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

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S1 Full equilibrium conditions and supplementary definitions

This section records the full equilibrium system, policy-experiment definitions, welfare calculation, and notation checks. The main text focuses on economic mechanisms and key first-order conditions. The Supplementary Information is provided to support reproducibility.

S1.1 Variables and parameters

Table S1 lists the endogenous variables. The notation is aligned with the Dynare implementation.

Table S1: Endogenous variables

Variable	Code name	Definition
C_t	C	Household consumption
I_t	I	Investment
K_t	K	Total capital stock
K_t^Y	KY	Capital in final-goods production
K_t^R	KR	Capital in recycling
L_t	L	Total labor
L_t^Y	LY	Labor in final-goods production

L_t^R	LR	Labor in recycling
Y_t	Y	Final output
Mat_t	Mat	Material composite
V_t	V	Virgin material input
R_t	R	Recycled material output
W_t	W	Gross waste flow
X_t	X	Effective recycling flow
N_t^w	Nw	Unrecycled waste flow
Z_t	Z	Waste stock
w_t	w	Real wage
r_t	r	Rental rate of capital
P_t^M	PM	Material-composite price
P_t^R	PR	Recycled-material price
P_t^X	PX	Transaction price of effective recycling flow
ρ_t	rho	Recycling conversion rate
Γ_t	Gamma	Life-cycle design cost
q_t	q	Life-cycle design quality
τ_t^R	tauR	Recycling subsidy intensity
ℓ_t^R	ltau	Log state for recycling-subsidy shock
τ_t^Z	tauZ	EPR liability intensity
ℓ_t^Z	ltz	Log state for EPR shock
Tax_t	Tax	Net taxes or transfers

Table S2 lists the main parameters. In the text, Λ_t is the final-goods firm's net private marginal value, corresponding to the local code object `Omega`. $\mathcal{M}_t$ is the recycling-sector marginal value of effective recycling flows, corresponding to `Mcal`. They are local definitions rather than independent state variables.

Table S2: Main parameters

Parameter	Definition	Comment
β	Discount factor	Intertemporal preference
δ_K	Capital depreciation	Depreciation of aggregate capital
α	Final-goods capital share	Production parameter
μ	Material-input share	Production parameter
ω	CES weight of recycled materials	Material-composite parameter
σ	Material substitution elasticity	Virgin to recycled substitution
α_R	Recycling capital elasticity	Conversion-index parameter
β_R	Recycling labor elasticity	Conversion-index parameter

η	Recycling-flow elasticity parameter	Structural role of X_t in the conversion index
δ_Z	Waste-stock decay rate	Natural decay or treatment
χ	Labor-disutility weight	Household utility
ν	Labor-supply curvature	Related to Frisch elasticity
ξ_Z	Waste-stock damage weight	Welfare evaluation
ψ_q	Design-cost parameter	Marginal cost of life-cycle design
q_0	Baseline design quality	Normalized to one
P^V	Virgin-material price	Exogenous or normalized price
A	Final-goods productivity	Baseline value one
A_R	Recycling scale	Normalized scale
ϕ_0	Baseline waste intensity	With ϖ_W determines W/Y
θ_0	Baseline effective recyclability ratio	Satisfies $\theta(1) = \theta_0$
$\bar{\theta}$	Upper bound on recyclability	Technological boundary
κ	Recyclability scale	Implied by θ_0 and $\bar{\theta}$
ϖ_W	Material-to-value conversion factor	Standardizes waste-flow units
$\bar{\rho}$	Upper bound on recycling conversion	Ensures $R_t < X_t$
a	Recyclability design elasticity	Effect of q_t on θ_t
b	Source-reduction design elasticity	Effect of q_t on ϕ_t
λ_X	Recycling-value pass-through parameter	Reduced-form transmission of downstream recycling value upstream
$\bar{\tau}^R$	Steady-state recycling subsidy	Equals one without subsidy
$\bar{\tau}^Z$	Steady-state EPR liability	Baseline EPR intensity
ρ_R	Persistence of recycling-subsidy shock	AR(1) parameter
ρ_Z	Persistence of EPR shock	AR(1) parameter

S1.2 Equilibrium system

The deterministic core of the model is given below. In the stochastic model, intertemporal conditions are interpreted under conditional expectations. Household conditions are

$$\frac{1}{C_t} = \beta E_t \left[\frac{1}{C_{t+1}} (r_{t+1} + 1 - \delta_K) \right], \tag{S1}$$

$$\chi L_t^{\nu} = \frac{w_t}{C_t}, \tag{S2}$$

$$K_t = (1 - \delta_K) K_{t-1} + I_t. \tag{S3}$$

Factor allocation is

$$K_{t-1} = K_t^Y + K_t^R, \tag{S4}$$

$$L_t = L_t^Y + L_t^R. \tag{S5}$$

Life-cycle functions are

$$\phi_t = \varpi_W \phi_0 q_t^{-b}, \tag{S6}$$

$$\theta_t = \bar{\theta} \frac{\kappa q_t^a}{1 + \kappa q_t^a}, \tag{S7}$$

$$\varepsilon_{q,t}^{\theta} = a \left(1 - \frac{\theta_t}{\bar{\theta}}\right). \tag{S8}$$

Final-goods production and first-order conditions are

$$Y_t = A_t (K_t^Y)^{\alpha} (L_t^Y)^{1-\alpha-\mu} (\text{Mat}_t)^{\mu}, \tag{S9}$$

$$\Lambda_t = 1 - \tau_t^Z (1 - \theta_t) \phi_t + P_t^X \theta_t \phi_t, \tag{S10}$$

$$r_t = \Lambda_t \alpha \frac{Y_t}{K_t^Y}, \tag{S11}$$

$$w_t = \Lambda_t (1 - \alpha - \mu) \frac{Y_t}{L_t^Y}, \tag{S12}$$

$$P_t^M = \Lambda_t \mu \frac{Y_t}{\text{Mat}_t}. \tag{S13}$$

The material composite satisfies

$$\text{Mat}_t = \left[(1 - \omega) V_t^{\frac{\sigma-1}{\sigma}} + \omega R_t^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{S14}$$

$$P^V = P_t^M (1 - \omega) \left(\frac{\text{Mat}_t}{V_t}\right)^{1/\sigma}, \tag{S15}$$

$$P_t^R = P_t^M \omega \left(\frac{\text{Mat}_t}{R_t}\right)^{1/\sigma}. \tag{S16}$$

Waste and recycling flows are

$$W_t = \phi_t Y_t, \tag{S17}$$

$$X_t = \theta_t W_t, \tag{S18}$$

$$N_t^w = (1 - \theta_t) W_t. \tag{S19}$$

The recycling sector is governed by

$$R_t = \rho_t X_t, \tag{S20}$$

$$\rho_t = \bar{\rho}\frac{S_t}{1+S_t}, \tag{S21}$$

$$S_t = A_R (K_t^R)^{\alpha_R} (L_t^R)^{\beta_R} X_t^{\eta-1}, \tag{S22}$$

$$r_t = \tau_t^R P_t^R \bar{\rho} X_t \frac{\alpha_R S_t}{K_t^R (1+S_t)^2}, \tag{S23}$$

$$w_t = \tau_t^R P_t^R \bar{\rho} X_t \frac{\beta_R S_t}{L_t^R (1+S_t)^2}, \tag{S24}$$

$$\mathcal{M}_t = \tau_t^R P_t^R \bar{\rho} \frac{S_t(S_t+\eta)}{(1+S_t)^2}, \tag{S25}$$

$$P_t^X = \lambda_X \mathcal{M}_t. \tag{S26}$$

Because X_t is generated by the material-flow identity and is taken as available by the recycling sector, the transaction-price equation is a reduced-form pass-through rule rather than a Walrasian demand condition for X_t.

Holding K_t^R and L_t^R fixed, the local elasticity of recycled output with respect to the effective recycling flow is

$$\frac{\partial \log R_t}{\partial \log X_t} = \frac{S_t+\eta}{1+S_t}. \tag{S27}$$

Accordingly, η is the structural recycling-flow elasticity parameter in the conversion index rather than the unconditional elasticity of recycled material output R_t with respect to X_t; the corresponding local elasticity also depends on S_t. The waste stock, design cost, design condition, policies, and resource constraint are

$$Z_t = (1-\delta_Z) Z_{t-1} + N_t^w, \tag{S28}$$

$$\Gamma_t = \frac{\psi_q}{2}(q_t - q_0)^2, \tag{S29}$$

$$D_t^q = \frac{Y_t \phi_t}{q_t}\left[\varepsilon_{q,t}^{\theta}\theta_t + b(1-\theta_t)\right], \tag{S30}$$

$$\psi_q(q_t - q_0) = \tau_t^Z D_t^q + P_t^X \frac{X_t}{q_t}\left[\varepsilon_{q,t}^{\theta} - b\right], \tag{S31}$$

$$\ell_t^R = \rho_R \ell_{t-1}^R + \varepsilon_t^R, \qquad \tau_t^R = \bar{\tau}^R \exp(\ell_t^R), \tag{S32}$$

$$\ell_t^Z = \rho_Z \ell_{t-1}^Z + \varepsilon_t^Z, \qquad \tau_t^Z = \bar{\tau}^Z \exp(\ell_t^Z), \tag{S33}$$

$$\text{Tax}_t = (\tau_t^R - 1) P_t^R R_t - \tau_t^Z N_t^w, \tag{S34}$$

$$Y_t = C_t + I_t + \Gamma_t + P^V V_t. \tag{S35}$$

S1.3 Marginal effects of life-cycle design

From the bounded recyclability function,

$$\frac{\partial \theta_t}{\partial q_t} = \frac{\theta_t}{q_t} a \left(1 - \frac{\theta_t}{\bar{\theta}}\right) = \frac{\theta_t}{q_t} \varepsilon^{\theta}_{q,t}. \tag{S36}$$

Given $W_t = \varpi_W \phi_0 q_t^{-b} Y_t$,

$$\frac{\partial W_t}{\partial q_t} = -\frac{b}{q_t} W_t. \tag{S37}$$

Therefore,

$$\frac{\partial X_t}{\partial q_t} = \frac{\partial (\theta_t W_t)}{\partial q_t} = \frac{X_t}{q_t} \left[\varepsilon^{\theta}_{q,t} - b\right]. \tag{S38}$$

Similarly,

$$-\frac{\partial N^w_t}{\partial q_t} = \frac{Y_t \phi_t}{q_t} \left[\varepsilon^{\theta}_{q,t} \theta_t + b(1 - \theta_t)\right] \equiv D^q_t > 0. \tag{S39}$$

Thus life-cycle design always lowers the unrecycled waste flow locally, but its effect on effective recycling flows and recycled material output depends on the sign of $\varepsilon^{\theta}_{q,t} - b$.

S1.4 Policy experiments and complementarity indicators

The four steady-state regimes are baseline 0, $(\tau^R, \tau^Z) = (1.00, 0.00)$, recycling-subsidy-only R, $(1.05, 0.00)$, EPR-only Z, $(1.00, 0.05)$, and policy mix M, $(1.05, 0.05)$. For any physical or macroeconomic outcome $x \in \{q, R, Z, C, Y, \ldots\}$, steady-state complementarity is

$$Comp^{SS}_x = x^M_{SS} - x^R_{SS} - x^Z_{SS} + x^0_{SS}. \tag{S40}$$

The local dynamic scripts introduce a common innovation ε^M_t in addition to the two single-policy innovations:

$$\ell^R_t = \rho_R \ell^R_{t-1} + \varepsilon^R_t + \varepsilon^M_t, \tag{S41}$$

$$\ell^Z_t = \rho_Z \ell^Z_{t-1} + \varepsilon^Z_t + \varepsilon^M_t. \tag{S42}$$

Each innovation has standard deviation 0.01. The single-policy shocks therefore represent equal one-percent log innovations around their own steady states, not equal absolute policy-point changes. Dynamic complementarity is defined from impulse responses. If Δx^j_h is the response of x at horizon $h = 1, \ldots, H$ under policy experiment j relative to the baseline steady state, then

$$Comp^{IRF}_{x,h} = \Delta x^M_h - \Delta x^R_h - \Delta x^Z_h. \tag{S43}$$

The MATLAB scripts report the finite-horizon, undiscounted cumulative statistic

$$Comp_x^{Cum} = \sum_{h=1}^{H} Comp_{x,h}^{IRF}, \qquad H = 40. \tag{S44}$$

S1.5 Consumption-equivalent welfare changes

Welfare is evaluated across the deterministic steady states used in the permanent policy-regime comparisons. For regime $j \in \{0, R, Z, M\}$, steady-state period utility is

$$u^j = \log C^j - \chi \frac{(L^j)^{1+\nu}}{1+\nu} - \xi_Z Z^j. \tag{S45}$$

The associated infinite-horizon welfare level is $\Omega^j = u^j/(1-\beta)$. The consumption-equivalent welfare change relative to the no-new-policy baseline is

$$CEV_j = \exp\left(u^j - u^0\right) - 1 = \exp\left((1-\beta)(\Omega^j - \Omega^0)\right) - 1. \tag{S46}$$

This is the exact formula implemented in the welfare scripts. Welfare interaction is first measured in utility space,

$$Comp_u = u^M - u^R - u^Z + u^0, \tag{S47}$$

and then transformed into consumption-equivalent units:

$$Comp_{CEV} = \exp(Comp_u) - 1 = \frac{1 + CEV_M}{(1 + CEV_R)(1 + CEV_Z)} - 1. \tag{S48}$$

A positive $Comp_{CEV}$ therefore indicates a positive utility-space interaction relative to the multiplicative benchmark implied by the two single-policy welfare changes. It is not exactly equal to $CEV_M - CEV_R - CEV_Z$, although the two expressions are numerically close when all welfare changes are small.

Because ξ_Z enters period utility linearly, the break-even damage weight for the policy mix is obtained exactly from $u^M = u^0$:

$$\xi_Z^* = \frac{\log(C^M/C^0) - \frac{\chi}{1+\nu}\left[(L^M)^{1+\nu} - (L^0)^{1+\nu}\right]}{Z^M - Z^0}, \qquad Z^M \neq Z^0. \tag{S49}$$

S1.6 Notation consistency

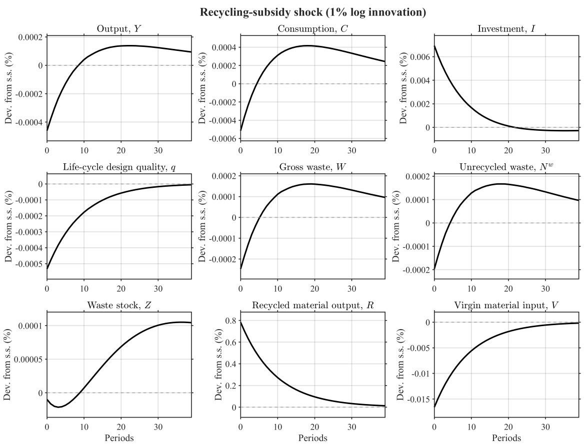
Unrecycled waste flow is denoted by N_t^w in the paper and by `Nw` in the code. The recycling subsidy is τ_t^R and `tauR`. EPR liability is τ_t^Z and `tauZ`. The material composite is Mat_t and `Mat`. Design quality is q_t, and design cost is Γ_t. Physical and macroeconomic complementarity indicators use the additive interaction $Comp_x$, while welfare complementarity uses the exact transformed utility interaction $Comp_{CEV}$. δ_Z is the waste-stock decay parameter, whereas ξ_Z is the welfare damage weight.

S2 Additional core materials and policy-outcome details

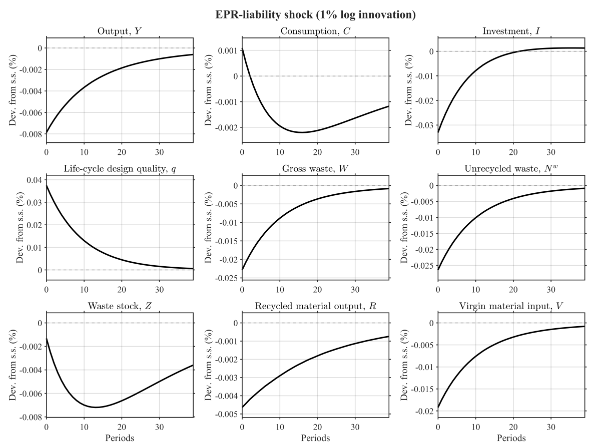
This section provides additional core response figures, calibration tables, and policy-regime details that support the main text. The variable table includes code names to support reproducibility.

S2.1 Core dynamic responses and steady-state policy outcomes

Supplementary Figure S1 reports the two separate core response figures for the single-policy shocks. These panels complement the channel-comparison figure in the main text. The qualitative interpretation is unchanged: recycling subsidies mainly expand downstream recycled material output, while EPR more directly raises life-cycle design quality and reduces unrecycled waste flows and the waste stock.



(a) Recycling-subsidy shock



(b) EPR-liability shock

Figure S1: Core dynamic responses to the two single-policy shocks. The panels show the core response variables used to compare downstream and upstream policy channels. Each shock is a one-percent log innovation around the existing-EPR steady state.

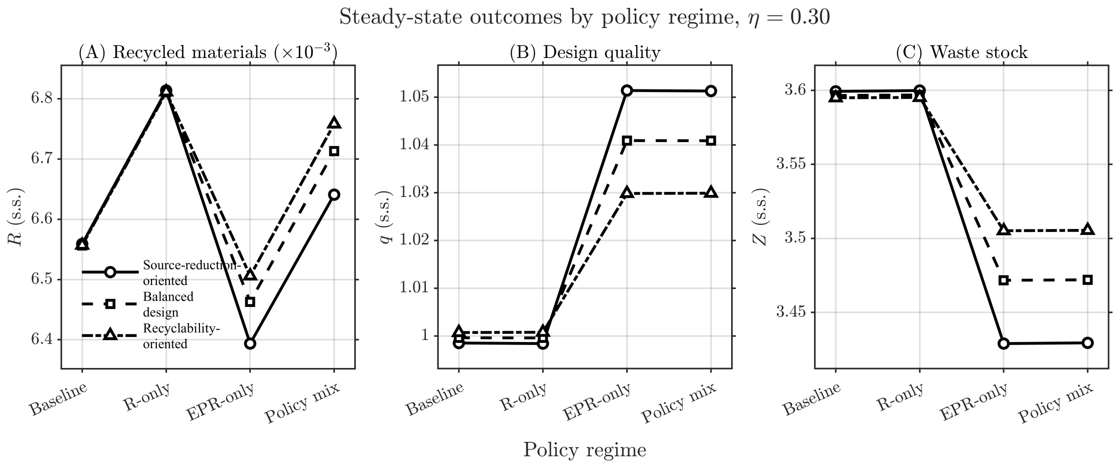


Figure S2: Steady-state outcomes under alternative policy regimes at the baseline recycling-flow elasticity parameter $\eta = 0.30$. The three design paths are source-reduction-oriented $(a, b) = (0.20, 0.60)$, balanced $(0.40, 0.40)$, and recyclability-oriented $(0.60, 0.20)$. The main text summarizes its interpretation and reports the policy-complementarity table.

S2.2 Calibration and policy-regime tables

Table S3: Standard macroeconomic parameters

Parameter	Value	Meaning	Basis
β	0.99	Discount factor	Quarterly DSGE benchmark
α	0.30	Capital share in final-goods production	Standard macro capital share
μ	0.10	Material-input share	Scale of material module
δ_K	0.025	Quarterly capital depreciation	About 10% annually
ν	1.00	Labor-supply curvature	Baseline Frisch elasticity
χ	7.7278315	Labor-disutility weight	Matches $L \simeq 1/3$

Table S4: Scale parameters and steady-state treatment

Parameter	Baseline	Meaning	Treatment
χ	7.7278315	Labor-disutility weight	Matches $L \simeq 1/3$
A	1.00	Final-goods productivity	Normalization
P^V	0.20	Virgin-material price	Exogenous normalized price
σ	2.00	Material substitution elasticity	Fixed baseline
ω	0.25	Material CES weight	Fixed baseline
q_0	1.00	Baseline design quality	Normalization
ϕ_0	0.30	Baseline waste intensity	Matches $W/Y \approx 0.30$ with ϖ_W
ϖ_W	1.00	Material-to-value conversion	Normalization
κ	$\theta_0/(\bar{\theta} - \theta_0)$	Recyclability scale	Implied by $\theta(1) = \theta_0$
A_R	1.00	Recycling conversion scale	Normalization

Table S5: Recycling-sector parameters

Parameter	Baseline	Meaning	Treatment
α_R	0.30	Capital elasticity in conversion index	Jointly determines S_t
β_R	0.40	Labor elasticity in conversion index	Jointly determines S_t
η	0.30	Recycling-flow elasticity parameter	Baseline structural calibration
η	0.20 to 0.80	Recycling-flow elasticity sensitivity	Phase and welfare grids
$\bar{\rho}$	0.90	Upper bound on conversion rate	Material conservation and recycling loss
A_R	1.00	Conversion-index scale	Normalization

Table S6: Institutional transmission and policy-experiment parameters

Parameter	Baseline	Sensitivity range	Meaning
λ_X	0.25	0 to 1	Recycling-value pass-through parameter
ψ_q	0.10	0.05 to 0.20	Curvature of design cost
(τ^R, τ^Z)	See text	Policy regimes	$(1, 0)$, $(1.05, 0)$, $(1, 0.05)$, $(1.05, 0.05)$
ρ_R, ρ_Z	0.90	Fixed	Persistence of policy shocks

Table S7: Waste-damage scenarios and welfare interpretation

Parameter or range	Interpretation
$\delta_Z = 0.05$	Waste-stock decay, treatment, or depreciation rate.
$\xi_Z = 0$	Accounting case without waste-stock damage. It isolates resource-allocation and policy-distortion costs.
$\xi_Z = 0.010$	Conservative low-damage scenario. The policy mix has positive welfare complementarity but negative absolute CEV_{mix}.
$\xi_Z = 0.050$	Higher-damage scenario. The absolute CEV_{mix} is positive throughout the current welfare grid.
ξ_Z^*	Break-even value for $CEV_{mix} = 0$. It is approximately 0.0188 to 0.0459 in the current grid.

Table S8: Steady-state target moments and model checks

Variable or ratio	Target or interpretation	Model steady state	Note
L	Steady-state labor supply	About $1/3$	Matched by $\chi = 7.7278315$
C/Y	Macro steady-state ratio	About 0.69	Consistent with quarterly DSGE allocation
I/Y	Macro steady-state ratio	About 0.21	Implied by $\delta_K K/Y$
K/Y	Determined by β, δ_K, α	About 8.5	Includes material and recycling sectors
X/W	About 0.25	About 0.25 to 0.26	Effective recyclability anchor
$R/$Mat	Non-targeted moment	About 0.04 to 0.06	Model-generated recycled-material share
N^w/W	$1 - X/W$	About 0.74 to 0.75	Unrecycled waste-flow share
W/Y	About 0.30	About 0.29 to 0.30	Waste-intensity anchor
q	Close to 1	About 1.00 to 1.09	Endogenous design quality
Γ/Y	Small positive value	Below 0.03%	Small design-cost share

Table S9: Steady-state policy outcomes for representative design paths ($\eta = 0.30$, $\lambda_X = 0.25$, $\xi_Z = 0.010$)

Design path (a, b)	R_{base}	R_{mix}	q_{base}	q_{mix}	Z_{base}	Z_{mix}	CEV_{mix}
Source-reduction-oriented $(0.2, 0.6)$	0.00656	0.00664	0.9985	1.0513	3.5993	3.4294	-0.0019
Balanced $(0.4, 0.4)$	0.00656	0.00671	0.9996	1.0409	3.5966	3.4720	-0.0023
Recyclability-oriented $(0.6, 0.2)$	0.00656	0.00676	1.0007	1.0299	3.5950	3.5054	-0.0026

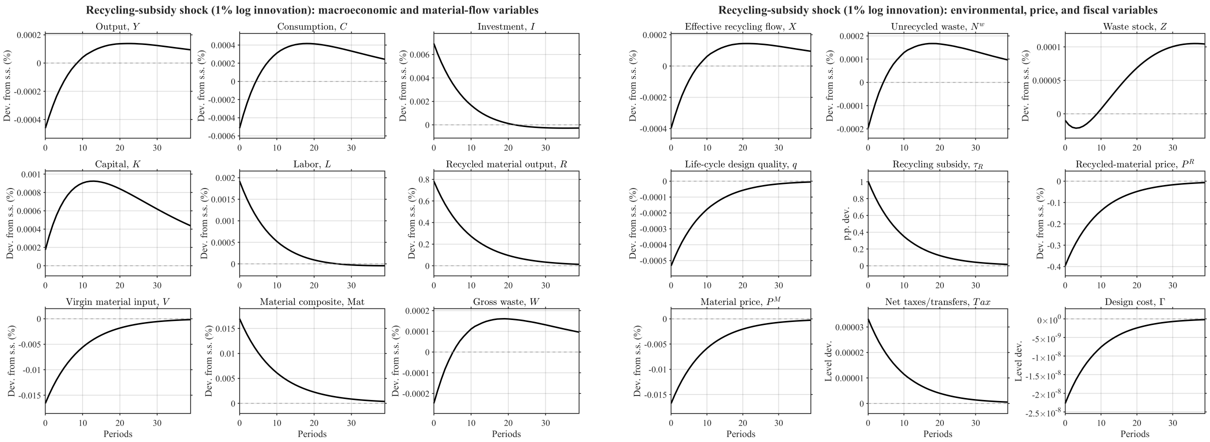
Note. Base denotes the no-new-policy regime and mix denotes the combination of recycling subsidy and EPR. CEV_{mix} is the consumption-equivalent welfare change of the policy mix relative to the no-new-policy benchmark.

S3 Supplementary numerical results and robustness checks

This section reports supplementary figures and parameter-grid statistics. The main text retains the figures needed for the core mechanism. The Supplementary Information provides full response sets, dynamic complementarity, single-policy welfare figures, phase-diagram decompositions, and sensitivity checks.

S3.1 Full policy-shock responses

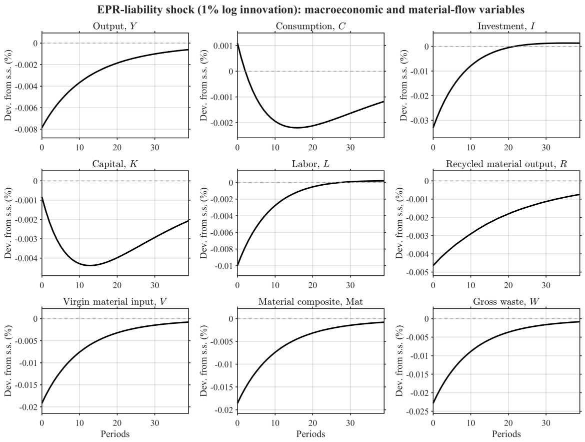
Figures S3 and S4 report the full variable sets for the two policy shocks. The recycling-subsidy shock mainly expands downstream recycled material output and changes material prices; its effects on design quality and the waste stock are much smaller and non-monotonic. The EPR-liability shock raises life-cycle design quality and lowers the unrecycled waste flow and the waste stock.



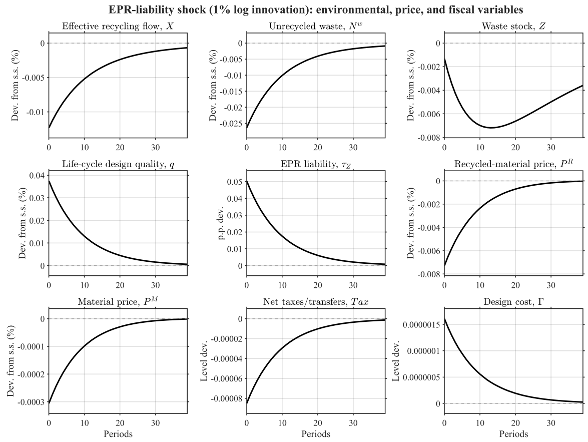
(a) Macroeconomic variables and material flows

(b) Environment, prices, and fiscal variables

Figure S3: Full dynamic responses to a recycling-subsidy shock. The shock is a one-percent log innovation around the existing-EPR steady state.



(a) Macroeconomic variables and material flows



(b) Environment, prices, and fiscal variables

Figure S4: Full dynamic responses to an EPR-liability shock. The shock is a one-percent log innovation around the existing-EPR steady state.

S3.2 Dynamic policy complementarity

Figure S5 reports dynamic policy complementarity under the baseline recycling-value pass-through parameter $\lambda_X = 0.25$. R_t complementarity is negative throughout the response horizon and converges toward zero. q_t complementarity is initially negative, becomes positive after the first few periods, and then dissipates. Z_t complementarity is positive at first but turns negative in the medium run; the later additional waste-stock reduction is strongest under source-reduction-oriented design, weaker under balanced design, and weakest under recyclability-oriented design.

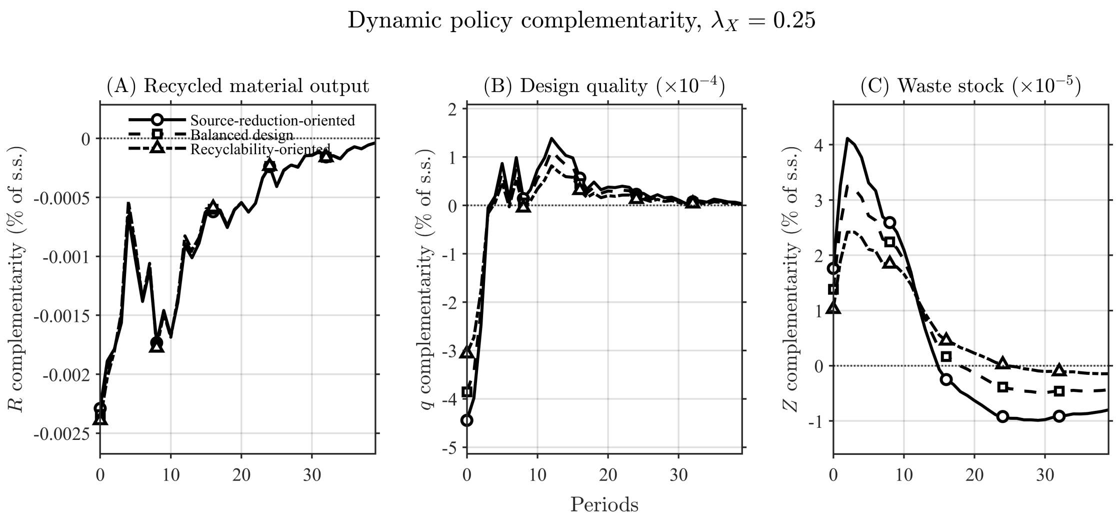


Figure S5: Dynamic policy-complementarity responses (baseline $\lambda_X = 0.25$)

S3.3 Higher recycling-flow elasticity parameter

Figure S6 reports the steady-state policy comparison for $\eta = 0.50$. A higher recycling-flow elasticity parameter changes the level of recycled material output but not the ordering of mechanisms. Recycling subsidies mainly increase R, EPR mainly increases q and lowers Z, and the policy mix reflects the trade-off between downstream activity and upstream waste reduction.

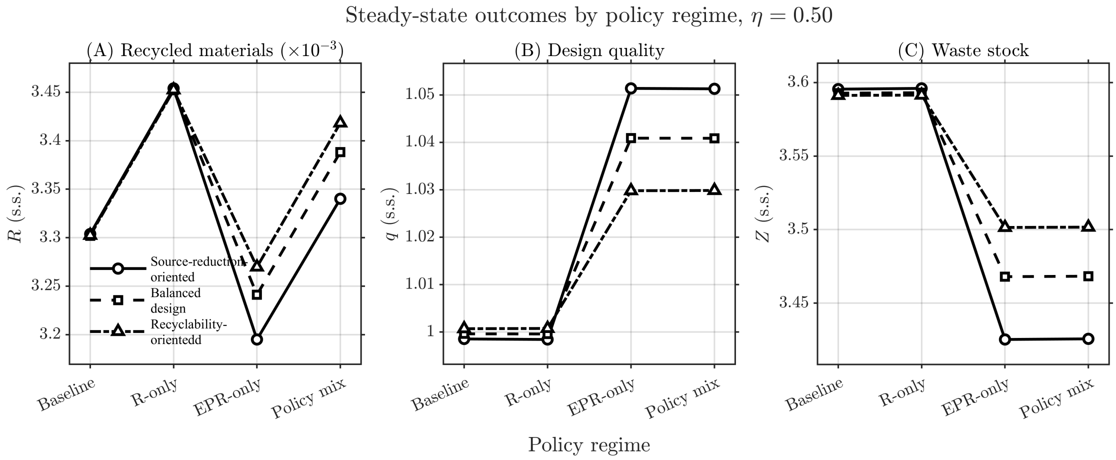


Figure S6: Steady-state outcomes under alternative policy regimes with a higher recycling-flow elasticity parameter at $\eta = 0.50$. The three design paths are defined in Table 2 of the main manuscript.

S3.4 Steady-state complementarity decompositions

Figures S7 and S8 show relative and level effects of steady-state policy complementarity across the recycling-flow elasticity parameter η. R-dimension complementarity remains negative throughout the range. In level terms, its magnitude moves closer to zero as η rises, whereas the corresponding relative interactions remain negative and do not show positive complementarity. q-dimension complementarity is positive under source-reduction-oriented design, smaller but positive under balanced design, and negative under recyclability-oriented design. Z-dimension complementarity indicates additional waste-stock reduction under source-reduction-oriented and balanced design, but not under recyclability-oriented design.

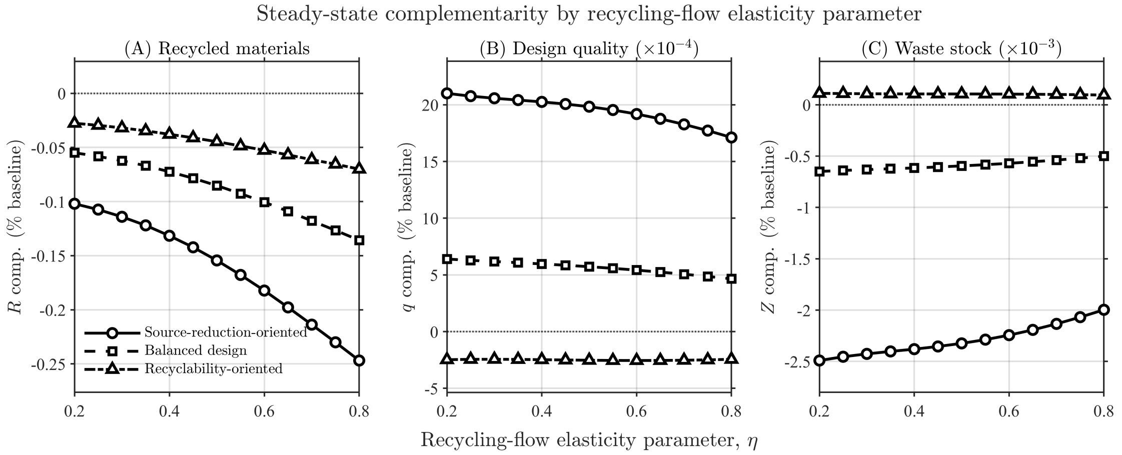


Figure S7: Relative steady-state policy complementarity across representative design paths and the recycling-flow elasticity parameter

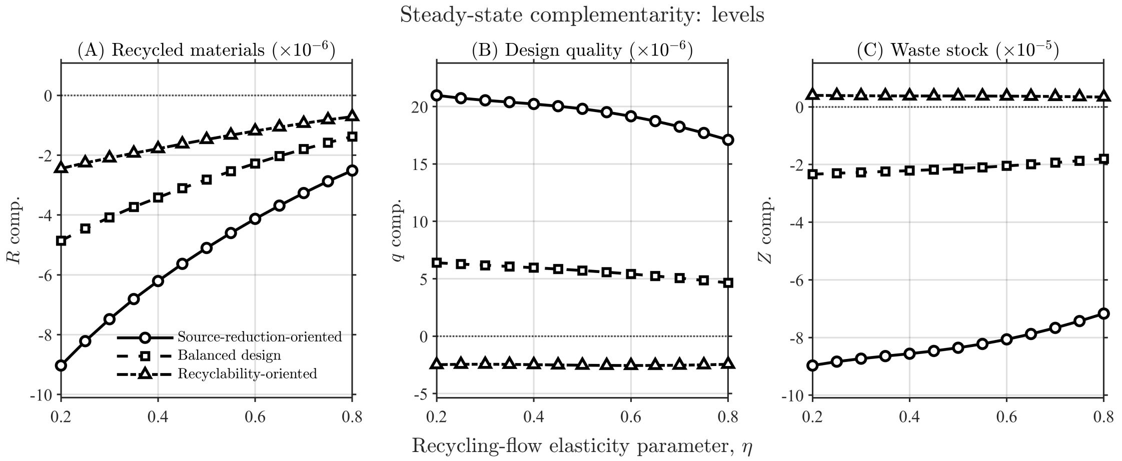
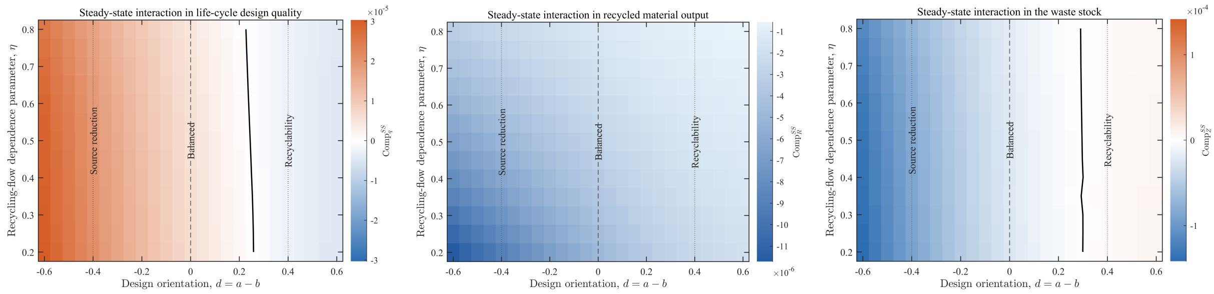


Figure S8: Level effects of steady-state policy complementarity across representative design paths and the recycling-flow elasticity parameter

S3.5 Two-dimensional phase-diagram decomposition

Figure S9 decomposes steady-state complementarity into design quality, recycled material output, and waste stock. The R dimension lacks robust positive complementarity over the grid. The q dimension is positive mainly in source-reduction regions. The Z dimension is the main source of the policy-region classification in the main text.



(a) Design-quality complementarity

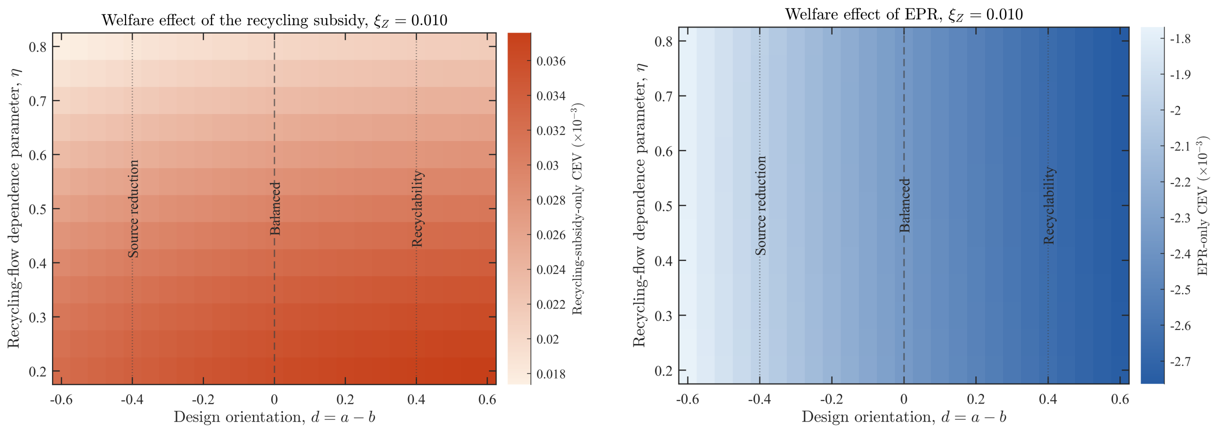
(b) Recycled material output complementarity

(c) Waste-stock complementarity

Figure S9: Steady-state complementarity decomposition in the two-dimensional phase diagram

S3.6 Single-policy welfare and welfare regions

Figure S10 reports the CEV of the two single-policy instruments under $\xi_Z = 0.010$. The recycling-subsidy-only policy delivers small positive welfare gains throughout the grid. The EPR-only CEV is negative throughout the grid and becomes more negative as design becomes more strongly recyclability-oriented. Figure S11 classifies welfare regions according to $CEV_{mix} > 0$ and $Comp_{CEV} > 0$. Under the conservative damage weight, all 325 grid points have positive welfare complementarity but a negative absolute CEV of the policy mix.



(a) Recycling-subsidy-only policy

(b) EPR-only policy

Figure S10: Consumption-equivalent welfare changes for single-policy instruments under $\xi_Z = 0.010$

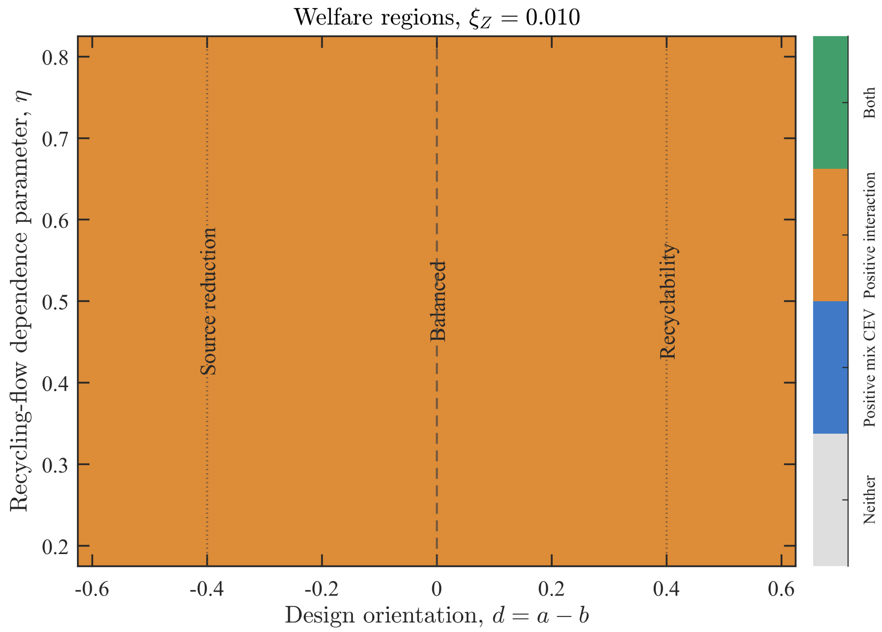


Figure S11: Policy regions from the welfare perspective. Colors represent combinations of $CEV_{mix} > 0$ and $Comp_{CEV} > 0$. Under the baseline, the entire evaluated grid has positive welfare complementarity but a negative absolute CEV of the policy mix.

S3.7 Sensitivity to the recycling-flow elasticity parameter, value pass-through, design cost, and conversion upper bound

Figures S12 to S15 report sensitivity to the recycling-value pass-through parameter λ_X, design cost ψ_q, and the recycling-flow elasticity parameter η. Figures S12 and S13 summarize peak, cumulative, and minimum dynamic-complementarity statistics rather than steady-state effects. Peak and cumulative R complementarity remain negative for all evaluated values of λ_X. Higher λ_X strengthens peak q complementarity and makes minimum Z complementarity more negative under source-reduction-oriented design. Higher ψ_q dampens design-quality complementarity and weakens the additional waste-stock reduction. Varying η mainly changes magnitudes and does not generate positive R complementarity.

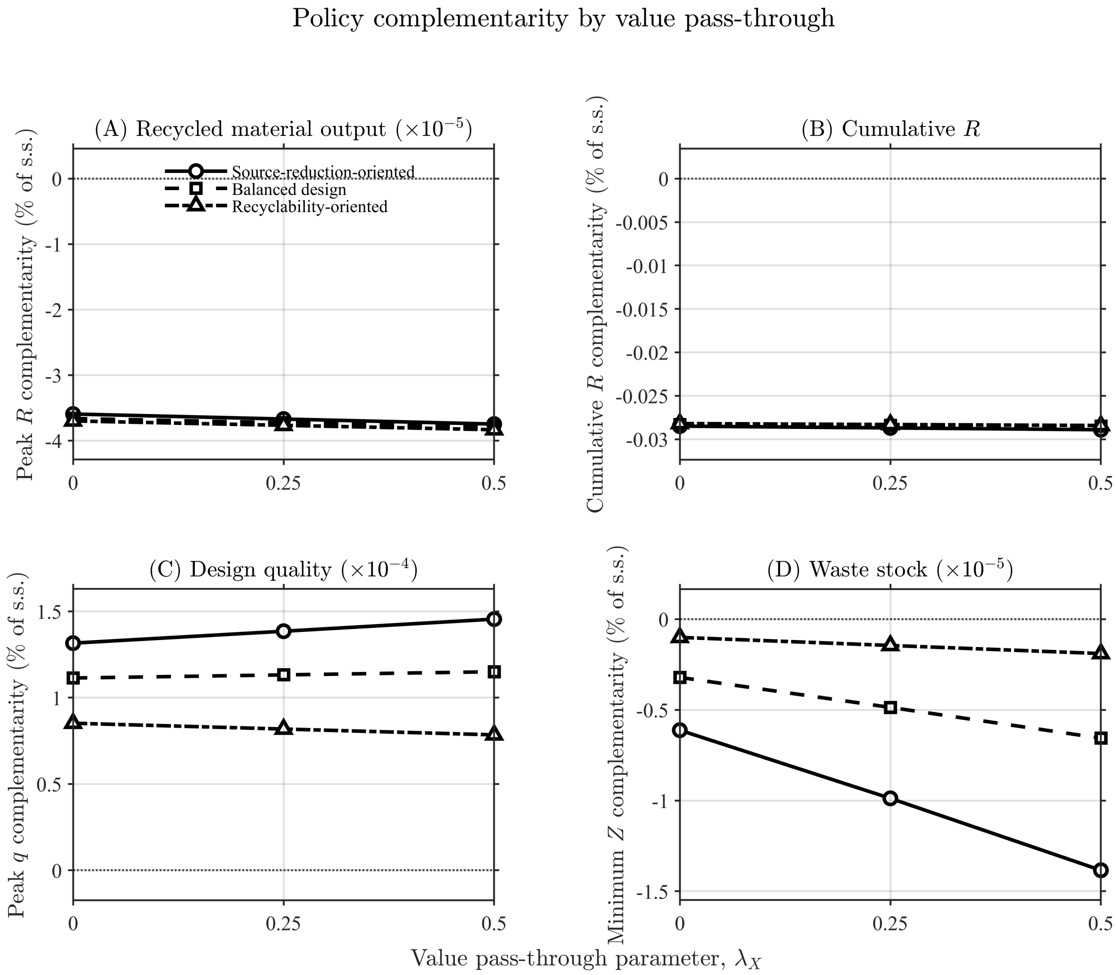


Figure S12: Relative dynamic-complementarity summaries under alternative values of the recycling-value pass-through parameter

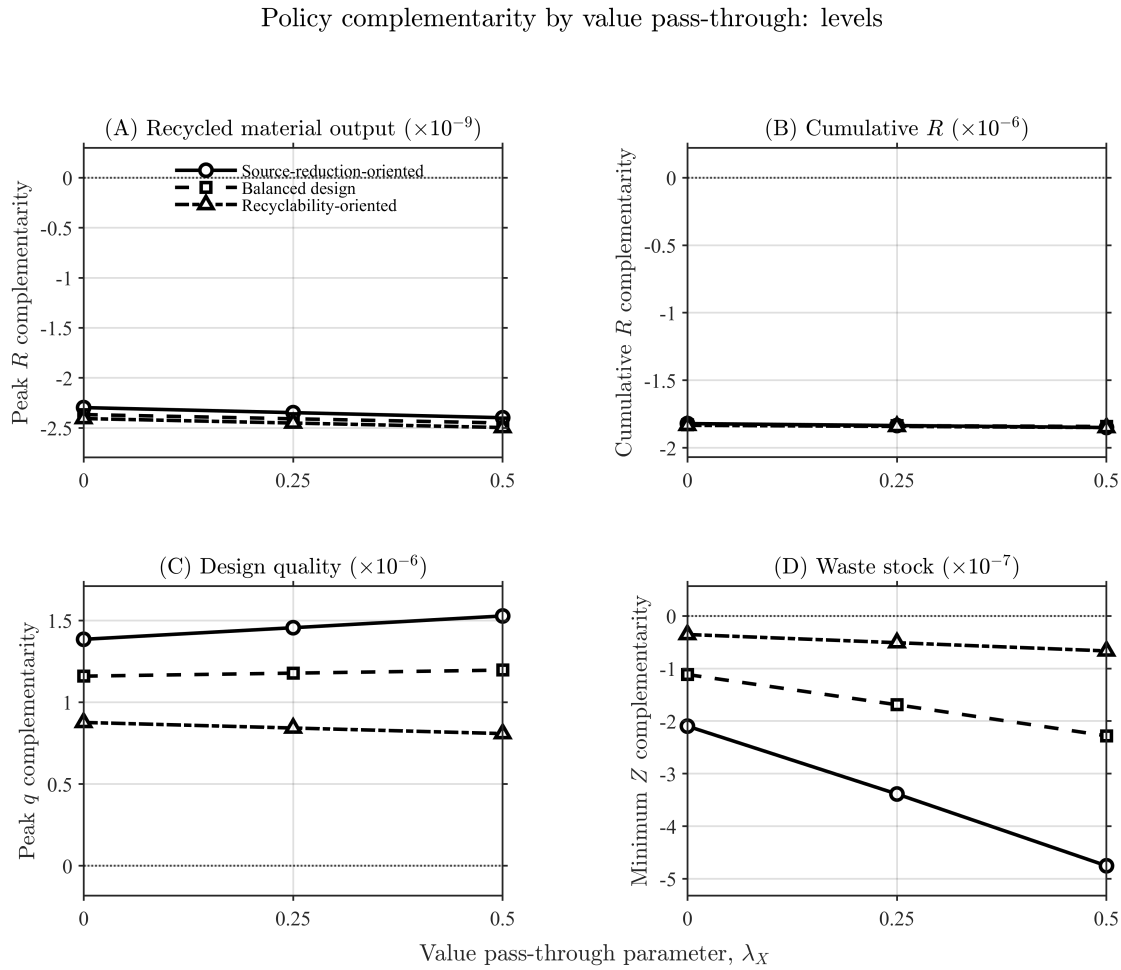


Figure S13: Level dynamic-complementarity summaries under alternative values of the recycling-value pass-through parameter

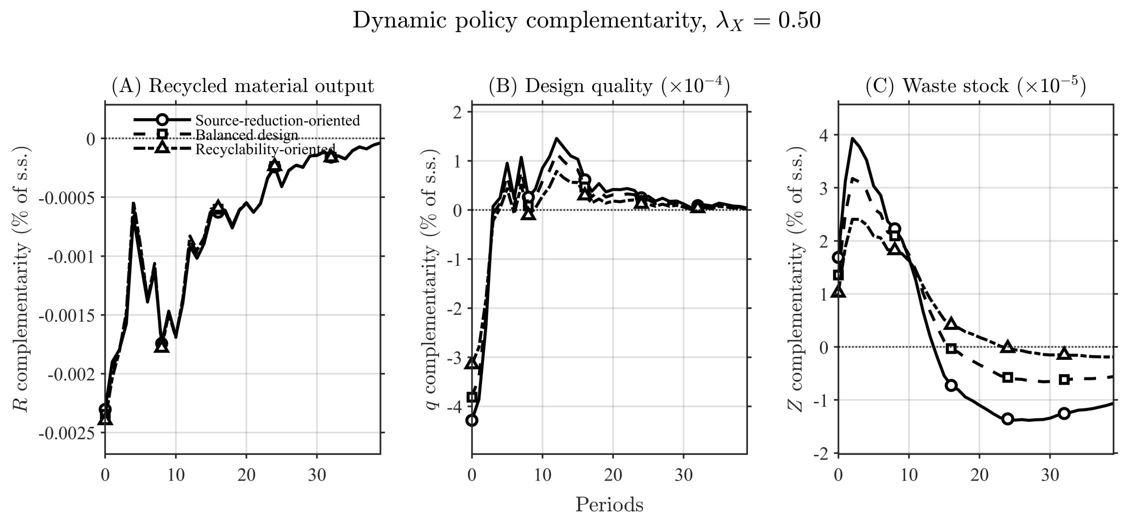


Figure S14: Dynamic policy-complementarity responses under a higher recycling-value pass-through parameter ($\lambda_X = 0.50$)

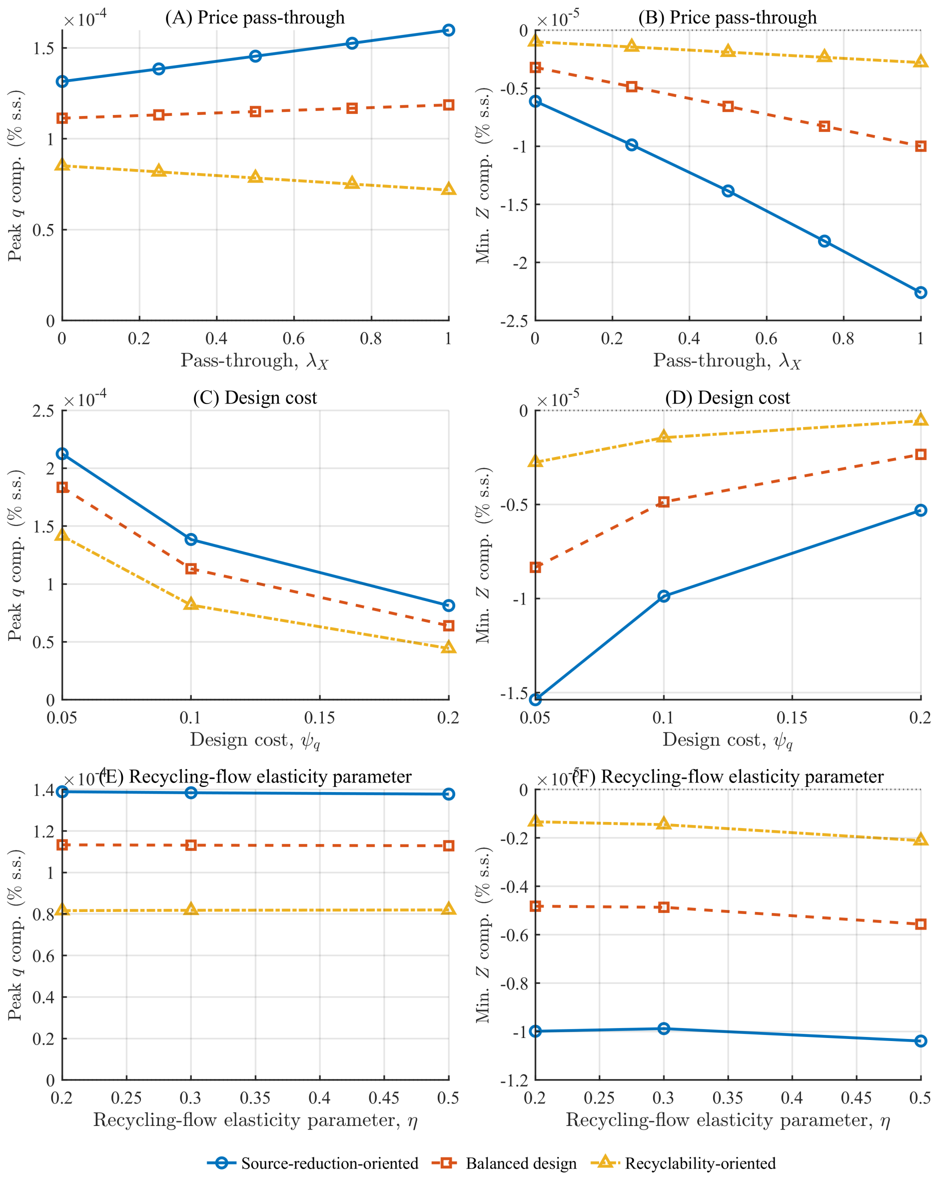


Figure S15: Policy-complementarity sensitivity to value pass-through, design cost, and the recycling-flow elasticity parameter

Figures S16 to S18 examine the conversion-rate upper bound $\bar{\rho}$. Increasing $\bar{\rho}$ from 0.80 to 0.95 leaves the signs of $Comp_R$, $Comp_q$, and $Comp_Z$ unchanged. The actual R/X ratio under the policy mix remains far below $\bar{\rho}$, so the main results are not mechanically driven by a binding conversion-rate ceiling.

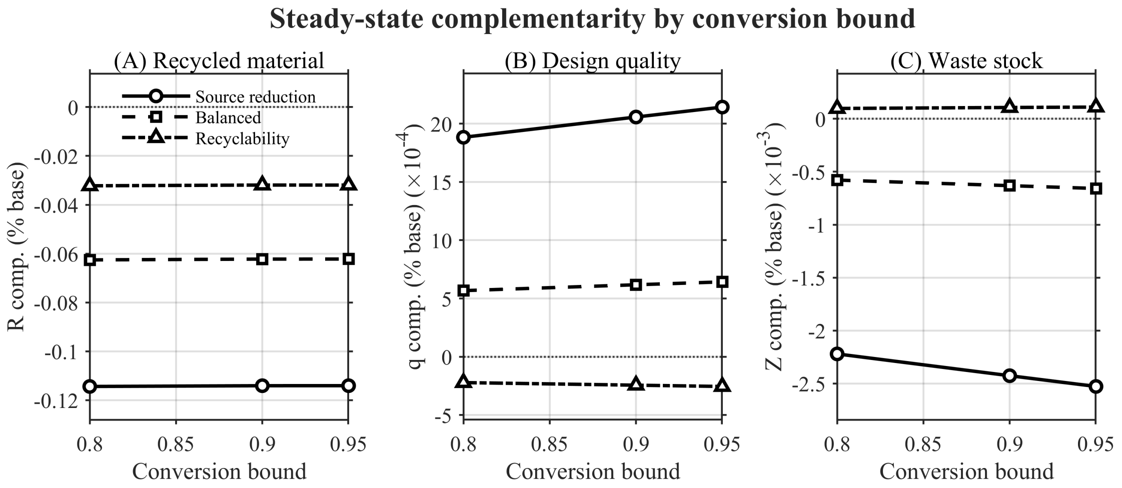


Figure S16: Steady-state policy complementarity under alternative recycling conversion-rate upper bounds

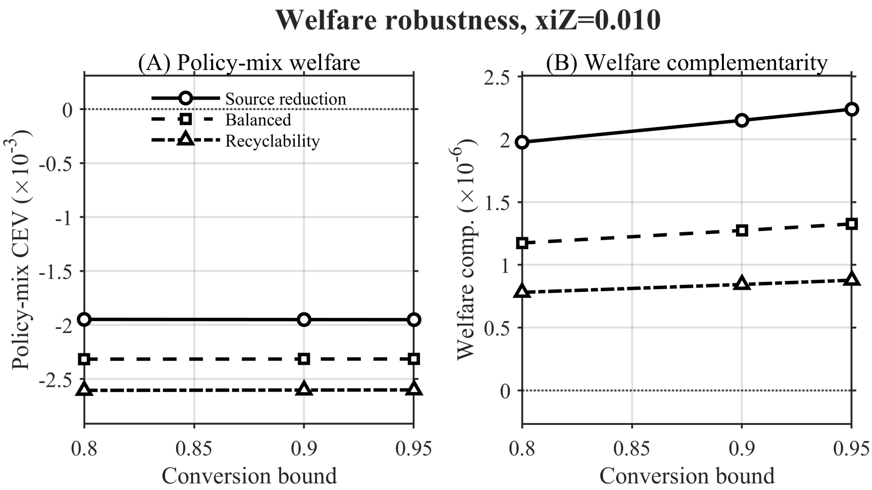


Figure S17: Welfare robustness under alternative recycling conversion-rate upper bounds ($\xi_Z = 0.010$)

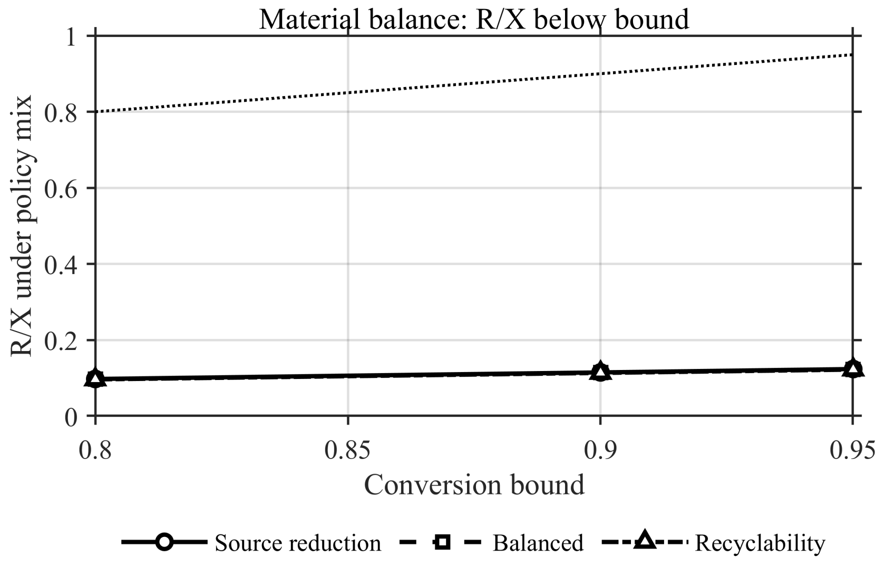


Figure S18: Material-conservation check for R/X under the policy mix and the conversion-rate upper bound

S3.8 Supplementary numerical tables

Table S10: Cross-check of steady-state policy-mix complementarity at the baseline recycling-flow elasticity parameter

Design path	η	$Comp_R/R_{base}$ (%)	$Comp_R \times 10^5$	$Comp_q \times 10^5$	$Comp_Z/Z_{base}$ (%)	$Comp_Z \times 10^4$
Source-reduction-oriented	0.30	-0.1141	-0.748	2.050	-0.0024	-0.864
Balanced	0.30	-0.0622	-0.408	0.618	-0.0006	-0.216
Recyclability-oriented	0.30	-0.0319	-0.209	-0.244	0.0001	0.036

Note. The relative columns reproduce Table 3 of the main manuscript. Level interactions are recovered using the path-specific baseline values in Supplementary Table S9. Negative $Comp_Z$ indicates additional waste-stock reduction relative to the additive benchmark.

Table S11: Supplementary welfare-grid statistics

Welfare scenario	$CEV_{mix} > 0$	$Comp_{CEV} > 0$	Main implication
$\xi_Z = 0$	0/325	325/325	Resource-reallocation and policy-distortion costs dominate without waste-stock damage.
$\xi_Z = 0.010$	0/325	325/325	Welfare complementarity is positive, but the absolute CEV of the policy mix remains negative.
$\xi_Z = 0.050$	325/325	325/325	The absolute CEV of the policy mix becomes positive throughout the current grid.

Note. The table reports grid-level welfare classifications for the same (d, η) grid used in the main text. The aggregate ranges under $\xi_Z = 0.010$ are reported in Table 4 of the main manuscript. Negative $Comp_Z$ indicates additional waste-stock reduction relative to the additive benchmark.

Table S12: Supplementary sensitivity statistics for mechanism parameters

Sensitivity group	Scenarios	Peak R comp. $\times 10^8$ range	Cum. R comp. $\times 10^5$ range	Peak q comp. $\times 10^6$ range	Min. Z comp. $\times 10^7$ range	Share with peak R comp. > 0
Recycling-flow elasticity parameter η	9	$[-0.24, -0.17]$	$[-0.18, -0.12]$	$[0.70, 1.78]$	$[-10.05, -1.12]$	0.0
Recycling-value pass-through parameter λ_X	15	$[-0.22, -0.18]$	$[-0.16, -0.15]$	$[0.71, 1.75]$	$[-9.44, -0.34]$	0.0
Design cost ψ_q	9	$[-0.23, -0.21]$	$[-0.17, -0.16]$	$[0.38, 2.90]$	$[-14.98, -0.99]$	0.0

Note. Peak and cumulative R complementarity are based on dynamic complementarity responses. Negative Z complementarity indicates additional waste reduction. No sensitivity group produces positive peak R complementarity.