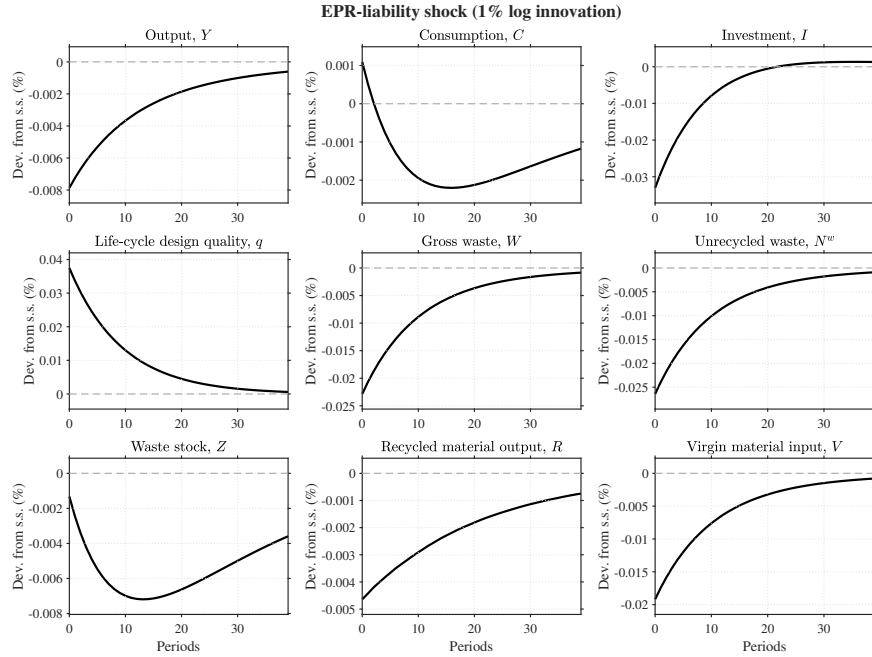
The EPR shock identifies an upstream life-cycle management channel. By increasing the liability associated with unrecycled waste, EPR raises the marginal value of improving design quality. Better design lowers waste intensity and increases effective recyclability, reducing the unrecycled waste flow and gradually lowering the waste stock. At the same time, source reduction may shrink the post-consumer material base available to recyclers. This explains why a policy that improves waste-stock outcomes may reduce recycled material output in the model. Separate core IRF figures are reported in Supplementary Figure S1, and the full variable responses are reported in Supplementary Figures S3–S4.

4.2 Local dynamic complementarity

To connect single-policy shocks with long-run institutional comparisons, the model computes local dynamic complementarity by comparing the joint-shock response with the sum of the two single-shock responses. The detailed responses are reported in Supplementary Figure S5. Under the baseline recycling-value pass-through parameter $\lambda_X = 0.25$, dynamic complementarity in R_t is negative throughout the response horizon and converges toward zero, so the joint shock does not create additional recycled material output. Complementarity in q_t is initially negative but becomes positive after the first few periods, indicating a delayed interaction between EPR and the transmission of recycling value to upstream design. Complementarity in Z_t is positive at first, crosses below zero in the medium run, and becomes most negative under source-reduction-oriented design, fol-



(a) Recycling-subsidy shock



(b) EPR-liability shock

Figure 2: Dynamic transmission of recycling-subsidy and EPR-liability shocks for core variables. Each shock is a one-percent log innovation around the existing-EPR steady state. The figure compares the downstream recycling channel with the upstream life-cycle design channel rather than ranking absolute policy strength.

lowed by balanced design. This check is mainly a mechanism test. The main policy interpretation is based on steady-state and welfare comparisons.

4.3 Long-run policy-regime comparison

The steady-state regime comparison shows that the policy instruments should not be interpreted as substitutes along a single recycling-rate dimension. Recycling subsidies are more effective at expanding downstream recycled output, while EPR is more effective at improving design quality and reducing accumulated waste. The policy mix partly combines these channels, but it does not dominate both single instruments in every indicator. This result motivates a dashboard interpretation of circular economy performance rather than a ranking based only on recycled material output. The supplementary steady-state figure and numerical values are reported in Supplementary Figure S2 and Supplementary Table S9.

Table 3 summarizes the policy-complementarity results for representative design paths. $Comp_R/R_{base}$ is negative in all three design paths, showing that the policy mix is not superadditive in recycled material output. By contrast, $Comp_Z/Z_{base} < 0$ under source-reduction-oriented and balanced design, indicating additional waste-stock reduction relative to the additive benchmark. The sign of $Comp_q$ also changes with design orientation. These results show that policy interaction is indicator-dependent: the same policy mix can be substitutive in recycled material output but complementary in design quality or waste-stock reduction.

Table 3: Policy-complementarity summary for representative design paths ($\eta = 0.30$, $\lambda_X = 0.25$, $\xi_Z = 0.010$)

Design path	$Comp_R/R_{base}$ (%)	$Comp_q$	$Comp_Z/Z_{base}$ (%)	$Comp_{CEV}$
Source-reduction-oriented	-0.1141	2.05×10^{-5}	-0.0024	2.15×10^{-6}
Balanced	-0.0622	6.18×10^{-6}	-0.0006	1.28×10^{-6}
Recyclability-oriented	-0.0319	-2.44×10^{-6}	0.0001	8.45×10^{-7}

Note. $Comp_R = R_{mix} - R_{Ronly} - R_{Zonly} + R_{base}$, with analogous definitions for q and Z . Positive values for R and q indicate superadditivity. Negative values for Z indicate additional waste-stock reduction. The source-reduction-oriented and balanced paths show positive q interaction and additional Z reduction; the recyclability-oriented path does not.

4.4 Life-cycle design orientation and two-dimensional policy regions

Figure 3 maps the conditions for additional waste-stock reduction over life-cycle design orientation $d = a - b$ and the recycling-flow elasticity parameter η . The boundary moves primarily along the design-orientation dimension, while η mainly changes local magnitudes and only modestly shifts the boundary. Additional waste-stock reduction appears mainly in source-reduction-oriented and balanced systems. In these regions, EPR reduces waste generation while recycling incentives maintain downstream returns and partly cushion the recycling-sector effects of a smaller material flow. In strongly recyclability-oriented systems, both the additional waste-stock effect and the design-quality interaction weaken. The full R , q , and Z decomposition is reported in Supplementary Figure S9.

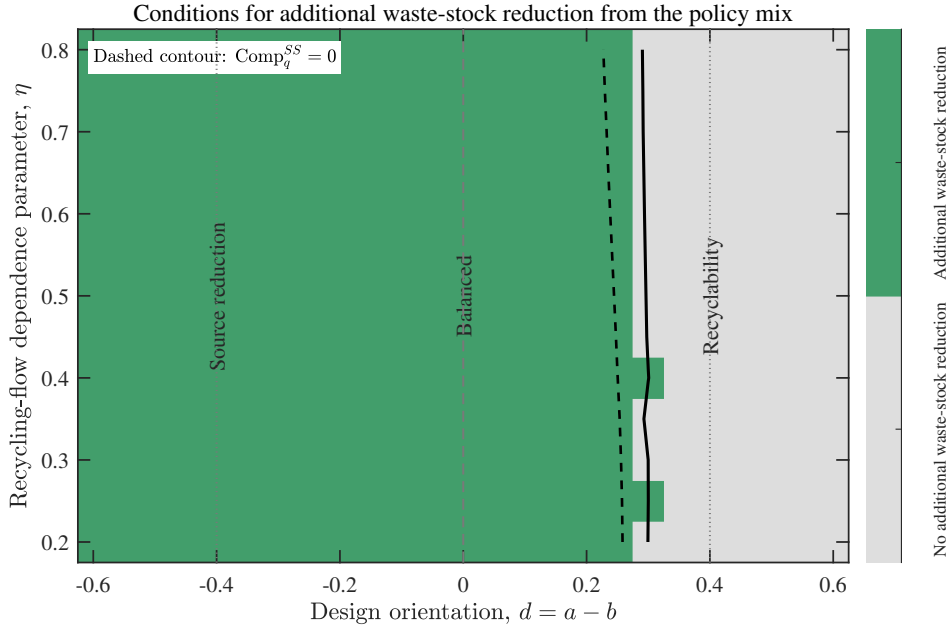


Figure 3: Conditions for additional waste-stock reduction from the policy mix across life-cycle design orientation and the recycling-flow elasticity parameter. Green cells indicate $Comp_Z^{SS} < 0$, and gray cells indicate no additional waste-stock reduction. The solid boundary marks $Comp_Z^{SS} = 0$, and the dashed contour marks $Comp_q^{SS} = 0$.

4.5 Welfare analysis

Figure 4 reports the absolute CEV of the policy mix and the welfare-complementarity term under the conservative low-damage scenario with $\xi_Z = 0.010$. The welfare magnitudes are small because the experiment compares nearby steady states, but the sign pattern is informative. Under the low-damage scenario, the modeled resource costs of design adjustment and macroeconomic reallocation outweigh the waste-stock benefits, so the absolute CEV of the policy mix remains negative. However, the positive welfare in-

teraction indicates that the two instruments work better together than would be implied by their separate welfare effects. This distinction is important because coordination value and absolute welfare improvement are conceptually different.

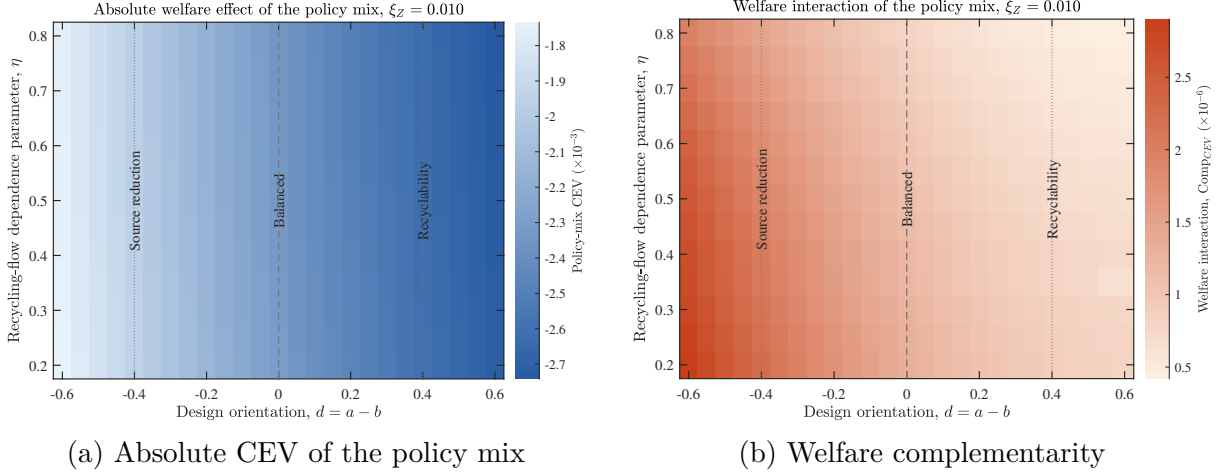


Figure 4: Welfare results under the low-damage scenario. The left panel reports the absolute consumption-equivalent welfare effect of the policy mix relative to the no-new-policy benchmark. The right panel reports the exact consumption-equivalent interaction term relative to the multiplicative benchmark implied by the two single-policy welfare changes.

Table 4: Complementarity and welfare summary over the two-dimensional grid

Indicator	Value
Number of grid points	325
Grid points with $Comp_R^{SS} > 0$	0
Grid points with $Comp_q^{SS} > 0$	226
Grid points with $Comp_Z^{SS} < 0$	236
Grid points with $CEV_{mix} > 0$ under $\xi_Z = 0.010$	0
Grid points with $Comp_{CEV} > 0$ under $\xi_Z = 0.010$	325
Range of CEV_{mix} under $\xi_Z = 0.010$	$[-2.74, -1.73] \times 10^{-3}$
Range of $Comp_{CEV}$ under $\xi_Z = 0.010$	$[0.42, 2.90] \times 10^{-6}$

Note. The grid uses $d \in [-0.60, 0.60]$ and $\eta \in [0.20, 0.80]$. Positive values of $Comp_R^{SS}$ and $Comp_q^{SS}$ indicate superadditivity in recycled material output and design quality. Negative values of $Comp_Z^{SS}$ indicate additional waste-stock reduction. CEV_{mix} is the consumption-equivalent welfare change of the policy mix relative to the no-new-policy benchmark, and $Comp_{CEV}$ is the exact consumption-equivalent interaction term defined from utility-space complementarity.

A threshold analysis shows that the negative CEV under the low-damage scenario is not a general welfare ranking. Because ξ_Z enters steady-state period utility linearly, the exact break-even condition $u^{mix} = u^{base}$ gives a damage weight ξ_Z^* between about 0.0188 and 0.0459, with a median around 0.0287. The threshold is lower in source-reduction

regions and higher in strong recyclability regions. Supplementary Table S11 shows that when $\xi_Z = 0.050$, CEV_{mix} becomes positive throughout the grid. Welfare conclusions therefore depend on the social valuation of waste-stock damage, while positive welfare complementarity holds throughout the evaluated baseline grid.

4.6 Robustness and mechanism checks

The Supplementary Information reports additional mechanism, welfare, sensitivity, and robustness checks in Supplementary Figures S6–S18 and Supplementary Tables S10–S12. First, varying the recycling-flow elasticity parameter η over the evaluated interval up to 0.80 does not change the qualitative ordering of the complementarity results. R -dimension complementarity remains negative throughout the evaluated range, while q -dimension complementarity remains positive over broad regions and Z -dimension complementarity is governed by design orientation. Second, varying λ_X and ψ_q does not generate systematic positive complementarity in R . Higher λ_X strengthens design-quality responses and additional waste reduction under source-reduction design, while higher ψ_q dampens design responses. Third, varying the conversion-rate upper bound $\bar{\rho}$ from 0.80 to 0.95 leaves the main signs unchanged. The actual R/X ratio under the policy mix remains far below the upper bound, indicating that the results are not mechanically driven by a binding conversion-rate constraint. Overall, the robustness checks support the main conclusion that policy complementarity is stable in direction but indicator-dependent.

5 Discussion

The results contribute to industrial ecology by showing how life-cycle material-flow mechanisms can be embedded in a macro-dynamic policy framework. Traditional industrial ecology tools are well suited to quantifying material flows, product-system impacts, and technological constraints. The present model adds a complementary perspective by asking how policy-induced changes in product design and recycling incentives propagate through material substitution, production, investment, labor allocation, waste accumulation, and welfare. The contribution is therefore not a large numerical prediction for a particular material system, but a mechanism framework for connecting life-cycle management with economy-wide adjustment.

The policy interpretation is that extended producer responsibility and recycling subsidies operate at different stages of the product life cycle. Recycling subsidies directly improve downstream returns and therefore increase recycling activity and recycled material output. EPR acts more directly on product design and liability for the unrecycled waste flow, which strengthens source reduction and lowers the waste stock. This division

is consistent with the broader producer-responsibility literature, which emphasizes that post-consumer obligations can alter upstream design incentives, while recycling support primarily changes downstream recovery conditions (Calcott & Walls, 2005; Fullerton & Wu, 1998; Larrain et al., 2022). The dynamic general-equilibrium results add that these effects also propagate through material substitution, investment, labor allocation, and consumption.

The indicator-dependent complementarity results have an important implication for sustainability assessment. In source-reduction-oriented and balanced regions, a policy mix can reduce the waste stock beyond the additive single-policy benchmark while remaining substitutive in recycled material output. Source reduction lowers the volume of waste available to recyclers, so a lower recycling quantity need not indicate weaker environmental performance. Policy evaluation should therefore jointly report recycled material output, life-cycle design quality, virgin material input, the unrecycled waste flow, the waste stock, and consumption-equivalent welfare. This multi-indicator approach is particularly relevant when governments combine packaging reduction, recyclability requirements, producer responsibility, and recycling incentives.

The welfare analysis separates coordination value from an unconditional policy recommendation. Positive welfare complementarity means that jointly using the instruments creates a positive utility-space interaction relative to the benchmark implied by their separate welfare changes. It does not necessarily mean that the policy mix improves welfare relative to the no-new-policy benchmark. Within the model, the absolute ranking depends on the social valuation of accumulated waste damage, design costs, recycling-value pass-through, and resource reallocation. Administrative, distributional, and compliance costs are not modeled and would also matter in applications. The mechanisms suggest a conditional design principle rather than a quantified policy ranking.

Several limitations qualify the interpretation. The model is stylized and should not be read as a process-based LCA, a detailed material-flow account, or a jurisdiction-specific policy forecast. It uses a representative household and competitive sectoral structure and does not explicitly represent firm heterogeneity, durable products, consumer sorting behavior, local waste-governance variation, international trade in secondary materials, or distributional impacts. Plastic packaging provides the main material-flow anchor, but the mechanism parameters are not structural estimates for a specific country or sector. These limitations define useful extensions rather than invalidating the mechanism. Future research could combine this type of macro-dynamic framework with product-level LCA, regional MFA, firm-level eco-design data, recycled-material prices, and policy variation to estimate key parameters and evaluate sector-specific policy designs.

6 Conclusions

This paper develops a stylized life-cycle-oriented dynamic general-equilibrium model to study how circular economy policies transmit through product design, post-consumer material flows, recycled material production, waste accumulation, and welfare. The framework links upstream life-cycle design quality with downstream recycling activity and distinguishes effective recycling flows from recycled material output under a bounded conversion technology.

The results show that extended producer responsibility and recycling subsidies operate through different stages of the life cycle. Recycling subsidies mainly strengthen downstream recycling and recycled material output, whereas EPR primarily improves design quality and reduces unrecycled waste flows and the waste stock. Their combination does not improve every indicator simultaneously. It is substitutive in recycled material output under the baseline parameterization, generally complementary in design quality, and capable of generating additional waste-stock reductions when design is oriented toward source reduction or balances source reduction with recyclability.

The policy implication is that circular economy performance should not be assessed by recycling volumes alone. For life-cycle policy design, recycled output, design quality, virgin-material dependence, unrecycled waste flows, waste stocks, and welfare need to be evaluated together. The welfare case for a policy mix remains conditional on the valuation of accumulated waste damage and on design and resource-reallocation costs. The framework offers a macro-dynamic complement to industrial ecology tools and can be extended by integrating more detailed LCA, MFA, sectoral, firm-level, and distributional evidence.

Declarations

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