Online Appendix for “Design Implications of Extended Producer Responsibility for Durable Products”

OA1. Proof of Lemma A1 in §A1

Under the recycling target R and the collection target λ imposed by EPR, the producer solves the following maximization problem:

$$\max_{p,r} \Pi(p,r;\rho,\delta) = \left(\frac{1+\delta-p}{1+3\delta}\right)\left(p-g(\rho,\delta)+\lambda(-\frac{1}{2}\beta r^2+(\alpha+\rho)r)\right),$$
$$\text{subject to: } R \leq r \leq 1, \quad 1-\theta_1 \geq 0, \quad \theta_1-\theta_2 \geq 0, \quad \theta_2 \geq 0, \quad p_u \geq 0.$$

The market clearing condition $1-\theta_1 = \theta_1-\theta_2$ means $\theta_1-\theta_2 \geq 0$ is redundant as we keep $1-\theta_1 \geq 0$. Furthermore, consumer θ_2 (by definition) is indifferent between choosing U or I, i.e., $\delta\theta_2 - p_u = 0$, yielding $\theta_2 = p_u/\delta$; hence $p_u \geq 0$ is redundant as we retain $\theta_2 \geq 0$. Therefore, the full set of constraints to analyze the problem is $1-r \geq 0$, $r-R \geq 0$, $1-\theta_1 \geq 0$ and $\theta_2 \geq 0$. Substituting the expressions of θ_1 and θ_2 from §3.1, the last two constraints can be written as $(1+\delta-p)/(1+3\delta) \geq 0$ and $(2p-1+\delta)/(1+3\delta) \geq 0$, which are equivalent to $1+\delta-p \geq 0$ and $2p-1+\delta \geq 0$ since $1+3\delta > 0$. We associate Lagrange multipliers with all the constraints to form the Lagrangian of the problem:

$$L = \frac{-p+(1+\delta)}{1+3\delta}\left(p-g(\rho,\delta)+\lambda(-\frac{1}{2}\beta r^2+(\alpha+\rho)r)\right)+\lambda_1(1-r)+\lambda_2(r-R)+\lambda_3(1+\delta-p)+\lambda_4(2p+\delta-1).$$

The Karush-Kuhn-Tucker (KKT) conditions yield the following:

$$0 = \frac{\partial L}{\partial p} = \left(-\frac{1}{1+3\delta}\right)\left(2p-(1+\delta+g(\delta,\rho)-\lambda((\alpha+\rho)r-\frac{1}{2}\beta r^2)\right)-\lambda_3+2\lambda_4,$$
$$0 = \frac{\partial L}{\partial r} = \left(-\frac{1}{1+3\delta}\right)((\alpha+\rho)-\beta r)-\lambda_1+\lambda_2.$$

There are 9 possible cases (excluding inconsistent cases such as the one with both $1-r=0$ and $r-R=0$).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$1-r$	>0	$=0$	$=0$	>0	>0	$=0$	>0	>0	>0
$r-R$	>0	>0	>0	$=0$	$=0$	>0	$=0$	>0	>0
$1+\delta-p$	>0	$=0$	>0	>0	$=0$	>0	>0	$=0$	>0
$2p-(1-\delta)$	>0	>0	$=0$	$=0$	>0	>0	>0	>0	$=0$

We analyze each of them below, and we suppress the arguments of $g(\rho,\delta)$ for brevity.

(1) In this case, $\lambda_1=\lambda_2=\lambda_3=\lambda_4=0$. Substituting them into the KKT conditions, we derive one candidate for the optimal solution to be $r=(\alpha+\rho)/\beta$ and $p=(1+\delta+g-\lambda(\alpha+\rho)^2/2\beta)/2$. Moreover, the resulting Hessian is negative definite, confirming this candidate solution to be a local maximizer.

To ensure the validity of this candidate solution, we need $R \leq r = (\alpha+\rho)/\beta \leq 1$ and $(1-\delta)/2 \leq p = (1+\delta+g-\lambda(\alpha+\rho)^2/2\beta)/2 \leq 1+\delta$. Simplifications reduce them to $0 \leq \alpha+\rho \leq \beta$ and $-(1+\delta-g) \leq \lambda(\alpha+\rho)^2/2\beta \leq (g+2\delta)$. Note that the latter inequality always holds because $\lambda(\alpha+\rho)^2/2\beta$ is the effective unit recycling value at $r = (\alpha+\rho)/\beta$, which has to be lower than the unit production cost, otherwise it leads to the unreasonable case where the producer can generate a steady profit stream by simply producing and then recycling the products. Therefore, $\lambda(\alpha+\rho)^2/2\beta \le g \le g + 2\delta$. Moreover, $1+\delta-g+\lambda(\alpha+\rho)^2/2\beta$ is the unit profit for the producer (accounting for both the production cost and the recycling value), which has to be non-negative to keep the producer in the market, and hence $-(1+\delta-g) \le \lambda(\alpha+\rho)^2/2\beta$.

(2) In this case, $r = 1$ and $p = 1+\delta$, which lead to zero production and zero profit. This uninteresting case is discarded.

(3) In this case, $r = 1$ and $p = (1-\delta)/2$, with $\lambda_1 = ((\alpha+\rho)-\beta)/(1+3\delta)$ and $\lambda_4 = (-2\delta - g + \lambda((\alpha+\rho)-\beta/2))/(2(1+3\delta))$. However, $\lambda_4 < 0$ because $\lambda(-\beta/2 + (\alpha+\rho)) < g < g + 2\delta$, with the LHS being the effective unit recycling value at $r = 1$, which has to be lower than the unit production cost. Therefore, this candidate solution is invalid and hence discarded.

(4) In this case, $r = R$ and $p = (1-\delta)/2$, with $\lambda_2 = ((\alpha+\rho)-\beta R)/(1+3\delta)$ and $\lambda_4 = (-2\delta - g + \lambda((\alpha+\rho)R - \beta R^2/2))/(2(1+3\delta))$. However, similar to Case (3), $\lambda_4 < 0$ and hence this candidate solution is discarded.

(5) In this case, $r = R$ and $p = 1+\delta$, which lead to zero production and zero profit. This uninteresting case is discarded.

(6) In this case, $r = 1$ and $p = (1+\delta+g-\lambda((\alpha+\rho)-\beta/2))/2$. To ensure the validity of this candidate solution, we need $\lambda_1 = (\alpha+\rho-\beta)/(1+3\delta) \ge 0$ and $(1-\delta)/2 \le p = (1+\delta+g-\lambda((\alpha+\rho)-\beta/2))/2 \le 1+\delta$, with the latter inequality being satisfied following an argument similar to that in Case (1).

(7) In this case, $r = R$ and $p = (1+\delta+g-\lambda((\alpha+\rho)R-\beta R^2/2))/2$. To ensure the validity of this candidate solution, we need $\lambda_2 = (\beta R - (\alpha+\rho))/(1+3\delta) \ge 0$ and $(1-\delta)/2 \le p = (1+\delta+g-\lambda((\alpha+\rho)R-\beta R^2/2))/2 \le 1+\delta$, with the latter inequality again satisfied following an argument similar to that in Case (1).

(8) In this case, $p = 1+\delta$, which leads to zero production and zero profit. This uninteresting case is discarded.

(9) In this case, $r = (\alpha+\rho)/\beta$ and $p = (1-\delta)/2$. However, similar to Case (3), $\lambda_4 = (-2\delta - g + \lambda(\alpha+\rho)^2/2\beta)/(2(1+3\delta)) < 0$ and hence this candidate solution is discarded.

Finally, the optimal new product price and recycling level are summarized below.

(i) When $(\alpha+\rho)/\beta \le R$	(ii) When $R < (\alpha+\rho)/\beta < 1$	(iii) When $1 \le (\alpha+\rho)/\beta$
$r^*(\delta,\rho) = R$	$r^*(\delta,\rho) = (\alpha+\rho)/\beta$	$r^*(\delta,\rho) = 1$
$p^* = (1+\delta+g-\lambda((\alpha+\beta)R-\beta R^2/2))/2$	$p^* = (1+\delta+g-\lambda(\alpha+\rho)^2/2\beta)/2$	$p^* = (1+\delta+g-\lambda((\alpha+\beta)-\beta/2))/2$

Equivalently, the optimal price is $p^*(\rho,\delta) = (1+\delta+g(\rho,\delta)-\lambda(-\beta(r^*(\rho,\delta))^2/2+(\alpha+\rho)r^*(\rho,\delta)))/2$.

Lemma A1 identifies three recycling scenarios that will be observed in equilibrium, which map well to the range of recycling choices in practice. The first case (i.e., $r^* = R$) represents scenarios where voluntary recycling is not profitable enough and hence the recycling target is binding at optimality. This outcome represents the case of regulated markets, either due to low recycling margins (α is small), or a quick drop in the marginal recycling value when the recycling level increases (β is high). The second case (i.e., $r^* = (\alpha + \rho)/\beta$) represents voluntary (and partial) recycling beyond compliance requirements. This outcome represents the case of the car industry subject to legislation such as the End of Life Vehicles Directive, where voluntary recycling has reportedly exceeded the compliance requirement levels (Smink 2006). Finally, the last case with full recycling, i.e., $r^* = 1$, represents markets for valuable commodities such as aluminum cans.

OA2. Details of the Proofs of Propositions 2 - 4 in §4.2 and Proposition A4 in §A2.

All of Propositions 2 - 4 are derived based on the closed-form solutions of δ^* and ρ^* from Propositions 1 and A1 - A3. For Proposition 2, we can prove that $\partial\delta^*/\partial R \geq 0$, $\partial\delta^*/\partial\lambda \geq 0$, $\partial\rho^*/\partial R \geq 0$ and $\partial\rho^*/\partial\lambda \geq 0$ when $d \leq 0$.

OA 2.1. Details of the Proof of Proposition 3

For Proposition 3 with $d > 0$, we first derive the recycling target thresholds R_{dl} and R_d based on the closed-form characterization of the optimal durability in Proposition A3. As mentioned in the paper, we focus on the case where the recycling targets are binding at optimality so as to highlight the EPR-induced design changes.

Note that when $\rho^* = (R\lambda - d\delta)/(2)\tau$:

$$\Pi(\delta) = \Pi_1(\delta) = \frac{(\delta - b_1\delta^2 + A_1)^2(F_1)^2}{4(1+3\delta)} \text{ with } A_1 = \frac{R^2\lambda^2 + 4(1-m)\tau + 4(R\alpha - R^2\beta/2)\lambda\tau}{-2dR\lambda + 4\tau} \text{ and } b_1 = \frac{4\tau b - d^2}{4\tau - 2dR\lambda}.$$

Hence δ^* will be as stated in Proposition A3 with $A = A_1$ and $b = b_1$, with

$$\delta_{int} = \frac{(4\tau - 2d\lambda R)\left(\sqrt{\frac{\left(d^2-4\tau^2\right)\left(4d^2+24d\lambda R-4\tau(27m+4\tau-15)+27\lambda R^2(\lambda-2\beta\tau)+108\alpha\lambda R\tau\right)}{(d\lambda R-2\tau)^2}+9} - \frac{2\left(d^2-4\tau^2\right)}{d\lambda R-2\tau} + 3\right)}{18\left(4\tau^2 - d^2\right)},$$

and

$$\frac{\partial\delta_{int}}{\partial R} = \frac{(4\tau - 2d\lambda R)\left(\frac{2d\lambda\left(d^2-4\tau^2\right)}{(d\lambda R-2\tau)^2} - \frac{2\lambda\left(d^2-4\tau^2\right)\left(2d^3+6d^2\lambda R+d\tau(-54m+27\alpha\lambda R-8\tau+42)+27\tau(2\alpha\tau+R(\lambda-2\beta\tau))\right)}{(d\lambda R-2\tau)^3\sqrt{\frac{\left(d^2-4\tau^2\right)\left(4d^2+24d\lambda R-4\tau(27m+4\tau-15)+27\lambda R^2(\lambda-2\beta\tau)+108\alpha\lambda R\tau\right)}{(d\lambda R-2\tau)^2}+9}}\right)}{18\left(4\tau^2 - d^2\right)}$$
$$- \frac{d\lambda\left(\sqrt{\frac{\left(d^2-4\tau^2\right)\left(4d^2+24d\lambda R-4\tau(27m+4\tau-15)+27\lambda R^2(\lambda-2\beta\tau)+108\alpha\lambda R\tau\right)}{(d\lambda R-2\tau)^2}+9} - \frac{2\left(d^2-4\tau^2\right)}{d\lambda R-2\tau} + 3\right)}{9\left(4\tau^2 - d^2\right)}.$$

When $\rho^* = 0$:

$$\Pi(\delta) = \Pi_4(\delta) = \frac{(\delta - b_4\delta^2 + A_4)^2 (F_4)^2}{4(1+3\delta)} \text{ with } A_4 = -m - \frac{1}{2}\beta\lambda R^2 + \alpha\lambda R + 1 \text{ and } b_4 = \tau.$$

Hence δ^* will be as stated in Proposition A3 with $A = A_4$ and $b = b_4$, with $\delta_{int} = (\sqrt{2\tau(54m + 27\lambda R(\beta R - 2\alpha) + 8(\tau+3)) + 9} - 4\tau + 3)/(18\tau)$, and $\partial\delta_{int}/\partial R = (3\lambda(\beta R - \alpha))/(\sqrt{2\tau(54m + 27\lambda R(\beta R - 2\alpha) + 8(\tau+3)) + 9})$.

Combining all these results, we can show that $(\partial\delta^*)/(\partial R) < 0$ when $R \in [R_{dl}, R_d]$ with

$$R_{dl} \doteq \min[1, \max[0, R'_1, R'_2, R^1_\delta]],$$

$$R_d \doteq \min[1, \max[0, \min[R_3, R^0_\delta]]], \text{ where}$$

$$R'_1 \doteq \frac{3d\lambda - 3d^2\alpha\lambda - 4d\lambda\tau + \sqrt{d^2\lambda\left(\lambda(-3+3d\alpha+4\tau)^2 - 6(-1+3m)\left(d^2\beta - 6\lambda\tau\right)\right)}}{3\lambda\left(-d^2\beta + 6\lambda\tau\right)},$$

$$R'_2 \doteq \frac{3d^2\alpha\lambda + d\lambda(-3+4\tau) + \sqrt{d^2\lambda\left(\lambda(-3+3d\alpha+4\tau)^2 - 6(-1+3m)\left(d^2\beta - 6\lambda\tau\right)\right)}}{3\lambda\left(d^2\beta - 6\lambda\tau\right)},$$

$$R^0_\delta \doteq \frac{\sqrt{(12\alpha\lambda\tau + 4d\lambda)^2 + 48\lambda(3m-1)\tau(\lambda - 2\beta\tau)} - 4\lambda(3\alpha\tau + d)}{6\lambda(\lambda - 2\beta\tau)},$$

$$R^1_\delta \doteq \frac{-6\alpha\lambda\tau + \sqrt{3\lambda(\lambda - 2\beta\tau)\left(13d^2 + 4\tau(3m - 13\tau + 2)\right) + (6\alpha\lambda\tau + 5d\lambda)^2} - 5d\lambda}{3\lambda(\lambda - 2\beta\tau)},$$

$$\begin{aligned} R_{1,2} \doteq {} & \frac{36\alpha\tau^3 - 2d^3 - 9\alpha d^2\tau + 8d\tau^2 + 3d\tau}{3\left(12\beta\tau^3 - 3\beta d^2\tau + 2d^2\lambda - 6\lambda\tau^2\right)} \pm \frac{1}{\sqrt{3}} \\ & \sqrt{\begin{aligned} & \Big(-2\beta d^8\tau - 12\alpha d^7\lambda\tau - 27\alpha^2 d^6\lambda\tau^2 + 24\beta d^6\tau^3 - 30\beta d^6\tau^2 - 4d^6\lambda\tau^2 + 24d^6\lambda\tau + 54\beta d^6 m\tau^2 - 36d^6\lambda m\tau \\ & + 96\alpha d^5\lambda\tau^3 + 18\alpha d^5\lambda\tau^2 + 216\alpha^2 d^4\lambda\tau^4 - 96\beta d^4\tau^5 + 240\beta d^4\tau^4 - 18\beta d^4\tau^3 + 32d^4\lambda\tau^4 - 156d^4\lambda\tau^3 \\ & + 9d^4\lambda\tau^2 - 432\beta d^4 m\tau^4 + 252d^4\lambda m\tau^3 - 192\alpha d^3\lambda\tau^5 - 72\alpha d^3\lambda\tau^4 - 432\alpha^2 d^2\lambda\tau^6 + 128\beta d^2\tau^7 - 480\beta d^2\tau^6 \\ & + 72\beta d^2\tau^5 - 64d^2\lambda\tau^6 + 240d^2\lambda\tau^5 - 36d^2\lambda\tau^4 + 864\beta d^2 m\tau^6 - 432d^2\lambda m\tau^5 \Big) \Big/ \Big((12\beta\tau^3 - 3\beta d^2\tau + 2d^2\lambda \\ & - 6\lambda\tau^2)^2 \left(24\beta\tau^3 - 6\beta d^2\tau + 3d^2\lambda - 12\lambda\tau^2\right) \Big) \end{aligned}}, \end{aligned}$$

$$R_3 \doteq \begin{cases} R_2 & \text{when } m \le \overline{m} \\ R_1 & \text{otherwise} \end{cases}, \text{ and}$$

$$\begin{aligned} \overline{m} \doteq {} & \Big(2d^4\beta + 12d^3\alpha\lambda - 6d\alpha\lambda\tau(3+8\tau) + d^2\left(2\beta(15-8\tau)\tau + \lambda\left(-24 + 4\tau + 27\alpha^2\tau\right)\right) + \tau(2\beta\tau(9 + 4\tau(-15+4\tau)) \\ & + \lambda(-4\left(4 + 27\alpha^2\right)\tau^2 - 9 + 60\tau)) \Big) \Big/ \Big(18\left(6\tau^2(\lambda - 2\beta\tau) + d^2(-2\lambda + 3\beta\tau)\right) \Big). \end{aligned}$$

Similarly, we derive the recycling target thresholds R_r and R_{rr} in Proposition 3 from the closed-form solution of ρ^* for $d > 0$ from Proposition A2. We show that $(\partial\rho^*)/(\partial R) < 0$ when $R \in [R_r, R_{rr}]$ with

$$R_r \doteq \begin{cases} R_d & \text{when } m \le \overline{m} \\ \min[1, \max[0, R^\rho_2, R^0_\rho]] & \text{otherwise} \end{cases},$$

$$R_{rr} \doteq \begin{cases} \min[1, \max[0, \min[R^\rho_1, R^1_\rho]]] & \text{when } d \le \overline{d} \\ 1 & \text{otherwise} \end{cases}, \text{ where } \overline{d} \doteq \sqrt{\frac{\lambda\tau}{\beta}},$$

$$
\begin{aligned}
&R_\rho^0 \doteq -\frac{4\lambda(3\alpha\tau+d)+\sqrt{(12\alpha\lambda\tau+4d\lambda)^2+48\lambda(3m-1)\tau(\lambda-2\beta\tau)}}{6\lambda(\lambda-2\beta\tau)},\\
&R_\rho^1 \doteq -\frac{6\alpha\lambda\tau+\sqrt{3\lambda(\lambda-2\beta\tau)\left(13d^2+4\tau(3m-13\tau+2)\right)+(6\alpha\lambda\tau+5d\lambda)^2}+5d\lambda}{3\lambda(\lambda-2\beta\tau)},\\
&R_{1,2}^\rho \doteq \frac{1}{3\left(\beta d^2-6\lambda\tau\right)\left(6\tau^2(\lambda-2\beta\tau)+d^2(3\beta\tau-2\lambda)\right)}\Biggl(\left(-36\alpha\tau^3+2d^3+9\alpha d^2\tau-d\tau(8\tau+3)\right)\left(\beta d^2-6\lambda\tau\right)\\
&\mp\sqrt{2}\sqrt{\begin{aligned}&\left(d^2-6\tau^2\right)^2\left(\beta d^2-6\lambda\tau\right)\left(2\beta d^4+12\alpha d^3\lambda+d^2\left(\lambda\left(27\alpha^2\tau+36m+4\tau-24\right)-2\beta\tau(27m+8\tau-15)\right)\right.\\&\left.-6\alpha d\lambda\tau(8\tau+3)+\tau(\lambda\left(-4\tau\left(27\alpha^2\tau+27m+4\tau-15\right)-9\right)+2\beta\tau(4\tau(27m+4\tau-15)+9))\right)\end{aligned}}\Biggr).
\end{aligned}
$$

Based on these closed-form results, it is straightforward to show that $R_{rr}=1$ when $d>\overline{d}$; and $R_d \le R_r$, with $R_d = R_r$ when $m \le \overline{m}$.

OA 2.2. Details of the Proof of Proposition 4

For Proposition 4 with $d>0$, we first derive the collection target threshold λ_d based on the closed-form characterization of the optimal durability in Proposition A3, we show that $(\partial\delta^*)/(\partial\lambda)<0$ when $\lambda \ge \lambda_d$ with

$$\lambda_d \doteq \min[1, \max[0, \lambda_1, \lambda_\delta^1, \lambda_\delta^0]], \text{ where}$$

$$
\begin{aligned}
&\lambda_\delta^1 \doteq \frac{\sqrt{R^2\left(3\left(13d^2+4\tau(3m-13\tau+2)\right)+(6\alpha\tau+5d-3\beta R\tau)^2\right)}-5dR+3\beta R^2\tau-6\alpha R\tau}{3R^2},\\
&\lambda_\delta^0 \doteq \frac{\sqrt{d^2R^2\left((-6\alpha d+3\beta dR-8\tau+6)^2+144(3m-1)\tau\right)}+3d^2R(\beta R-2\alpha)+2dR(3-4\tau)}{36R^2\tau},\\
&\lambda_1 \doteq \frac{1}{12R^2\left(d^2-3\tau^2\right)}\Biggl(R\left(-4d^3+9d^2\tau(\beta R-2\alpha)+2d\tau(8\tau+3)+36\tau^3(2\alpha-\beta R)\right)+\\
&\sqrt{\begin{aligned}&d^2R^2\tau(24d^3(\beta R-2\alpha)-d^2\left(144m+\tau\left(27(\beta R-2\alpha)^2+16\right)-96\right)+12d\tau(8\tau+3)(2\alpha-\beta R)+36\tau\\&+4\tau^2\left(108m+\tau(27(\beta R-2\alpha)^2+16)-60\right))\end{aligned}}\Biggr).
\end{aligned}
$$

To derive the thresholds λ_{rl}, λ_r in Proposition 4, we show that, based on the closed-form solution of ρ^* in Proposition A2, $\partial\rho^*/\partial\lambda<0$ when $\lambda\in[\lambda_{rl},\lambda_r]$ with

$$\lambda_{rl} = \min[1, \max[0, \lambda_3]],$$

$$\lambda_r = \min[1, \max[0, \min[\lambda_2, \lambda_\rho^0, \lambda_\rho^1]]], \text{ where}$$

$$
\begin{aligned}
&\lambda_\rho^0 = \frac{-\sqrt{d^2R^2\left((-6\alpha d+3\beta dR-8\tau+6)^2+144(3m-1)\tau\right)}+3d^2R(\beta R-2\alpha)+2dR(3-4\tau)}{36R^2\tau},\\
&\lambda_\rho^1 = -\frac{\sqrt{R^2\left(3\left(13d^2+4\tau(3m-13\tau+2)\right)+(6\alpha\tau+5d-3\beta R\tau)^2\right)}+5dR-3\beta R^2\tau+6\alpha R\tau}{3R^2},\\
&\lambda_3 = -\frac{\sqrt{R^2\left((6\alpha\tau+2d-3\beta R\tau)^2+12(3m-1)\tau\right)}+R(6\alpha\tau+2d-3\beta R\tau)}{3R^2},\\
&\lambda_2 \doteq \frac{1}{36R^2\tau\left(d^2-3\tau^2\right)}\Biggl(3R\tau\left(-4d^3+9d^2\tau(\beta R-2\alpha)+2d\tau(8\tau+3)+36\tau^3(2\alpha-\beta R)\right)+\\
&+\sqrt{3}\sqrt{\begin{aligned}&R^2\tau\left(d^2-6\tau^2\right)^2(24d^3(\beta R-2\alpha)-d^2\left(144m+\tau\left(27(\beta R-2\alpha)^2+16\right)-96\right)+12d\tau(8\tau+3)(2\alpha-\beta R)\\&+4\tau\left(\tau\left(108m+\tau\left(27(\beta R-2\alpha)^2+16\right)-60\right)+9\right))\end{aligned}}\Biggr).
\end{aligned}
$$

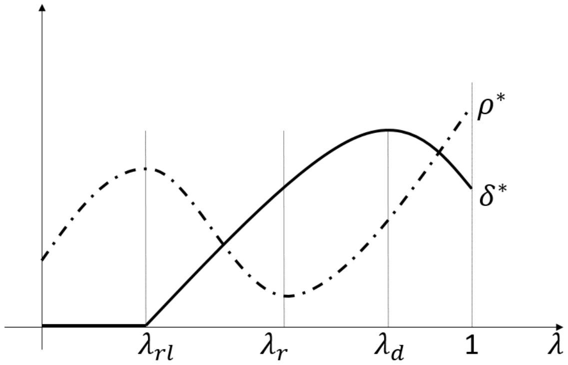


Figure OA1 **The structure of the effect of λ on δ^* and ρ^*.**

Based on these closed-form results, it is straightforward to show that $\lambda_r \leq \lambda_d$.

Figure OA1 provides a concise visualization of the optimal equilibrium durability and recyclability choices.

OA 2.3. Details of the Proof of Proposition A4

Based on the expression of the new production volume, we can show that $\partial q(p^*(\rho^*, \delta^*), \delta^*)/\partial R > 0$ when $\alpha > \overline{\alpha_R}$ and $\underline{m_R} < m < \overline{m_R}$ with:

$$\overline{\alpha_R} = \frac{-2d^3 + 9\beta d^2 R\tau - 6d^2 R + 8d\tau^2 + 3d\tau - 36\beta R\tau^3 + 18R\tau^2}{9d^2\tau - 36\tau^3},$$

$$\underline{m_R} = (2d^4 + 12d^3 R - 27\beta d^2 R^2\tau + 18d^2 R^2 + 54\alpha d^2 R\tau - 16d^2\tau^2 + 30d^2\tau - 48dR\tau^2 - 18dR\tau + 108\beta R^2\tau^3$$
$$- 54R^2\tau^2 - 216\alpha R\tau^3 + 32\tau^4 - 120\tau^3 + 18\tau^2)/(54d^2\tau - 216\tau^3),$$

$$\overline{m_R} = (-144\alpha^2\tau^5 - 4\alpha d^5 + 4\beta d^5 R - 9\alpha^2 d^4\tau - 9\beta^2 d^4 R^2\tau + 6\beta d^4 R^2 + 18\alpha\beta d^4 R\tau + 8d^4 + 32\alpha d^3\tau^2 + 6\alpha d^3\tau$$
$$- 32\beta d^3 R\tau^2 - 6\beta d^3 R\tau + 8d^3 R\tau + 72\alpha^2 d^2\tau^3 + 72\beta^2 d^2 R^2\tau^3 - 60\beta d^2 R^2\tau^2 + 12d^2 R^2\tau - 144\alpha\beta d^2 R\tau^3$$
$$+ 36\alpha d^2 R\tau^2 - 32d^2\tau^2 + 3d^2\tau - 64\alpha d\tau^4 - 24\alpha d\tau^3 + 64\beta dR\tau^4 + 24\beta dR\tau^3 - 32dR\tau^3 - 12dR\tau^2 - 144\beta^2 R^2\tau^5$$
$$+ 144\beta R^2\tau^4 - 36R^2\tau^3 + 288\alpha\beta R\tau^5 - 144\alpha R\tau^4)/(12d^4 - 48d^2\tau^2).$$

On the other hand, $\partial q(p^*(\rho^*, \delta^*), \delta^*)/\partial\lambda > 0$ when $\alpha > \overline{\alpha_\lambda}$ and $\underline{m_\lambda} < m < \overline{m_\lambda}$ with:

$$\overline{\alpha_\lambda} = \frac{-4d^3 + 9\beta d^2 R\tau - 12d^2\lambda R + 16d\tau^2 + 6d\tau - 36\beta R\tau^3 + 36\lambda R\tau^2}{18d^2\tau - 72\tau^3},$$

$$\underline{m_\lambda} = (2d^4 + 12d^3\lambda R - 27\beta d^2\lambda R^2\tau + 18d^2\lambda^2 R^2 + 54\alpha d^2\lambda R\tau - 16d^2\tau^2 + 30d^2\tau - 48d\lambda R\tau^2 - 18d\lambda R\tau$$
$$+ 108\beta\lambda R^2\tau^3 - 54\lambda^2 R^2\tau^2 - 216\alpha\lambda R\tau^3 + 32\tau^4 - 120\tau^3 + 18\tau^2)/(54d^2\tau - 216\tau^3),$$

$$\overline{m_\lambda} = (-10368\alpha^2\tau^6 - 24d^6 - 288\alpha d^5\tau + 144\beta d^5 R\tau - 144d^5\lambda R - 648\alpha^2 d^4\tau^2 - 162\beta^2 d^4 R^2\tau^2 + 324\beta d^4\lambda R^2\tau$$
$$- 216d^4\lambda^2 R^2 + 648\alpha\beta d^4 R\tau^2 - 648\alpha d^4\lambda R\tau + 192d^4\tau^2 + 216d^4\tau + 2304\alpha d^3\tau^3 + 432\alpha d^3\tau^2 - 1152\beta d^3 R\tau^3$$
$$- 216\beta d^3 R\tau^2 + 1152d^3\lambda R\tau^2 + 216d^3\lambda R\tau + 5184\alpha^2 d^2\tau^4 + 1296\beta^2 d^2 R^2\tau^4 - 2592\beta d^2\lambda R^2\tau^3 + 1512d^2\lambda^2 R^2\tau^2$$
$$- 5184\alpha\beta d^2 R\tau^4 + 5184\alpha d^2\lambda R\tau^3 - 384d^2\tau^4 - 864d^2\tau^3 - 4608\alpha d\tau^5 - 1728\alpha d\tau^4 + 2304\beta dR\tau^5 + 864\beta dR\tau^4$$
$$- 2304d\lambda R\tau^4 - 864d\lambda R\tau^3 - 2592\beta^2 R^2\tau^6 + 5184\beta\lambda R^2\tau^5 - 2592\lambda^2 R^2\tau^4 + 10368\alpha\beta R\tau^6 - 10368\alpha\lambda R\tau^5)$$
$$/(216d^4\tau - 864d^2\tau^3).$$

OA3. Robustness of Propositions 3 and 4 to the $b=\tau$ Assumption

In the paper,we assume $b=\tau$ to facilitate the derivation of the closed-form characterizations in Propositions 3 and 4. Our analysis below demonstrates that our results are also robust to the variations of the relative values of b and τ.

Step I. We fix the value of β (to simplify the analysis, as β does not seem critical in characterizing the optimal designs as shown by the previous analysis and results) and τ, we also let $d=\tau$ (so that $d>0$, where design trade-off matters). Meanwhile, we allow b to vary. Then we study how the optimal recyclability and durability choices are influenced by the recycling and the collection targets. We show that the optimal design solutions have similar structures as those in our main model with the assumption $b=\tau$; i.e., Propositions 3 and 4 are still valid. We show the results of the case with $\beta=1$ and $d=\tau=7$ below for an illustration. In this case,

—$\exists$ R^b_{dl}, R^b_d, where $0\le R^b_{dl}\le R^b_d\le 1$ such that the optimal durability δ^* decreases in R if $R\in[R^b_{dl}, R^b_d]$ and (weakly) increases otherwise.

—$\exists$ R^b_r, R^b_{rr} where $0\le R^b_r\le R^b_{rr}\le 1$ and $\overline{d}^b\ge 0$, such that the optimal recyclability ρ^* decreases in R if $R\in[R^b_r, R^b_{rr}]$ and (weakly) increases otherwise; moreover, $R^b_{rr}=1$ when $d\ge\overline{d}^b$; and $R^b_d\le R^b_r$, with $R^b_d=R^b_r$ when $m\le\overline{m}^b$.

—$\exists\lambda^b_d\ge 0$ such that the optimal durability δ^* decreases in λ if $\lambda\ge\lambda^b_d$, and (weakly) increases otherwise.

—$\exists\lambda^b_{rl}, \lambda^b_r$ such that $0\le\lambda^b_{rl}\le\lambda^b_r\le 1$ and the optimal recyclability ρ^* decreases in λ if $\lambda\in[\lambda^b_{rl}, \lambda^b_r]$, and (weakly) increases otherwise. Furthermore, $\lambda^b_r\le\lambda^b_d$.

Specifically, the recycling target thresholds for the durability are

$$R^b_{dl}\doteq\min[1,\max[0,R'^b_1,R'^b_2,R^{1b}_\delta]],$$

$$R^b_d\doteq\min[1,\max[0,\min[R^b_3,R^{0b}_\delta]]],\ \text{where}$$

$$R'^b_1\doteq-\frac{7\left(\sqrt{\lambda\left(\lambda\left(9(1-7\alpha)^2+16b^2+12b(14\alpha+9m-5)\right)-882m+294\right)}+\lambda(21\alpha+4b-3)\right)}{3\lambda(6b\lambda-49)},$$

$$R'^b_2\doteq\frac{7\left(\sqrt{\lambda\left(\lambda\left(9(1-7\alpha)^2+16b^2+12b(14\alpha+9m-5)\right)-882m+294\right)}+\lambda(-21\alpha-4b+3)\right)}{3\lambda(6b\lambda-49)},$$

$$R^{0b}_\delta\doteq\frac{2\left(\sqrt{7}\sqrt{\lambda((21\alpha(3\alpha+2)+4)\lambda+9(\lambda-14)m+42)}-7(3\alpha+1)\lambda\right)}{3(\lambda-14)\lambda},$$

$$R^{1b}_\delta\doteq\frac{-84\alpha\lambda+\sqrt{(84\alpha\lambda+70\lambda)^2-84(\lambda-14)\lambda(52b-12m-99)}-70\lambda}{6(\lambda-14)\lambda},$$

$$\begin{aligned}R^b_1\doteq&\frac{1}{3(\lambda-14)(6b(\lambda-14)-14\lambda+147)}+(-28(9\alpha+2)b(\lambda-14)+7(-154+63\alpha(\lambda-14)+11\lambda)\\&+7((\lambda-14)(16b^2(\lambda-14)+4b((21\alpha(9\alpha+4)-22)\lambda+27(\lambda-14)m+406)-3\lambda(7\alpha(63\alpha+22)+84m-59)\\&+2646m-2282))^{1/2}),\end{aligned}$$

$$R^b_2\doteq\frac{2\left(\sqrt{7}\sqrt{\lambda((21\alpha(3\alpha+2)+4)\lambda+9(\lambda-14)m+42)}-7(3\alpha+1)\lambda\right)}{3(\lambda-14)\lambda},$$

$$R_3^b \doteq \begin{cases} R_2^b & \text{when } m \leq \overline{m}^b \\ R_1^b & \text{otherwise} \end{cases}, \text{ and}$$

$$\overline{m}^b \doteq \frac{1323\alpha^2\lambda + 462\alpha\lambda - 16b^2\lambda + 224b^2 - 756\alpha^2 b\lambda - 336\alpha b\lambda + 88b\lambda - 1624b - 177\lambda + 2282}{108b\lambda - 1512b - 252\lambda + 2646}.$$

The recycling target thresholds for the recyclability are

$$R_r^{1b} \doteq \begin{cases} R_d^{1b} & \text{when } m \leq \overline{m}^b \\ \min[1, \max[0, R_2^{\rho b}, R_\rho^{0b}]] & \text{otherwise} \end{cases},$$

$$R_{rr}^{1b} \doteq \begin{cases} \min[1, \max[0, \min[R_1^\rho, R_\rho^{1b}]]] & \text{when } d \leq \overline{d}^b \\ 1 & \text{otherwise} \end{cases}, \text{ where } \overline{d}^b \doteq \sqrt{7\lambda},$$

$$R_\rho^{0b} \doteq -\frac{2\left(7(3\alpha+1)\lambda + \sqrt{7}\sqrt{\lambda((21\alpha(3\alpha+2)+4)\lambda + 9(\lambda-14)m + 42)}\right)}{3(\lambda-14)\lambda},$$

$$R_\rho^{1b} \doteq -\frac{84\alpha\lambda + \sqrt{(84\alpha\lambda + 70\lambda)^2 - 84(\lambda-14)\lambda(52b - 12m - 99)} + 70\lambda}{6(\lambda-14)\lambda},$$

$$\begin{aligned} R_{1,2}^{\rho b} \doteq {} & \frac{1}{3(6b(\lambda-14) - 14\lambda + 147)(6b\lambda - 49)}\Bigg(-343(63\alpha+11) + 14b(98(9\alpha+2) + 3\lambda(63\alpha - 4(9\alpha+2)b + 11)) \\ & + \sqrt{14}\sqrt{\begin{aligned} & (7-6b)^2(6b\lambda-49)(16b^2(\lambda-14) + 4b((21\alpha(9\alpha+4) - 22)\lambda + 27(\lambda-14)m + 406) + 2646m \\ & -2282 - 3\lambda(7\alpha(63\alpha+22) + 84m - 59)) \end{aligned}}\Bigg). \end{aligned}$$

The collection target threshold for the durability is

$$\lambda_d^b \doteq \min[1, \max[0, \lambda_1^b, \lambda_\delta^{1b}, \lambda_\delta^{0b}]], \text{ where}$$

$$\lambda_\delta^{1b} \doteq -\frac{2\sqrt{7}\sqrt{R^2\left(-156b + 36m + 7(6\alpha - 3R + 5)^2 + 297\right)} - 42R^2 + 84\alpha R + 70R}{6R^2},$$

$$\lambda_\delta^{0b} \doteq -\frac{7\left(\sqrt{R^2\left(64b^2 + 48b(14\alpha + 9m - 7R - 5) + 9(-14\alpha + 7R + 2)^2\right)} + R(42\alpha + 8b - 21R - 6)\right)}{36bR^2},$$

$$\begin{aligned} \lambda_1^b \doteq {} & \frac{7R}{12(-7+3b)R^2}\Bigg(126\alpha + 4b(-18\alpha + 9R - 4) - 63R + 22 + \\ & \sqrt{64b^2 + 4b\left(84\alpha(9\alpha+4) + 108m + 189R^2 - 84(9\alpha+2)R - 88\right) - 12(154\alpha + 84m - 77R - 59) - 1323(R - 2\alpha)^2}\Bigg). \end{aligned}$$

The collection target thresholds for the recyclability are

$$\lambda_{rl}^b = \min[1, \max[0, \lambda_3^b]],$$

$$\lambda_r^b = \min[1, \max[0, \min[\lambda_2^b, \lambda_\rho^{0b}, \lambda_\rho^{1b}]]], \text{ where}$$

$$\begin{aligned} \lambda_2^b \doteq {} & \frac{1}{36b(3b-7)R^2}\Bigg(21bR(126\alpha + 4b(-18\alpha + 9R - 4) - 63R + 22) + \sqrt{21} \\ & \sqrt{\begin{aligned} & (7-6b)^2 bR^2(64b^2 + 4b\left(84\alpha(9\alpha+4) + 108m + 189R^2 - 84(9\alpha+2)R - 88\right) - 1323(R-2\alpha)^2 \\ & -12(154\alpha + 84m - 77R - 59)) \end{aligned}}\Bigg), \end{aligned}$$

$$\lambda_\rho^{0b} = \frac{7\left(\sqrt{R^2\left(64b^2 + 48b(14\alpha + 9m - 7R - 5) + 9(-14\alpha + 7R + 2)^2\right)} + R(-42\alpha - 8b + 21R + 6)\right)}{36bR^2},$$

$$\lambda_\rho^{1b} = \frac{2\sqrt{7}\sqrt{R^2\left(-156b + 36m + 7(6\alpha - 3R + 5)^2 + 297\right)} + 42R^2 - 84\alpha R - 70R}{6R^2},$$

$$\lambda_3^b = -\frac{\sqrt{7}\sqrt{R^2\left(36m + 7(6\alpha - 3R + 2)^2 - 12\right)}}{3R^2} - \frac{14(3\alpha+1)}{3R} + 7.$$

Step II. We fix the value of β and b, and let $d=b$, but this time we allow τ to vary. We again solve for the optimal design decisions, and the results in Propositions 3 and 4 still remain robust. We continue with the example in Step I with $\beta=1$, but this time we change $d=b=7$ and we let τ to vary. Then in this case,

—$\exists\ R_{dl}^{\tau}, R_{d}^{\tau}$, where $0 \leq R_{dl}^{\tau} \leq R_{d}^{\tau} \leq 1$ such that the optimal durability δ^* decreases in R if $R \in [R_{dl}^{\tau}, R_{d}^{\tau}]$ and (weakly) increases otherwise.

—$\exists\ R_{r}^{\tau}, R_{rr}^{\tau}$ where $0 \leq R_{r}^{\tau} \leq R_{rr}^{\tau} \leq 1$ and $\overline{d}^{\tau} \geq 0$, such that the optimal recyclability ρ^* decreases in R if $R \in [R_{r}^{\tau}, R_{rr}^{\tau}]$ and (weakly) increases otherwise; moreover, $R_{rr}^{\tau}=1$ when $d \geq \overline{d}^{\tau}$; and $R_{d}^{\tau} \leq R_{r}^{\tau}$, with $R_{d}^{\tau}=R_{r}^{\tau}$ when $m \leq \overline{m}^{\tau}$.

—$\exists \lambda_{d}^{\tau} \geq 0$ such that the optimal durability δ^* decreases in λ if $\lambda \geq \lambda_{d}^{\tau}$, and (weakly) increases otherwise.

—$\exists \lambda_{rl}^{\tau}, \lambda_{r}^{\tau}$ such that $0 \leq \lambda_{rl}^{\tau} \leq \lambda_{r}^{\tau} \leq 1$ and the optimal recyclability ρ^* decreases in λ if $\lambda \in [\lambda_{rl}^{\tau}, \lambda_{r}^{\tau}]$, and (weakly) increases otherwise. Furthermore, $\lambda_{r}^{\tau} \leq \lambda_{d}^{\tau}$.

The expressions of the thresholds have similar structures as the Step I results, and hence are omitted for brevity.

The above analyses combined demonstrate that the insights provided by Propositions 3 and 4 continue to hold when $b \neq \tau$.

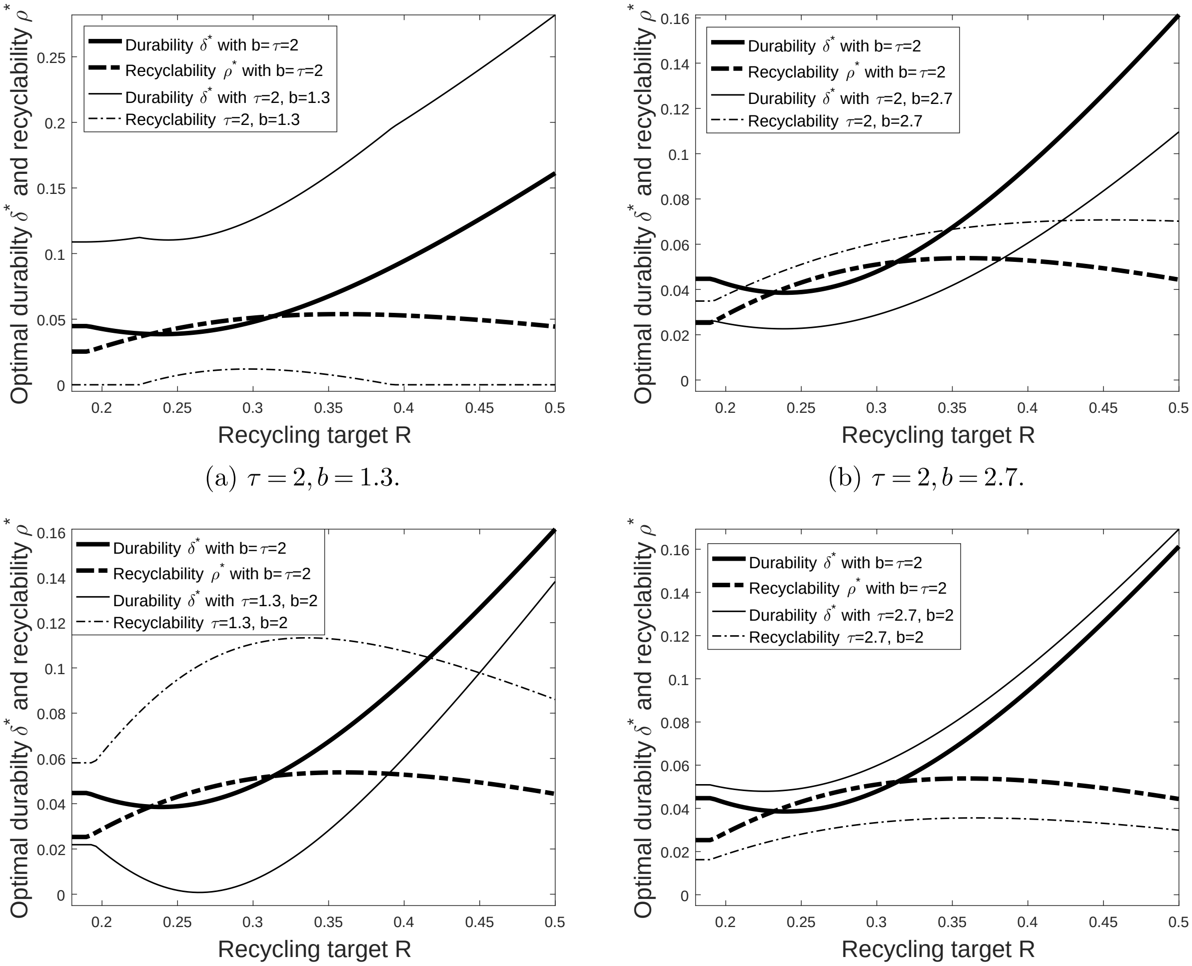
Step III. We also conduct extensive numerical analyses with varying values of b and τ (we show one set of examples in which we change the relative values of b and τ in Figure OA2, more examples are also available from the authors), all the results further support the robustness of our results to the assumption of $b=\tau$.

OA4. Details of the Calibrated Numerical Study in §5

We describe the details of the three steps of the calibrated numeral study as mentioned in Appendix A3.

Step I. We derive the values of $\alpha_j+\rho_j$ and β_j for both c-Si ($j=1$) and CdTe ($j=2$) technologies by using the recycling data. To this end, we first capture the recoverable material value from recycling, and then incorporate the costs of transportation and treatment for recycling into the analysis.

To capture the recoverable material value from recycling, we collect data on the material components of PVPs, as well as the recovery rates and the market prices of all the composition elements. Note that the market prices correspond to a 100% purity level, which may not always be achieved by the current recycling technologies. Therefore, the actual values of the recovered materials may be lower but these values are good approximations. The table shown in Figure OA3 summarizes the data (Cucchiella et al. 2015, BIO 2011, BINE 2010, Takahashi et al. 2011, USGS 2015). We



(a) $\tau = 2, b = 1.3$.

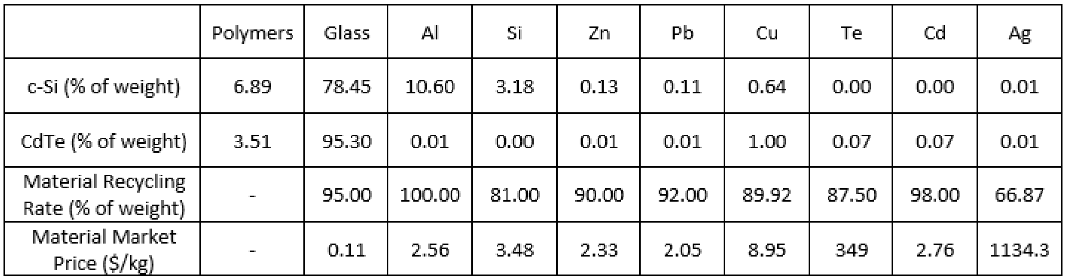
(b) $\tau = 2, b = 2.7$.

(c) $\tau = 1.3, b = 2$.

(d) $\tau = 2.7, b = 2$.

Figure OA2 Optimal design choices under varying values of b and τ.

$\alpha = 1.5, \beta = 8, m = 0.6, d = 2$.



	Polymers	Glass	Al	Si	Zn	Pb	Cu	Te	Cd	Ag
c-Si (% of weight)	6.89	78.45	10.60	3.18	0.13	0.11	0.64	0.00	0.00	0.01
CdTe (% of weight)	3.51	95.30	0.01	0.00	0.01	0.01	1.00	0.07	0.07	0.01
Material Recycling Rate (% of weight)	-	95.00	100.00	81.00	90.00	92.00	89.92	87.50	98.00	66.87
Material Market Price ($/kg)	-	0.11	2.56	3.48	2.33	2.05	8.95	349	2.76	1134.3

Figure OA3 The material composition of different PVPs.

also obtain the average weights of the panels to be 102 kg/kW and 200 kg/kW for the c-Si and the CdTe technologies, respectively (BIO 2011, Okopol 2007). We can now calculate the recycling level (r_{mj}) that accounts for the recoverable material value for a panel based on technology j in the following way: For every composition element of the panel, multiply its percentage of the total weight by its recovery rate; and then sum over all the elements of the panel. We can also derive the unit recycling material value v_{mj} in the following way: For every composition element, multiply its percentage of the total weight by the average weight of the panel, and further multiply the result by the market price; and then sum over all the elements of the panel. Next, let $\alpha_{mj}+\rho_j$ represent the highest marginal recycling value of the product that only accounts for the recoverable material value, given the recyclability of the technology. Then based on $r_{mj}=\min[1,\max[(\alpha_{mj}+\rho_j)/\beta_j,0]]$ and $v_{mj}=-\beta_j r_{mj}^2/2+(\alpha_{mj}+\rho_j)r_{mj}^2$, we can calculate $\alpha_{mj}+\rho_j$ and β_j for both technologies, by $\beta_j=2v_{mj}/r_{mj}^2$ and $\alpha_{mj}+\rho_j=2v_{mj}/r_{mj}$ (since $0<(\alpha_{mj}+\rho_j)/\beta_j<1$).

Now we incorporate the cost of recycling into our estimates. The transportation and treatment cost arising from end-of-life product recycling can vary depending on the location and the quantity, but it is estimated to have an industrial average of $c=\$420$/ton (Choi and Fthemakis 2014, Fthenmakis and Moskowitz 2008, BIO 2011), and it is comparable for both technologies. Based on the average weights of the panels, we convert the cost into \$/kW (a measure that is commonly used in the industry); specifically, $c_1=\$42.4$/kW and $c_2=\$89$/kW. Note that the transportation and treatment cost applies to the entire product unit. Therefore, the final unit recycling value v_{j0} should be the unit recycled material value net of the transportation and treatment cost; i.e., $v_{j0}=v_{mj}-c_j$. We assume the transportation and treatment cost applies in a uniform manner to the product unit and hence β_j remains unchanged. Substituting the relevant data into the equations, we arrive at the following results: $\beta_1=0.1425$ and $\beta_2=0.2257$; $v_{10}=24.57$ and $v_{20}=30.706$. Then we can also solve for r_{j0} and $\alpha_j+\rho_{j0}$ based on $r_{j0}=\min[1,\max[0,(\alpha_j+\rho_j)/\beta_j]]$ and $v_j=-\beta_j r_j^2/2+(\alpha_j+\rho_j)r_j$. The results are: $r_{10}=0.587$ and $r_{20}=0.522$; $\alpha_1+\rho_1=83.69$ and $\alpha_2+\rho_2=117.72$.

Step II. Studies show that the degradation rates for c-Si and CdTe technologies are approximately 0.5%/year and 1.95%/year, respectively (Belluardo et al. 2014, Ye et al. 2014, Coker 2015, Haroon 2015). Moreover, PVPs commonly have an expected lifespan of 25 years, which makes a 12.5-year period consistent with our model assumption of a two-period product useful life. Therefore, we estimate the durabilities as $\delta_1=(1-0.5\%)^{12.5}=0.94$ and $\delta_2=(1-1.95\%)^{12.5}=0.78$.

Step III. We show how we recover X_j from the market data. First, we collect data on the current prices of PVPs and the production costs: $p_1=\$1.31\times10^3$/kW, $p_2=\$1.07\times10^3$/kW, $g_1=\$0.98\times10^3$/kW and $g_2=\$0.74\times10^3$/kW (Goodrich et al. 2012, Woodhouse et al. 2013, IRENA 2012). When consumers of type θ obtain a per-period utility of $X_j\theta$ from a new panel, we re-solve our model in a similar way as before and derive the equilibrium price in the baseline case to be $p_j=(X_j(1+\delta_j)+g_j-\lambda_0 v_{j0})/2$. Therefore, $X_j=(2p_j-g_j+\lambda_0 v_{j0})/(1+\delta_j)$; and calculations give $X_1=0.848$ and $X_2=0.791$. Next, based on the generalization of our model with X_j, the producer profit in the baseline case is $\Pi_{j0}=(X_j(1+\delta_j)-g_j+\lambda_0 v_{j0})^2/4X_j(1+\delta_j)$, whereas the profit in the legislated case will be $\Pi_j=(X(1+\delta_j)-g_j+\lambda v_j)^2/4X_j(1+\delta_j)$ with $r_j=\max[R,r_{j0}]$

and $v_j = -\beta_j (r_j)^2/2 + (\alpha_j + \rho_j) r_j$. Then $\Delta\Pi_j = (\Pi_{j0} - \Pi_j)/\Pi_{j0}$. Based on this measure, Figure 3 in the paper shows the regions defined by $\min[\Delta\Pi_1, \Delta\Pi_2]$, i.e., the range of the collection and the recycling targets within which technology j has a lower EPR-induced profit margin erosion. Moreover, the figure also demonstrates how the regions change as the transportation cost varies.

OA5. Details of the Extension with A Competitive Market in §6

In this section, we describe the process of constructing the numerical study for the case where the primary market for new product sales is competitive with both the focal (high-end) and the competing (low-end) producers. Given the sequential nature of the problem, we solve the problem backward by first identifying the optimal new product prices and the recycling levels chosen by the two producers and then solve for the design decisions.

We first derive the market demands for both producers given the product designs. The per-period utilities that a type θ consumer can obtain from the different consumer strategies are (recall that k is the relative perceived value of the competitor's new products compared to the focal producer's, with $0 < k < 1$): $V[N_f, \theta] = \theta - p_f + p_{uf}$, $V[U_f, \theta] = \delta_f \theta - p_{uf}$, $V[N_c, \theta] = k\theta - p_c + p_{uc}$, $V[U_c, \theta] = k\delta_c \theta - p_{uc}$, and $V[I, \theta] = 0$. As mentioned in the paper, the different design decisions of the producers may lead to the following three different market segmentation outcomes: (i) The FFCC outcome emerges ($l = 1$) when $0 \le k\delta_c \le k \le \delta_f \le 1$; (ii) the FCFC outcome emerges ($l = 2$) when $0 \le k\delta_c \le \delta_f \le k \le 1$; and (iii) the FCCF outcome emerges ($l = 3$) when $0 \le \delta_f \le k\delta_c \le k \le 1$.

When the FFCC outcome emerges (given that $0 \le k\delta_c \le k \le \delta_f \le 1$), consumers of descending type θ choose N_f, U_f, N_c, U_c, I, respectively. Specifically, there exist $\theta_1^{c1}, \theta_2^{c1}, \theta_3^{c1}, \theta_4^{c1} \in [0,1]$such that, consumers of type $\theta \in (\theta_1^{c1}, 1]$ choose N_f, those of type $\theta \in (\theta_2^{c1}, \theta_1^{c1}]$ choose U_f, those of type $\theta \in (\theta_3^{c1}, \theta_2^{c1}]$ choose N_c, those of type $\theta \in (\theta_4^{c1}, \theta_3^{c1}]$ choose U_c and the rest remain inactive and buy nothing. The θ_i^{c1}'s can be solved by studying the indifferent consumers with $V[N_f, \theta_1^{c1}] = V[U_f, \theta_1^{c1}]$, $V[U_f, \theta_2^{c1}] = V[N_c, \theta_2^{c1}]$, $V[N_c, \theta_3^{c1}] = V[U_c, \theta_3^{c1}]$, and $V[U_c, \theta_4^{c1}] = V[I, \theta_4^{c1}]$. Moreover, when the used products are sold in the respective secondary markets, the used product prices are determined by the market clearing conditions with $1 - \theta_1^{c1} = \theta_1^{c1} - \theta_2^{c1}$ and $\theta_2^{c1} - \theta_3^{c1} = \theta_3^{c1} - \theta_4^{c1}$, for the products of the focal and the competing producers, respectively. This analysis give:

$$
\begin{aligned}
\theta_1^{c1} &= \frac{p_f^{c1} - \frac{2\left((\delta_c^{c1}+1)^2 k(\delta_f^{c1}+2p_f^{c1}-1)+(\delta_c^{c1}+1)(\delta_f^{c1}-1)p_c^{c1}-(3\delta_c^{c1}+1)\delta_f^{c1}(\delta_f^{c1}+2p_f^{c1}-1)\right)}{4(\delta_c^{c1}+1)^2 k-(3\delta_c^{c1}+1)(3\delta_f^{c1}+1)}}{1-\delta_f^{c1}}, \\
\theta_2^{c1} &= \frac{\delta_c^{c1}(k(\delta_c^{c1}+\delta_f^{c1}-\delta_c^{c1}(\delta_f^{c1}-4p_c^{c1}+2p_f^{c1})+4p_c^{c1}+2p_f^{c1}-1)-2(3\delta_f^{c1}p_c^{c1}+p_c^{c1}))}{(4(\delta_c^{c1}+1)^2 k-(3\delta_c^{c1}+1)(3\delta_f^{c1}+1))(\delta_f^{c1}-k)} - \frac{p_c^{c1}}{\delta_f^{c1}-k} \\
&\quad + \frac{(\delta_c^{c1}+1)^2 k(\delta_f^{c1}+2p_f^{c1}-1)+(\delta_c^{c1}+1)(\delta_f^{c1}-1)p_c^{c1}-(3\delta_c^{c1}+1)\delta_f^{c1}(\delta_f^{c1}+2p_f^{c1}-1)}{(4(\delta_c^{c1}+1)^2 k-(3\delta_c^{c1}+1)(3\delta_f^{c1}+1))(\delta_f^{c1}-k)}, \\
\theta_3^{c1} &= \frac{p_c^{c1} - \frac{2\delta_c^{c1}(k(\delta_c^{c1}+\delta_f^{c1}-\delta_c^{c1}(\delta_f^{c1}-4p_c^{c1}+2p_f^{c1})+4p_c^{c1}+2p_f^{c1}-1)-2(3\delta_f^{c1}p_c^{c1}+p_c^{c1}))}{4(\delta_c^{c1}+1)^2 k-(3\delta_c^{c1}+1)(3\delta_f^{c1}+1)}}{k-\delta_c^{c1}k}, \\
\theta_4^{c1} &= \frac{k(\delta_c^{c1}+\delta_f^{c1}-\delta_c^{c1}(\delta_f^{c1}-4p_c^{c1}+2p_f^{c1})+4p_c^{c1}+2p_f^{c1}-1)-2(3\delta_f^{c1}p_c^{c1}+p_c^{c1})}{k\left(4(\delta_c^{c1}+1)^2 k-(3\delta_c^{c1}+1)(3\delta_f^{c1}+1)\right)}.
\end{aligned}
$$

As a result, the demands for the two producers can be calculated as $q_f = 1-\theta_1^{c1}$ and $q_c = \theta_2^{c1}-\theta_3^{c1}$, respectively. Then the profits can be written as:

$$\Pi_f^{c1} = \left(\frac{\delta_f^{c1} - 2(\delta_c^{c1}+1)^2 k + \delta_c^{c1}(3\delta_f^{c1} - 3p_f^{c1} + 2p_c^{c1} + 3) - p_f^{c1} + 2p_c^{c1} + 1}{(3\delta_f^{c1}+1)(3\delta_c^{c1}+1) - 4(\delta_c^{c1}+1)^2 k}\right)\left(p_f^{c1} - g_f^{c1}(\rho_f^{c1}, \delta_f^{c1}) + \lambda(-\beta r_f^2/2 + (\alpha+\rho_f^{c1})r_f)\right),$$

$$\Pi_c^{c1} = \left(\frac{-(\delta_c^{c1}+1)k(\delta_f^{c1} + 2p_f^{c1} - 1) + 3\delta_f^{c1} p_c^{c1} + p_c^{c1}}{k\left(4(\delta_c^{c1}+1)^2 k - (3\delta_f^{c1}+1)(3\delta_c^{c1}+1)\right)}\right)\left(p_c^{c1} - g_c^{c1}(\rho_c^{c1}, \delta_c^{c1}) + \lambda(-k\beta r_c^2/2 + (k\alpha+\rho_c^{c1})r_c)\right),$$

with $g_f^{c1}(\rho_f^{c1}, \delta_f^{c1}) = m + \tau(\rho_f^{c1})^2 + d\rho_f^{c1}\delta_f^{c1} + b(\delta_f^{c1})^2$ and $g_c^{c1}(\rho_c^{c1}, \delta_c^{c1}) = k(m + \tau(\rho_c^{c1})^2 + d\rho_c^{c1}\delta_c^{c1} + b(\delta_c^{c1})^2)$. We then solve $\max_{p_f^{c1}, r_f^{c1}} \Pi_f^{c1}$ and $\max_{p_c^{c1}, r_c^{c1}} \Pi_c^{c1}$ simultaneously, subject to $R \le r_f \le 1$, $R \le r_c \le 1$, $1-\theta_1^{c1} \ge 0$, $\theta_1^{c1} - \theta_2^{c1} \ge 0$, $\theta_2^{c1} - \theta_3^{c1} \ge 0$, $\theta_3^{c1} - \theta_4^{c1} \ge 0$, $\theta_4^{c1} \ge 0$, $p_{uf} \ge 0$ and $p_{uc} \ge 0$. The results are summarized below. The optimal recycling levels are $r_f^{c1*} = \min[1, \max[0, (\alpha+\rho_f^{c1})/\beta]]$ and $r_c^{c1*} = \min[1, \max[0, (k\alpha+\rho_c^{c1})/(k\beta)]]$. Denoting $M_f^{c1} = g_f^{c1}(\rho_f^{c1}, \delta_f^{c1}) - \lambda(-\beta(r_f^{c1*})^2/2 + (\alpha+\rho_f^{c1})r_f^{c1*})$ and $M_c^{c1} = g_c^{c1}(\rho_c^{c1}, \delta_c^{c1}) - \lambda(-k\beta(r_c^{c1*})^2/2 + (k\alpha+\rho_c^{c1})r_c^{c1*})$, the optimal new product prices are:

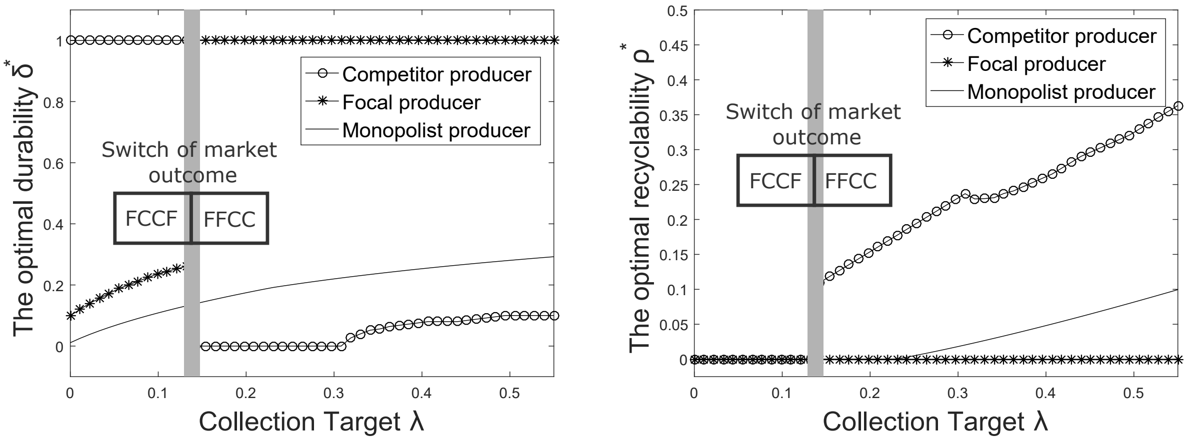
$$p_f^{c1*} \frac{(5\delta_f^{c1}+3)(\delta_c^{c1}+1)^2 k - (3\delta_f^{c1}+1)(\delta_f^{c1} + \delta_c^{c1}(3\delta_f^{c1} + 3M_f^{c1} + M_c^{c1} + 3) + M_f^{c1} + M_c^{c1} + 1)}{2\left((\delta_c^{c1}+1)^2 k - (3\delta_f^{c1}+1)(3\delta_c^{c1}+1)\right)},$$

$$p_c^{c1*} = -\frac{-2(\delta_c^{c1}+1)^3 k^2 + (3\delta_c^{c1}+1)(\delta_c^{c1}+1)k(2\delta_f^{c1} + M_f^{c1}) + 3M_c^{c1}(3\delta_f^{c1}\delta_c^{c1} + \delta_f^{c1} + \delta_c^{c1}) + M_c^{c1}}{2\left((\delta_c^{c1}+1)^2 k - (3\delta_f^{c1}+1)(3\delta_c^{c1}+1)\right)}.$$

We can then substitute these results to calculate the profits $\Pi_i^{c1}(p_i^{c1*}, r_i^{c1*}, p_j^{c1*}, r_j^{c1*}; \rho_i^{c1}, \delta_i^{c1}, \rho_j^{c1}, \delta_j^{c1})$ for $i = f, c$ with $j = \{f, c\} \backslash \{i\}$ (details of the expressions omitted for brevity).

Following similar procedures, we can solve for (p_f^{cl*}, r_f^{cl*}), (p_c^{cl*}, r_c^{cl*}) and the resulting profits, when the FCFC and FCCF outcomes emerge.

We next solve for the design choices that maximize the profits. From the first-order condition equations for the design choices, we find that under each of the market segmentation outcomes, the optimal recyclability choice for each of the producers in the competitive market still has the same structure as that in the main model for the monopolist producer (as presented in Proposition A2). To focus on the legislation effect, we only present the results with $r_i^{cl*} = R$ for $i = f, c$ and $d > 0$ (for $l = 1, 2, 3$). For the focal producer: $\rho_f^{cl*} = (R\lambda - d\delta_f^{cl})/(2\tau)$ for $\delta_f^{cl} \le R\lambda/d$, and 0 otherwise; for the competitor: $\rho_c^{cl*} = (R\lambda - dk\delta_c^{cl})/(2\tau)$ for $\delta_c^{cl} \le R\lambda/(dk)$, and 0 otherwise. Based on these, the producers' profits can be written as $\Pi_i^{cl}(\delta_i^{cl}, \delta_j^{cl})$. We next solve for the optimal δ_i^{c1}'s for the two producers numerically with the following details (similar approach has been adopted by Moorthy 1988 to solve for the simultaneous optimal decisions on product quality levels for two competing producers): We first identify the focal producer's best response function given the competing producer's choice δ_c. To this end, we search for the $\delta_f^{c1*} \in [k, 1]$ (in which case the FFCC outcome emerges) that maximizes $\Pi_f^{c1}(\delta_f^{c1}, \delta_c)$ with the given δ_c; similarly, we search for the $\delta_f^{c2*} \in [k\delta_c, k]$ (in which case the FCFC outcome emerges) that maximizes $\Pi_f^{c2}(\delta_f^{c2}, \delta_c)$, and the $\delta_f^{c3*} \in [0, k\delta_c]$ (in which case the FCCF outcome emerges) that maximizes $\Pi_f^{c3}(\delta_f^{c3}, \delta_c)$. We then compare the profits $\Pi_f^{cl}(\delta_f^{cl*}, \delta_c)$ for $l = 1, 2, 3$ and $\delta_f(\delta_c) = \arg\max_l \Pi_f^{cl}(\delta_f^{cl*}, \delta_c)$. Following a similar procedure, we identify the competing producer's best response function $\delta_c(\delta_f)$ given the focal producer's choice δ_f.



(a) The optimal durability choices (δ^*, δ_f^* and δ_c^*) as a function of λ.

(b) The optimal recyclability choices (ρ^*, ρ_f^* and ρ_c^*) as a function of λ.

Figure OA4 The optimal design choices under competitive market as a function of the collection target.
$R=1$, $\alpha=-1$, $\beta=1$, $\tau=1.2$, $b=1.2$, $d=1.2$, $m=0.345$, $k=0.65$.

Since the optimal design choices (δ_f^*, δ_c^*) in equilibrium will be such that $\delta_f(\delta_c^*)=\delta_f^*$ and $\delta_c(\delta_f^*)=\delta_c^*$, therefore $\delta_f^*=\delta_f(\delta_c^*)=\delta_c^{-1}(\delta_f^*)$ where $\delta_c^{-1}(\cdot)$ is the inverse function of $\delta_c(\cdot)$. As such, we identify δ_f^* and δ_c^* and the corresponding ρ_f^* and ρ_c^* as presented in Figure 4 in the paper for the recycling target, and Figure OA4 here for the collection target.

OA6. Extension: No Secondary Markets

Our main model analysis has focused on a scenario with active secondary market trade of used products. While active secondary market trade is common for a wide range of products (including consumer electronics and PVPs), it may be limited for others due to factors such as high transaction costs or lack of a consumer-to-consumer trade infrastructure. Nevertheless, producers of such products can still deploy durability as a design lever to reduce their recycling obligations under EPR. The only difference is that in this case the effect of durability manifests itself by increasing the utility from direct usage of the used products rather than the resale value on the secondary market. In this section, we analyze the implications of EPR on product durability and recyclability in such markets that do not have consumer-to-consumer transactions of used products and we denote this scenario by the superscript "ns".

In this case, in a similar vein to our demand characterization for the main model, we can show that there are three non-dominated consumer strategies, which are (i) N^{ns}: to buy a new product in every period (and then discard the used item upon the repeated new purchase, with no resale value due to the absence of a secondary market); (ii) H^{ns}: to buy a new product and keep it for two periods; and (iii) I^{ns}: to always remain inactive. In this case, one of two possible equilibria can emerge (details are provided in the proof of Proposition OA1 in §OA6.1): (i) the

(H^{ns}, I^{ns}) equilibrium, with $\delta^{ns*} \in [0,1]$ and consumers with descending type θ follow the H^{ns} and the I^{ns} strategies, respectively; and (ii) the (N^{ns}, I^{ns}) equilibrium, with $\delta^{ns*} = 0$ and consumers with descending type θ follow the N^{ns} and the I^{ns} strategies, respectively. In what follows, we focus on the first case where the products are durable in equilibrium (i.e., $\delta^{ns*} > 0$) because of our focus on durable products. Furthermore, to highlight the effect of legislation in the existence of the recyclability-durability trade-off in design, we restrict our attention to the case where the recycling target is binding at optimality ($r^{ns*} = R$) and $d > 0$. Proposition OA1 below characterizes the optimal design decisions.

Proposition OA1 *Let $d > 0$. When a secondary market is absent, then under the (H^{ns}, I^{ns}) equilibrium, $\exists$ $R_{dl}^{ns}, R_d^{ns}, R_r^{ns}, R_{rr}^{ns}, \lambda_{rl}^{ns}, \lambda_d^{ns}, \lambda_r^{ns}$, where $0 \le R_{dl}^{ns} \le R_d^{ns} \le R_r^{ns} \le R_{rr}^{ns} \le 1$ and $0 \le \lambda_{rl}^{ns} \le \lambda_r^{ns} \le \lambda_d^{ns} \le 1$, such that:*

- *The optimal durability δ^{ns*} decreases in R for $R \in [R_{dl}^{ns}, R_d^{ns}]$ and (weakly) increases otherwise. The optimal recyclability ρ^{ns*} decreases in R for $R \in [R_r^{ns}, R_{rr}^{ns}]$ and (weakly) increases otherwise. Moreover, $R_d^{ns} \le R_r^{ns}$.*
- *The optimal durability δ^{ns*} decreases in λ for $\lambda \in [\lambda_d^{ns}, 1]$, and (weakly) increases otherwise. The optimal recyclability ρ^{ns*} decreases in λ for $\lambda \in [\lambda_{rl}^{ns}, \lambda_r^{ns}]$, and (weakly) increases otherwise. Moreover, $\lambda_r^{ns} \le \lambda_d^{ns}$.*

Proposition OA1 shows that the structural results regarding the effects of the recycling and the collection targets on the optimal recyclability and durability choices from our main model as presented in §4 are robust to the absence of secondary markets. In other words, our results remain valid regardless of the specific market structure and the channel through which durability takes its effect: through influencing either the resale value of the used products in the secondary market, or the direct value of usage for consumers who buy and keep the products.

OA 6.1. Proof of Proposition OA1

As mentioned, when the secondary market for consumer-to-consumer trade of used products is absent, there exist three non-dominated consumer strategies including N^{ns}, H^{ns}, and I^{ns}. As such, two market segmentation outcomes are possible in equilibrium: (i) consumers with descending type θ follow H^{ns} and I^{ns}, respectively; or (ii) consumers with descending type θ follow N^{ns}, H^{ns} and I^{ns}, respectively.

For consumers of type θ, the per-period utilities corresponding to the three consumer strategy choices are: $V[N^{ns}, \theta] = \theta - p^{ns}$, $V[H^{ns}, \theta] = ((1+\delta^{ns})\theta - p^{ns})/2$ and $V[I^{ns}, \theta] = 0$. Note that both the differences $V[N^{ns}, \theta] - V[H^{ns}, \theta]$ and $V[H^{ns}, \theta] - V[I^{ns}, \theta]$ are increasing functions in θ, therefore:

- In Case (ii), $\exists \theta_1^{ns}, \theta_2^{ns} \in [0,1]$, such that consumers of type $\theta \in (\theta_1^{ns}, 1]$ choose N^{ns}, those of type $\theta \in (\theta_2^{ns}, \theta_1^{ns}]$ choose H^{ns} and all others remain inactive. By analyzing the indifferent consumers θ_1^{ns} with $V[N^{ns}, \theta_1^{ns}] = V[H^{ns}, \theta_1^{ns}]$, we derive $\theta_1^{ns} = p^{ns}/(1-\delta^{ns})$; similarly, we derive $\theta_2^{ns} = p^{ns}/(1+\delta^{ns})$. In this case, the new product demand $q^{ns}(p,\delta)$ can be written as $q^{ns} = (1-\theta_1^{ns}) + (\theta_1^{ns} - \theta_2^{ns})/2 = (1 - p^{ns} - (\delta^{ns})^2)/(1-(\delta^{ns})^2)$. The producer's profit function can be written as:

$$\Pi^{ns}(p^{ns}, r^{ns}; \rho^{ns}, \delta^{ns}) = \left(\frac{1-(\delta^{ns})^2 - p^{ns}}{1-(\delta^{ns})^2}\right)\left(p^{ns} - g^{ns} + \lambda(-\frac{1}{2}\beta(r^{ns})^2 + (\alpha+\rho^{ns})r^{ns})\right). \quad \text{(OA1)}$$

As in the main model, we solve the problem by backward induction, starting from solving $\max_{p^{ns}, r^{ns}} \Pi^{ns}(p^{ns}, r^{ns}; \rho^{ns}, \delta^{ns})$, subject to $R \le r^{ns} \le 1$, $1-\theta_1^{ns} \ge 0$, $\theta_1^{ns} - \theta_2^{ns} \ge 0$, $\theta_2^{ns} \ge 0$, given the product design (ρ^{ns}, δ^{ns}).

- In Case (i), $\exists \theta_{1H}^{ns}$, such that consumers of type $\theta \in (\theta_{1H}^{ns}, 1]$ choose H^{ns} and the rest remain inactive. θ_{1H}^{ns} can be solved by studying the indifferent consumers with $V[H^{ns}, \theta_{1H}^{ns}] = V[I, \theta_{1H}^{ns}]$, which yields $\theta_{1H}^{ns} = p/(1+\delta^{ns})$. The demand of new products in this case is $q^{ns} = (1-\theta_{1H}^{ns})$, so the producer's profit function will be:

$$\Pi^{ns}(p^{ns}, r^{ns}; \rho^{ns}, \delta^{ns}) = \left(\frac{1+\delta^{ns} - p^{ns}}{1+\delta^{ns}}\right)\left(p^{ns} - g^{ns} + \lambda(-\frac{1}{2}\beta(r^{ns})^2 + (\alpha+\rho^{ns})r^{ns})\right). \quad \text{(OA2)}$$

We then solve $\max_{p^{ns}, r^{ns}} \Pi^{ns}(p^{ns}, r^{ns}; \rho^{ns}, \delta^{ns})$, subject to $R \le r^{ns} \le 1$, $1-\theta_{1H}^{ns} \ge 0$, $\theta_{1H}^{ns} \ge 0$, given the product design (ρ^{ns}, δ^{ns}).

We first respectively solve for the optimal new product price and the recycling level for each of the two cases, then we compare the resulting profits to identify the final optimal decisions for the producer (and the resulting market segmentation outcome). The results are presented below.

Lemma OA1 *When a secondary market is absent, given a product design with ρ^{ns} and δ^{ns}, the optimal recycling level $r^{ns*}(\rho^{ns}, \delta^{ns})$ and the new product price $p^{ns*}(\rho^{ns}, \delta^{ns})$ can be summarized below. For the optimal recycling level: When $(\alpha+\rho^{ns})/\beta \le R$, $r^{ns*}(\rho^{ns}, \delta^{ns}) = R$; when $R < (\alpha+\rho^{ns})/\beta < 1$, $r^{ns*}(\rho^{ns}, \delta^{ns}) = (\alpha+\rho^{ns})/\beta$; and when $1 \le (\alpha+\rho^{ns})/\beta$, $r^{ns*}(\rho^{ns}, \delta^{ns}) = 1$.*

For the optimal new product price: When $g^{ns} \le 1 - \delta^{ns} + \lambda\left(-\beta(r^{ns*})^2/2 + (\alpha+\rho^{ns})r^{ns}\right) - \delta^{ns}\sqrt{2(1-\delta^{ns})}$, then $p^{ns*} = \left(1-(\delta^{ns})^2 + g^{ns} - \lambda(-\beta(r^{ns*})^2/2 + (\alpha+\rho^{ns})r^{ns*})\right)/2$ and the market segmentation outcome will be as that in Case (i) where all the N^{ns}, H^{ns} and I^{ns} segments exist; when $g^{ns} < 1 - \delta^{ns} + \lambda\left(-\beta(r^{ns*})^2/2 + (\alpha+\rho^{ns})r^{ns}\right) - \delta^{ns}\sqrt{2(1-\delta^{ns})}$, then $p^{ns*} = (1 + \delta^{ns} + g^{ns} - \lambda(-\beta(r^{ns*})^2/2 + (\alpha+\rho^{ns})r^{ns*}))/2$ and the market segmentation outcome will be as that in Case (ii) where only H^{ns} and I^{ns} segments exist.

The proof of Lemma OA1 is similar to that of Lemma A1 in Appendix A1 and hence omitted for brevity.

Next, the producer further solves for the optimal design decisions to maximize $\Pi^{ns}(p^{ns*}, r^{ns*}; \rho^{ns}, \delta^{ns})$. We first show that when all N^{ns}, H^{ns} and I^{ns} segments exist in the market in equilibrium as in Case (i), then it is always optimal for the producer to choose $\delta^{ns*} = 0$. As a result, the effect of legislation in this case is straightforward as the design choices reduce to the choice of recyclability, which can be easily shown to be increasing in the binding legislative targets. To show this, we follow a similar solution procedure as in our main model to solve for the optimal design choices. We can first prove that the optimal recyclability in this case has a similar structure as that presented in Proposition A2. As such, the profit function in the case of $r^{ns*} = R$, with the optimal choices of new product price, recycling level and recyclability, can be rewritten as:

$$\Pi^{ns}(\delta^{ns}) = \frac{\left(-F^{ns}\delta^{ns} - B^{ns}(\delta^{ns})^2 + A^{ns}\right)^2}{4\left(1-(\delta^{ns})^2\right)}, \text{ with } A^{ns} = \tfrac{-4m\tau+\lambda^2R^2-2\lambda R\tau(\beta R-2\alpha)+4\tau}{4\tau} \text{ and } B^{ns} = \tfrac{4(\tau+1)\tau-d^2}{4\tau}.$$

Solving the first-order condition equation

$$\frac{\partial \Pi^{ns}}{\partial \delta^{ns}} = \frac{\left(A^{ns} - \delta(B^{ns}\delta + F^{ns})\right)\left(\delta\left(A^{ns} + B^{ns}\left(\delta^2-2\right)\right) - F^{ns}\right)}{2\left(\delta^2-1\right)^2} = 0$$

yields the following candidate solutions:

$$\delta^{ns}_{a,b} = \pm\frac{\sqrt{4A^{ns}B^{ns} + (F^{ns})^2} - F^{ns}}{2B^{ns}}, \quad \delta^{ns}_c = \frac{D^{ns}}{3\sqrt[3]{2}B^{ns}} - \frac{\sqrt[3]{2}(A^{ns} - 2B^{ns})}{D^{ns}},$$

with $D^{ns} = (\sqrt{108(B^{ns})^3(A^{ns}-2B^{ns})^3 + 729(B^{ns})^4(F^{ns})^2} + 27(B^{ns})^2F^{ns})^{1/3}$, and two other roots that can be proved to always be complex. Moreover, we can also prove that $\delta^{ns}_b < 0$. Therefore, only δ^{ns}_a and δ^{ns}_c are the candidate solutions for maximizing the profit. We can further prove that only one of δ^{ns}_a or δ^{ns}_c will be in the range of $[0,1]$, and we denote it as $\overline{\delta^{ns}}$. By studying $\partial\Pi^{ns}(\delta^{ns})/\partial\delta^{ns}$, we derive the following:

$$\frac{\partial \Pi^{ns}(\delta^{ns})}{\partial \delta^{ns}} < 0 \text{ for } \delta^{ns} \in [0, \overline{\delta^{ns}}]; \text{ and } \quad \frac{\partial \Pi^{ns}(\delta^{ns})}{\partial \delta^{ns}} > 0 \text{ for } \delta^{ns} \in (\overline{\delta^{ns}}, 1).$$

Moreover, we also show that $\delta^{ns} > \overline{\delta^{ns}}$ is infeasible as it leads to negative producer profit. Combining all these results, the maximum profit is always achieved at $\delta^{ns} = 0$; i.e., $\delta^{ns*} = 0$ in this case. Consequently, the design implications under EPR straightforwardly reduce to promoting higher recyclability in product designs.

We proceed to study Case (ii) where only H^{ns} and I^{ns} segments exist in the market in equilibrium. We solve for the optimal design choices based on the Lemma OA1 results, following a similar solution procedure as in our main model. We can first show that the optimal recyclability in this case has a simialr structure as that presented in Propositions A2. As such, the profit function in the case of $r^{ns*} = R$, with the optimal choices of new product price, recycling level and recyclability, can be rewritten as:

$$\Pi^{ns}(\delta^{ns}) = \frac{(\delta^{ns} - B^{ns}_H\delta^{ns} + A^{ns}_H)^2(F^{ns}_H)^2}{8(1+\delta^{ns})} \text{ with } A^{ns}_H = \tfrac{4(1-m)\tau+\lambda R(4\alpha\tau+R(\lambda-2\beta\tau))}{4\tau-2dR\lambda} \text{ and } B^{ns}_H = \tfrac{4\tau^2-d^2}{4\tau-2dR\lambda}.$$

Solving the first-order condition equation

$$\frac{\partial \Pi^{ns}(\delta^{ns})}{\partial \delta^{ns}} = \frac{(F_H^{ns})^2\,(A_H^{ns} - B_H^{ns}(\delta^{ns})^2 + \delta^{ns})\,(A_H^{ns} + \delta^{ns}(B_H^{ns}(3\delta^{ns}+4)-1)-2)}{-8(\delta^{ns}+1)^2} = 0$$

yields the candidate solutions:

$$\delta^{ns}_{Ha,Hb} = \frac{1 \mp \sqrt{1+4A_H^{ns}B_H^{ns}}}{2B_H^{ns}}, \delta^{ns}_{Hc,Hd} = \frac{1-4B_H^{ns} \mp \sqrt{1+4B_H^{ns}(4-3A_H^{ns}+4B_H^{ns})}}{6B_H^{ns}}.$$

Note that $\delta^{ns}_{Ha,Hb} \in \mathbb{R}$ with $\delta^{ns}_{Hb} \geq 0$ and $\delta^{ns}_{Ha} \leq 0$. Moreover, since δ^{ns}_{Hb} can be shown to be a minimizer, both δ^{ns}_{Ha} and δ^{ns}_{Hb} are eliminated as optimal solution. When $\delta^{ns}_{Hc,Hd} \notin \mathbb{R}$, then the profit maximizing solution δ^{ns*} can only take the value of 0 or 1, at the boundaries. The final optimal solution can be identified by comparing the profits at $\delta^{ns}=0$ and $\delta^{ns}=1$. When $\delta^{ns}_{Hc,Hd} \in \mathbb{R}$, by pairwise comparisons, we can determine the relation between the δ_i^{ns}'s to be $\delta^{ns}_{Hc} \leq \delta^{ns}_{Ha} \leq \delta^{ns}_{Hd} \leq^{ns}_{Hb}$; hence the optimal δ_H^{ns*} can only take the value of 0, 1, or δ^{ns}_{Hd}. The final optimal solution can be identified by comparing the profits at these three points. We characterize the results below, with $\overline{A_{H1}} \doteq (1+\sqrt{2})(1-B_H^{ns})$, $\overline{A_{H2}} \doteq 2\left(9+8B_H^{ns}+\sqrt{(27+108B_H^{ns}+144(B_H^{ns})^2+64(B_H^{ns})^3)/B_H^{ns}}\right)/27$, $\overline{A_{H3}} \doteq 3-7B_H^{ns}$, $\overline{B_{H1}} \doteq (5-2\sqrt{2})/17$ and $\delta^{ns}_{int} \doteq \delta^{ns}_{Hd}$.

($\mathrm{D^h}$i) When $0 \leq B_H^{ns} < \overline{B_{H1}}$	($\mathrm{D^h}$ii) When $\overline{B_{H1}} \leq B_H^{ns} < 1/4$	($\mathrm{D^h}$iii) When $1/4 \leq B_H^{ns} < 3/7$	($\mathrm{D^h}$iv) When $3/7 \leq B_H^{ns}$
$\delta^{ns*} = \begin{cases} 1 & \text{if } A < \overline{A_{H1}}, \\ 0 & \text{otherwise.} \end{cases}$	$\delta^{ns*} = \begin{cases} 1 & \text{if } A^{ns} < \overline{A_{H3}}, \\ \delta^{ns}_{int} & \text{if } \overline{A_{H3}} \leq A^{ns} < \overline{A_{H2}}, \\ 0 & \text{otherwise.} \end{cases}$	$\delta^{ns*} = \begin{cases} 1 & \text{if } A^{ns} < \overline{A_{H3}}, \\ \delta^{ns}_{int} & \text{if } \overline{A_{H3}} \leq A^{ns} < 2, \\ 0 & \text{otherwise.} \end{cases}$	$\delta^{ns*} = \begin{cases} \delta^{ns}_{int} & \text{if } A^{ns} < 2, \\ 0 & \text{otherwise.} \end{cases}$

Based on this closed-form characterization of $(\rho^{ns*}, \delta^{ns*})$, Proposition OA1 can be obtained by calculating $\partial\rho^{ns*}/\partial R$, $\partial\rho^{ns*}/\partial\lambda$, $\partial\delta^{ns*}/\partial R$ and $\partial\delta^{ns*}/\partial\lambda$. Note that all the thresholds $R^{ns}_{dl}, R^{ns}_{d}, R^{ns}_{r}, R^{ns}_{rr}, \lambda^{ns}_{rl}, \lambda^{ns}_{d}, \lambda^{ns}_{r}$ are in closed-form, with the expressions omitted here for brevity.

Moreover, by comparing the results in Propositions 3 and 4 in the main model with Proposition OA1 with the absence of a secondary market, we also derive the following results:

Corollary OA1 *$\exists \overline{m}_1^R, \overline{m}_2^R$ such that, when $m < \overline{m}_1^R$, then $R_d^{ns} < R_d$ and $R_r^{ns} < R_r$; when $m > \overline{m}_2^R$, then $R_d^{ns} > R_d$ and $R_r^{ns} > R_r$.*

Corollary OA2 *$\exists \overline{m}_1^\lambda, \overline{m}_2^\lambda$ such that, when $m < \overline{m}_1^\lambda$, then $\lambda_d^{ns} > \lambda_d$ and $\lambda_r^{ns} > \lambda_r$; when $m > \overline{m}_2^\lambda$, then $\lambda_d^{ns} < \lambda_d$ and $\lambda_r^{ns} < \lambda_r$.*

OA7. Extension: Profitable Recycling

In the main model, we focus on products with costly recycling (i.e., $v(R,0) \leq 0$) as they are the primary targets of EPR legislation. In this section, however, we extend the analysis further to cover a profitable recycling scenario, which also involves additional end-of-life product market dynamics. Specifically, when the inherent recyclability of a product is sufficiently high (e.g., α is large enough) and a binding recycling target still maintains a net profit from recycling in a regulated market (i.e., $v(R,0) > 0$), we anticipate competition in the recycling market from third-party recyclers who can generate profits from recycling the cores (i.e., end-of-life products). For example, the removal of toxic materials from batteries led to a flourishing battery recycling industry involving a large number of third-party recyclers (BU 2015). As such, in this section, we analyze the producer's optimal recyclability and durability choices under EPR with third-party recycler competition for profitable-to-recycle end-of-life products.

We consider n independent, for-profit third-party recyclers along with the producer. We assume all the third-party recyclers are homogeneous, so as to obtain insights while keeping the analysis tractable. When recycling a unit of end-of-life product is profitable, then in order to elicit returns, the producer and the third parties offer respective buyback options to consumers for the cores. Such buyback options can take various forms including trade-in discounts, coupons, checks or cash. We denote the unit buyback price offered by the producer and the i-th third-party recycler as p_0 and p_i, respectively (regardless of the product condition). As the producer is the only party subject to EPR, we assume that the producer has enough capacity to accept and recycle all arriving returns. In contrast, a third party only has a limited capacity that can accept and recycle a fraction h ($0 \leq h \leq 1$) of all the end-of-life products. When the aggregate third-party capacity covers the whole collection and recycling volume, $h = 1/n$. We let w denote the unit recycling value that the third parties can extract from recycling an end-of-life product. We focus on cases with binding collection and recycling targets (λ and R) to highlight the effects of legislation.

We construct a model similar to the one in Arnold (2001) to study the recycling market: We consider that when consumers are faced with this capacitated recycling market, they perform a random search among the producer and all the third parties to decide where to return the core. In every search attempt, a consumer incurs a cost s (which can be regarded as a search or delivery cost). When the consumer encounters a third party that is currently out of capacity, another search (along with the associated cost) is needed, until the core is accepted for a buyback payment. Then when all consumers are risk neutral, there exists a symmetric mixed strategy for consumers represented by $\pi = \{\pi_0, \pi_1, \cdots, \pi_n\}$ such that in every attempt to return the core, a consumer chooses the producer and the i-th third party with probabilities π_0 and π_i ($i = 1, \cdots, n$), respectively.

Given this returning strategy of the consumers, in every period, a portion π_i of the total returns arrive at the i-th third party. Each of these recyclers accept returns up to capacity. Then they start recycling and stop accepting returns during a time period Y for recycling the cores, where Y is assumed to be exponentially distributed with parameter μ and hence $E(Y) = 1/\mu$. Without loss of generality, we assume $\mu = 1$ in the following analysis (the actual value of μ is not a critical assumption). We assume the arrivals of returns follow a Poison process, then the rate of arrivals will be $\pi_i q$ where q is the total volume of the cores. Therefore, the period of time that the third party is able to accept returns (i.e., the time period before the returns reach the capacity) is the sum of exponentially distributed random variables (i.e., the time intervals between returns) and hence has a gamma distribution with $E(X) = kq/\pi_i q = k/\pi_i$. The collection (when returns are accepted) and the recycling phases form an alternating renewal process. Following standard results from alternating renewal process, the probability that the third party has available capacity to accept consumer returns will be $\alpha_i = E(X)/(E(X)+E(Y)) = k/(k+\pi_i)$ for $i = 1, 2, ..., n$. For the producer, $\alpha_0 = 1$ since it is able to accept any arriving returns.

For consumers, the expected payoff from following the strategy $\pi = \{\pi_0, \cdots, \pi_n\}$ is $U = \pi_0(p_0 - s) + \sum_1^n \pi_i(\alpha_i p_i + (1-\alpha_i)U - s)$. In order for $\pi = \{\pi_0, \cdots, \pi_n\}$ to be an equilibrium consumer strategy, it must hold that $U = p_0 - s = \alpha_i(p_i) + (1-\alpha_i)U - s$. Solving it yields: $p_i - p_0 = s\pi_i/k$, where $p_i - p_0$ can be regarded as the price premium the third party has to offer over the producer to compensate the consumers for a possible out-of-capacity situation. Note that the result can also be rewritten as $\pi_i = (p_i - p_0)k/s$; i.e., the probability that the i-th third party will be chosen in the equilibrium consumer strategy (π_i) increases in the third party's recycling capacity (in which case it has a lower out-of-capacity probability, i.e., higher service rate) and the price premium, but decreases in the consumers' searching cost.

For the i-th third party, the actual amount of returns that it is able to accept is α_j portion of all the returns that arrive. The third party chooses a buyback price p_i to maximize its profit from buying back and recycling the end-of-life product returns, where $\text{Profit}_i = (w - p_i)(\alpha\pi_i q)$. Solving the maximization problem, along with all our results above, yields $p_i^* = p_0 + \sqrt{s^2 + (w-p_0)s} - s$. Consequently, when the aggregate third party capacity covers the whole collection and recycling volume, the buyback price the producer needs to offer to ensure the collection level λ (i.e., $\pi_0 = \lambda$) of end-of-life products for compliance will be $p_\lambda = w - s((2-\lambda)^2 - 1)$.

With the buyback price p_λ by the producer derived above, we first calculate the consumer demand of new products to be $((1+\delta) - p + (p_\lambda - s))/(1+3\delta)$. Comparing this to the demand in §3.1, the change in demand is due to consumers' anticipation that each product will generate an extra expected value $p_\lambda - s$ at the end-of-life when returned for recycling. Then the producer maximizes the following profit by determining the recyclability and durability in the design stage, and setting the market price and the recycling level in every sequential period:

$$\Pi(p, r; \rho, \delta) = -\frac{(1+\delta) - p + (p_\lambda - s)}{1+3\delta}\left(p - (m + \tau\rho^2 + d\rho\delta + b\delta^2) + \lambda(-\frac{1}{2}\beta r^2 + (\alpha+\rho)r - p_\lambda)\right).$$

With this profit function, we solve for ρ^* and δ^* in closed-form, based on which we can then study how the legislative targets influence the optimal design choices, by following the similar solution procedure as in the main model. We restrict our attention to the case with $d > 0$.

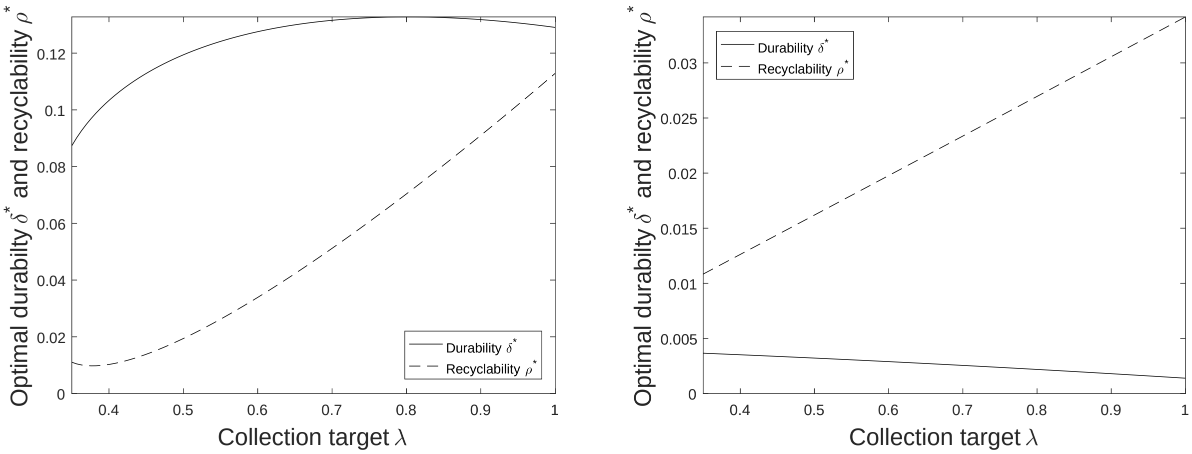
For the recycling target, the analysis of this extension shows the robustness of our results from the main model: The recycling target shapes the optimal recyclability and durability choices in this profitable recycling case with third-party recycler competition in a similar way as that in the costly recycling case; i.e., the structural results in Proposition 3 remain valid (although the threshold expressions will be different).

Similarly, we find that our previous results regarding the effects of the collection target (presented in Proposition 4) also remain valid in this extension, given that the third-party recyclers extract a higher unit recycling value than the producer. In the other case where the unit recycling value extracted by the third-party recyclers (w) is lower than that for the producer, we observe an interesting result, which we summarize in the proposition below.

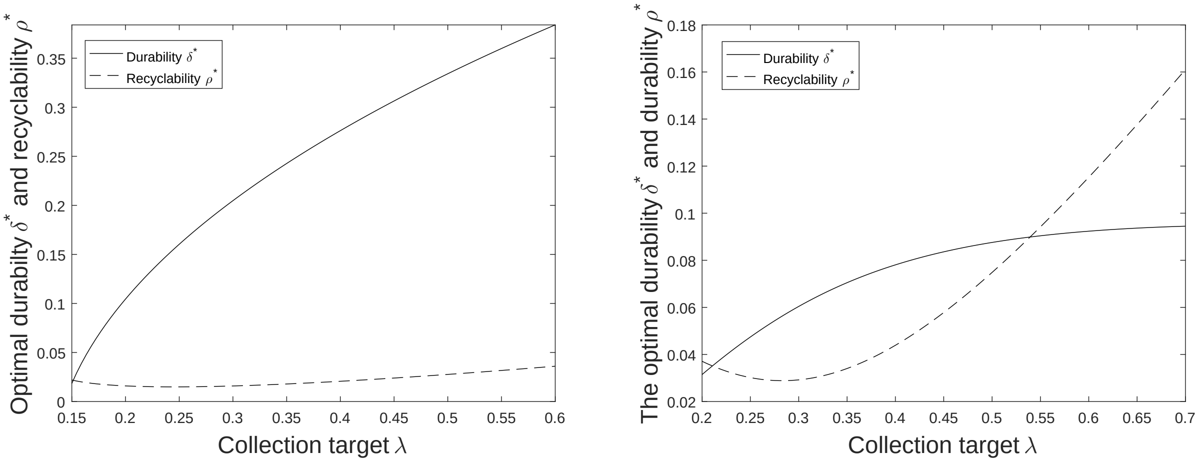
Proposition OA2 *When* $v(R, 0) > 0$ *and* $d > 0$*,* ρ^* *is (weakly) increasing and* δ^* *is (weakly) decreasing in* λ*.*

In contrast to the results in Proposition 4 where ρ^* may decrease over certain range of λ, Proposition OA2 states that ρ^* is monotonically increasing in λ. This suggests that improving recyclability in the presence of competing third-party recyclers is advantageous for the producer. To see this, recall that when making the decisions on recyclability and durability to deal with the EPR obligations, the producer is essentially comparing the marginal benefits of the two attributes, while controlling the associated cost. First, to meet a higher collection target, the producer is also retaining a larger percentage of the return from improving recyclability, hence it is profitable to invest more on recyclability. Meanwhile, a higher ρ^* creates a pressure to compromise durability to achieve cost-effectiveness in the presence of the design trade-off. Second, expanding demand (by forgoing the option of durability improvement) has an additional benefit now because every new product can be sold at a higher price to reflect the buyback value of the product at end-of-life, but part of this benefit is "free" to the producer since a portion of the buyback payments to consumers are made by third parties. Consequently, the producer redirects more investment from durability to recyclability.

On the other hand, however, when the third-party recyclers extract a higher unit recycling value than the producer, the high unit recycling value will drive the third parties to act more aggressively in acquiring the cores and raise the buyback price. As the producer has to match this price to ensure a sufficient collection level for complying with the collection target, the producer incurs higher cost for the buybacks. This higher cost will then offset or even completely wash away the aforementioned additional benefit from expanding the demand of new products that are of higher price. As such, increasing durability to sell less may still be the more effective design option for the producer to directly respond to the higher volume of collection mandated by the collection



(a) $\alpha = -0.5, \beta = 1, m = 0.3, \ \tau = 1, d = 1, w = 0.2.$ (b) $\alpha = 1.3, \beta = 5.6, m = 0.4, \ \tau = 7.8, d = 5.5, w = 0.2.$



(c) $\alpha = -0.5, \beta = 1, m = 0.3, \ \tau = 1, d = 1, w = 0.5.$ (d) $\alpha = 0.6, \beta = 3.6, m = 0.5, \ \tau = 2, d = 2, w = 0.1.$

Figure OA5 The optimal design choices when the third-party recyclers extract higher unit recycling value than the producer.

target, especially when λ initially increases. Therefore, the optimal durability may increase in the collection target when λ is low, as stated in Proposition 4 (four numerical examples are shown in Figure OA5 for a demonstration).

References

Alsema, E., de Wild-Scholten, M., 2005. Environmental Impact of Crystalline Silicon Photovoltaic Module Production. In: *Material Research Society Fall Meeting, Symposium G: Life Cycle Analysis Tools for "Green" Materials and Process Selection, Boston, MA*.

Arnold, M. 2001. Costly Search, Capacity Constraints, and Bertrand Equilibrium Price Dispersions. *International Economic Review*, 41(1), pp. 117–132.

Battery University. 2015. How to Recycle Batteries. http://batteryuniversity.com/learn/, accessed June, 2015.

Belluardo, G., P. Ingenhoven, D. Moser. 2014. Medium-Term Degradations of Different Photovoltaic Technologies Under Outdoor Conditions in Alpine Area. *EURAC Research Publications*, 2014.

BINE, 2010. Recycling PhotoVoltaic Modules. http://www.bine.info/fileadmin/content/Publikationen/Englische_Infos/projekt_0210_engl_internetx.pdf, accessed December 2016.

BIO Intelligence Service, 2011 Study on Photovoltaic Panels. http://ec.europa.eu/environment/waste/weee/pdf/Study%20on%20PVs%20Bio%20final.pdf, accessed June, 2015.

Choi, J. K. , V. Fthenakis, 2014. Crystalline Silicon Photovoltaic Recycling Planning: Macro and Micro Perspectives. *Journal of Clean Production*, 66, pp. 443–449.

Coker, A. 2015. Personal communications, Hannah Solar LLC, Atlanta, GA.

Cyccguekka, F, I. D'Adamo, R. Rosa, 2015. End-of-Life of Used Photovoltaic Modules: A Financial Analysis. *Renewable and Sustainable Energy Reviews*, 47, pp. 552–561.

Esenduran, G., A. Atasu, L. N. Van Wassenhove. 2016. Valuable E-waste: Implications for Extended Producer Responsibility. Working Paper.

Fthenakis, V., E. Alsema, 2006. Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004early 2005 status. *Progress in Photovoltaics: Research and Applications*, 14(3), pp. 275–280.

Fthenakis, V.M., H. C. Kim, 2005. Energy Use and Greenhouse Gas Emissions in the Life Cycle of CdTe Photovoltaics. In: *Material Research Society Fall Meeting, Symposium G: Life Cycle Analysis Tools for "Green" Materials and Process Selection, Boston, MA.*

Fthenakis, V.M., H. C. Kim, 2011. Photovoltaics: Life-cycle Analyses. *Solar Energy*, 85(8), pp. 1609–1628.

Fthenakis V. M., P. D. Moskowitz, 2008. The Value and Feasibility of Proactive Recycling. https://www.bnl.gov/pv/abs/abs_142.asp, accessed December 2016.

Fthenakis V.M., M. Raugei, M. Held, 2009. Update of Environmental Impacts and Energy Payback Times of Photovoltaics. In: *24th European Photovoltaic Solar Energy Conference (EU PVSEC).*

Goodrich A., M. Woodhouse, T. James, 2012. PV Manufacturing Cost Analysis: Future Cost Reduction Opportunities. http://www.academia.edu/28717528/PV_Manufacturing_Cost_Analysis_Future_Cost_Reduction_Opportunities_Future_Cost_Reduction_Opportunities, accessed December 2016.

Haroon, Sol. 2015. Personal communications, Pursuit Engineering, Atlanta, GA.

Held, M., R. Ilg, 2011. Update of Environmental Indicators and Energy Payback Time of CdTe PV Systems in Europe. *Progress in Photovoltaics: Research and Applications*, 19(5), pp. 614–626.

Held, M., 2009, September. Life Cycle Assessment of CdTe Module Recycling. In: *24th EU PVSEC Conference, Hamburg, Germany.*

International Renewable Energy Agency, 2012. Renewable Energy Technologies: Cost Analysis Series. https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-SOLAR_PV.pdf, accessed December 2016.

Knut Sander, Institut fur Okologie und Politik Study on the Development of a Take Back and Recovery System for Photovoltaic Products.

Moorthy, K.S., 1988. Product and price competition in a duopoly. Marketing science, 7(2), pp.141-168.

Smink, C. K.,2006. Vehicle Recycling Regulations: Lessons From Denmark. *Journal of Cleaner Production*, 15, pp. 1135–1146.

Takahashi J., N. Yamada, Y. Shikamori, 2011. Ultratrace Analysis of Phosphorus, Boron and Other Impurities in Photovoltaic Silicon and Trichlorosilane by ICP-MS with High Energy Collision Cell. European Winder Conference on Plasma Spectrochemistry - Zaragoza.

U.S. Geological Survey, 2015. Mineral Commodity Summaries. https://minerals.usgs.gov/minerals/pubs/mcs /2015/mcs2015.pdf, accessed December 2016.

Woodhouse M., A. Goodrich, R. Margolis, T. James, R. Dhere, T. Gessert, T. Barnes, R. Eggert, D. Albin, 2013. Perspectives on the Pathways for Cadmium Telluride Photovoltaic Module Manufacturers to Address Expected Increases in the Price for Tellurium, *Solar Energy Materials & Solar Cells*, 115, pp 199–212.

Ye, J. Y., T. Reindl, A. G. Aberle, T. M. Walsh. 2014. Performance Degradation of Various PV Module Technologies in Tropical Singapore. *IEEE Journal OF Photovaltaics*, 4(5), 2014.