

Online Appendix to “Choice of E-Waste Recycling Standard Under Recovery Channel Competition”

A. Proofs of Analytical Results

Throughout the analysis, in order to ensure that the recyclers' profit functions are concave, we assume $b < 2$ in the single recovery channel and $b < 3/2$ in the competing recovery channel; otherwise, all e-waste goes to a recycler and nothing is sold in the secondary market. We also require that $b < \frac{a}{2Q}$ so that the recyclers always incur positive marginal processing cost. In order to guarantee the optimal fraction of e-waste sold in the secondary market $\phi_i^{k*} \in (0, 1)$ and the optimal wholesale price $w_i^* \geq 0$, we assume that $\max\{a + \epsilon + (b - 1)(\kappa - 2Q), a + \epsilon + \kappa - 2Q\} < r < a + \epsilon + \kappa + 2Q(1 - b)$ for single recovery channel, and $\max\{a + \epsilon - \frac{4b-3}{12}(3Q - 2\kappa), a + \epsilon_i + \kappa - \frac{3}{2}Q\} < r < a + \epsilon_i + \kappa + Q(\frac{3}{4} - b)$ for competing recovery channel throughout the analysis.

Proof of Lemma 1. We solve the problem using backward induction. For the collector's problem, we write the Lagrangian as $L_c = \pi_c + \gamma_1 \phi^I + \gamma_2 \phi^{II} + \gamma_3(1 - \phi^I) + \gamma_4(1 - \phi^{II})$. We find that the Hessian is negative semi-definite in (ϕ^I, ϕ^{II}) . At the optimality, the first-order conditions (FOC) (i.e., $\frac{\partial L_c}{\partial \phi^I} = 0$ and $\frac{\partial L_c}{\partial \phi^{II}} = 0$) and the complementary slackness conditions (i.e., $\gamma_1 \phi^I = 0$, $\gamma_2 \phi^{II} = 0$, $\gamma_3(1 - \phi^I) = 0$, and $\gamma_4(1 - \phi^{II}) = 0$) should hold. Solving these optimality conditions (OCs), we find nine solutions, as shown in Table 1. From the expressions given in Table 1, we observe that Solution 1 (because $\phi^{II} < 0$), Solution 2 (because $\gamma_1 < 0$), Solution 5 (because $\gamma_4 < 0$), and Solution 7 (because $\gamma_1 > 0$ and $\gamma_4 > 0$ cannot hold simultaneously) can never be feasible. From the remaining solutions, we deduce that, regardless of the recycler's choice of standard, $\phi^{II*} > 0$ only if $\phi^{I*} = 1$.

Table 1: Solutions for the collector's problem under single recovery channel

	ϕ^I	ϕ^{II}	Optimality Conditions
Soln 1	$\frac{\kappa}{2Q\tau\beta}$	$-\frac{w}{2Q\tau\alpha(1-\beta)}$	$\gamma_1 = 0, \gamma_2 = 0, \gamma_3 = 0, \gamma_4 = 0$
Soln 2	0	$\frac{-(\alpha\kappa-w)}{2Q\tau\alpha(\beta-1)}$	$\gamma_1 = -(1-\alpha)Q\tau\beta\kappa, \gamma_2 = 0, \gamma_3 = 0, \gamma_4 = 0$
Soln 3	$\frac{\kappa-w}{2Q\tau\beta}$	0	$\gamma_1 = 0, \gamma_2 = Q\tau w(1-\beta)(1-\alpha), \gamma_3 = 0, \gamma_4 = 0$
Soln 4	1	$\frac{2Q\tau\alpha\beta-\alpha\kappa+w}{2Q\tau\alpha(\beta-1)}$	$\gamma_1 = 0, \gamma_2 = 0, \gamma_3 = -(1-\alpha)(2Q\tau\beta - \kappa)Q\tau\beta, \gamma_4 = 0$
Soln 5	$\frac{2Q\tau\alpha(\beta-1)+\kappa-w}{2Q\tau\beta}$	1	$\gamma_1 = 0, \gamma_2 = 0, \gamma_3 = 0, \gamma_4 = Q\tau(1-\beta)(1-\alpha)(2Q\tau\alpha\beta - 2Q\tau\alpha - w)$
Soln 6	1	0	$\gamma_1 = 0, \gamma_2 = Q\tau(1-\beta)(2Q\tau\alpha\beta - \alpha\kappa + w), \gamma_3 = -Q\tau\beta(2Q\tau\beta - \kappa + w), \gamma_4 = 0$
Soln 7	0	1	$\gamma_1 = -Q\tau\beta(2Q\tau\alpha(\beta-1) + \kappa - w), \gamma_2 = 0, \gamma_3 = 0, \gamma_4 = Q\tau(1-\beta)(2Q\tau\alpha(\beta-1) + \alpha\kappa - w)$
Soln 8	1	1	$\gamma_1 = 0, \gamma_2 = 0, \gamma_3 = Q\tau\beta(2Q\tau\alpha(\beta-1) - 2Q\tau\beta + \kappa - w), \gamma_4 = -Q\tau(1-\beta)(2Q\tau\alpha - \alpha\kappa + w)$
Soln 9	0	0	$\gamma_1 = -Q\tau\beta(\kappa - w), \gamma_2 = -Q\tau(1-\beta)(\alpha\kappa - w), \gamma_3 = 0, \gamma_4 = 0$

Furthermore, note that the recycler does not receive any e-waste under Solution 8 and, because we are analyzing the choice of recycling standard, this solution is not relevant. Solution 9 is the case where the secondary market does not exist; we analyze this case separately under § 4.2. Note that when $Q > \frac{\kappa}{2\beta\tau}$, Solution 4 (because $\gamma_3 < 0$ if $Q > \frac{\kappa}{2\beta\tau}$) and Solution 6 (because $\gamma_3 < 0$ if $Q > \frac{\kappa}{2\beta\tau}$) can never be feasible. Therefore, only Solution 3 remains when $Q > \frac{\kappa}{2\beta\tau}$ and we have $\phi^{I*} = \frac{\kappa-w}{2Q\beta\tau} < 1$ and $\phi^{II*} = 0$.

Proof of Proposition 1. Focusing on the case when Q is large, i.e., $Q > \frac{\kappa}{2\beta\tau}$, from the proof of Lemma 1, we know that $\phi^{I*} = \frac{\kappa-w}{2Q\beta\tau}$ and $\phi^{II*} = 0$. Then, the recycler profit becomes $\pi_R(w) = \frac{1}{4}(\kappa - 2Q - w)(2a + b(\kappa - 2Q - w) + 2(w - r + \epsilon))$. The recycler profit is concave in w because $\frac{\partial^2 \pi_R(w)}{\partial w^2} = \frac{b-2}{2} < 0$ (recall we focus our analysis on the region where $b < 2$). Solving the FOC $\frac{\partial \pi_R(w)}{\partial w} = \frac{r-a-\epsilon+(b-2)w+(2Q-\kappa)(b-1)}{2} = 0$, the optimal wholesale price is $w^*(\epsilon) = \frac{r-a-\epsilon+(1-b)(\kappa-2Q)}{2-b}$.

Substituting w^* , we have $\phi^{I*}(\epsilon) = \frac{a+\epsilon+\kappa-r+2Q(1-b)}{2Q(2-b)\beta\tau}$, $\pi_C^*(\epsilon) = \frac{(r-a-\epsilon)^2+(4Q-2\kappa)(r-a-\epsilon)+\kappa^2-4Q(b-1)(b-3)(Q-\kappa)}{4(2-b)^2}$, and $\pi_R^*(\epsilon) = \frac{(r-a-\epsilon-\kappa+2Q)^2}{4(2-b)}$. Lastly, to find the recycler's choice on t , we calculate the difference between the recycler profits evaluated at $\epsilon = 0$ (for $t=L$) and $\epsilon = e$ (for $t=H$): $\Delta_R = \pi_R^*(\epsilon = 0) - \pi_R^*(\epsilon = e) = \frac{e(4Q-2a-e-2\kappa+2r)}{4(b-2)}$ which is always positive because the difference can be equivalently written as $\Delta_R = \frac{e^2}{4(2-b)} + (1-\beta)\phi^{I*}(\epsilon = e)Qe$ and $\phi^{I*}(\epsilon = e) < 1$. Thus, it is optimal for the recycler to choose $t^*=L$ (i.e., $\epsilon = 0$). As a result, we have $\phi^{I*} = \frac{a+\kappa-r+2Q(1-b)}{2Q(2-b)\beta\tau}$ and $w^* = \frac{r-a+(1-b)(\kappa-2Q)}{2-b}$. In addition, we find $q_S^{I*} = \frac{a+\kappa-r+2Q(1-b)}{2(2-b)}$, $q_S^{II*} = 0$, and $q_R^* = \frac{r+2Q-a-\kappa}{2(2-b)}$, whereas the secondary market price for high-quality items is $p^{I*} = \frac{2(b-1)(Q-\kappa)-a+\kappa+r}{2(2-b)}$ (Note that p^{II*} is not relevant because, at the optimality, no low-quality items are sold in the secondary market, i.e., $q_S^{II*} = 0$). \square

Proof of Corollary 1. Taking derivatives of q_S^{I*} , q_R^* , w^* , p^{I*} , π_C^* , and π_R^* given in Proposition 1 with respect to Q , we find that: (i) $\frac{\partial q_S^{I*}}{\partial Q} = \frac{1}{2-b} > 0$, and $\frac{\partial q_R^*}{\partial Q} = \frac{1-b}{2-b} > 0$ if and only if $b < 1$; (ii) $\frac{\partial w^*}{\partial Q} = -\frac{2(1-b)}{2-b} < 0$ if and only if $b < 1$, $\frac{\partial p^{I*}}{\partial Q} = -\frac{1-b}{2-b} < 0$ if and only if $b < 1$; (iii) $\frac{\partial \pi_R^*}{\partial Q} = \frac{r-a-\kappa+2Q}{2-b} > 0$ and $\frac{\partial \pi_C^*}{\partial Q} = \frac{r-a+(3-b)(1-b)(\kappa-2Q)}{(2-b)^2} = \frac{2(b-1)(3-b)q_R^*}{2-b} + r - a$. If $b \geq 1$ then $\frac{\partial \pi_C^*}{\partial Q} \geq 0$ (because $r > a$). If $b < 1$ then the sign of $\frac{\partial \pi_C^*}{\partial Q}$ depends on Q . Note that $\frac{\partial^2 \pi_C^*}{\partial Q^2} = \frac{2(b-1)(3-b)}{(b-2)^2} \leq 0$. Solving for Q in $\frac{\partial \pi_C^*}{\partial Q} = 0$, we have $Q = \bar{Q} = \frac{r-a+(3-b)(1-b)\kappa}{2(3-b)(1-b)}$; and thus $\frac{\partial \pi_C^*}{\partial Q} < 0$ if and only if $Q > \bar{Q}$ and $b < 1$. Lastly, note that $\frac{\partial \bar{Q}}{\partial b} = \frac{(2-b)(r-a)}{(b-1)^2(b-3)^2} \geq 0$. \square

Proof of Corollary 2. Taking derivatives of q_S^{I*} , q_R^* , w^* , p^{I*} , π_C^* , and π_R^* given in Proposition 1, with respect to b , we find that: (i) $\frac{\partial q_S^{I*}}{\partial b} = \frac{a+\kappa-r-2Q}{2(2-b)^2} < 0$ and $\frac{\partial q_R^*}{\partial b} = \frac{r+2Q-a-\kappa}{2(2-b)^2} > 0$, (ii) $\frac{\partial w^*}{\partial b} = \frac{r+2Q-a-\kappa}{(2-b)^2} > 0$, $\frac{\partial p^{I*}}{\partial b} = \frac{r+2Q-a-\kappa}{2(2-b)^2} > 0$ (iii) $\frac{\partial \pi_R^*}{\partial b} = \frac{(a+\kappa-r-2Q)^2}{4(2-b)^2} > 0$ and $\frac{\partial \pi_C^*}{\partial b} = \frac{(a+\kappa-r-2Q)^2}{2(2-b)^3} > 0$. \square

Proof of Lemma 2. When there is no secondary market, a collector sells all the collected e-waste to his recycler, i.e., $\phi_i^k = 0$ for $k = \{I, II\}$ and $q_{Ri} = Q_i$. In this case, the recycler's profit $\pi_{Ri} = (r - w_i - a - \epsilon_i)Q_i + bQ_i^2$ decreases with w_i , hence the recycler sets $w_i^* = 0$. \square

Proof of Proposition 2. First, we find $\pi_{Ri}^{t_i t_j}$ for $t_i, t_j \in \{H, L\}$ by substituting in $w_i^* = 0$ and $q_{Ri} = Q_i$ in recycler's profit given in (6). When both recyclers choose the same standard, this leads to $\pi_{R1}^{LL*} = \frac{LL*}{\pi_{R2}} = \frac{Q(bQ+2(r-a))}{4}$ and $\pi_{R1}^{HH*} = \pi_{R2}^{HH*} = \frac{HH*}{4} = \frac{Q(bQ+2(r-a-e))}{4}$. When the recyclers choose different standards, their profits are $\pi_{R1}^{HL*} = \pi_{R2}^{LH*} = \frac{HL*}{4} = \frac{Q(1+\eta)(bQ(1+\eta)+2(r-a-e))}{4}$ and $\pi_{R1}^{LH*} = \pi_{R2}^{HL*} = \frac{LH*}{4} = \frac{Q(1-\eta)(bQ(1-\eta)+2(r-a))}{4}$. Next, we start with characterizing the conditions under which (H,H) or (L,L) is a unique equilibrium.

i. (H,H) outcome is a unique equilibrium when the following conditions hold: 1. $\pi_{R1}^{HH*} - \pi_{R1}^{LH*} \geq 0$, 2. $\pi_{R1}^{HL*} - \pi_{R1}^{LL*} \geq 0$, 3. $\pi_{R2}^{HH*} - \pi_{R2}^{HL*} \geq 0$, and 4. $\pi_{R2}^{LH*} - \pi_{R2}^{LL*} \geq 0$. Having symmetric recyclers, Conditions 1. and 2. will be the same as conditions 3. and 4., respectively. Thus, without loss of generality, we analyze for recycler 1 and find when conditions 1. and 2. hold. Here, Condition 1. $\pi_{R1}^{HH*} - \pi_{R1}^{LH*} = \frac{Q}{4} ((2r - 2a + (2 - \eta)bQ)\eta - 2e) \geq 0$ is equivalent to $e \leq e_1 = \frac{\eta(2r-2a+(2-\eta)bQ)}{2}$. Condition 2. $\pi_{R1}^{HL*} - \pi_{R1}^{LL*} = -\frac{Q((2e(1+\eta)-\eta(2r-2a+bQ(2+\eta))))}{4} \geq 0$ is equivalent to $e \leq e_2 = \frac{\eta(2r-2a+bQ(2+\eta))}{2(1+\eta)}$. In sum, (H,H) is a unique equilibrium when $e \leq \min\{e_1, e_2\}$.

ii. (L,L) outcome is a unique equilibrium when the following conditions hold: 1. $\pi_{R1}^{LL*} - \pi_{R1}^{HL*} \geq 0$, 2. $\pi_{R1}^{LH*} - \pi_{R1}^{HH*} \geq 0$, 3. $\pi_{R2}^{LL*} - \pi_{R2}^{LH*} \geq 0$, and 4. $\pi_{R2}^{HL*} - \pi_{R2}^{HH*} \geq 0$. Since the recyclers are symmetric, Conditions 1. and 2. will be the same as Conditions 3. and 4., respectively. Therefore, without loss of generality, we provide the analysis for recycler 1 and find when Conditions 1. and 2.

hold. Here, Condition 1. $\pi_{R1}^{LL*} - \pi_{R1}^{HL*} = \frac{Q((2e(1+\eta) - \eta(2r - 2a + bQ(2+\eta)))}{4} \geq 0$ simplifies to $e \geq e_2$. Condition 2. $\pi_{R1}^{LH*} - \pi_{R1}^{HH*} = -\frac{Q}{4}((2r - 2a + (2 - \eta)bQ)\eta - 2e) \geq 0$ simplifies to $e \geq e_1$. To sum up, (L,L) is a unique equilibrium when $e \geq \max\{e_1, e_2\}$.

iii. Comparing e_1 and e_2 reveals that $e_1 \geq e_2$ if and only if $b \leq \frac{2(r-a)}{\eta Q}$. When $e_2 \leq e \leq e_1$, (H,H) and (L,L) are both equilibria. In that case, note that (L,L) dominates (H,H) because $\pi_{Ri}^{LL} > \pi_{Ri}^{HH}$. For $b > \frac{2(r-a)}{\eta Q}$ (i.e., $e_1 < e_2$), for intermediate values of e , i.e., when $e_1 < e < e_2$, we have $\pi_{R1}^{HL*} > \pi_{R1}^{LL*}$ and $\pi_{R2}^{HL*} > \pi_{R2}^{HH*}$, implying that (H,L) is an equilibrium. Likewise, (L,H) is another equilibrium when $e_1 < e < e_2$ due to symmetry. \square

Proof of Corollary 3. Taking derivatives of π_{Ri}^* with respect to b and Q , we find: $\frac{\partial \pi_{Ri}^{HH*}}{\partial b} = \frac{\partial \pi_{R(3-i)}^{HH*}}{\partial b} = \frac{\partial \pi_{Ri}^{LL*}}{\partial b} = \frac{\partial \pi_{R(3-i)}^{LL*}}{\partial b} = \frac{Q^2}{4} > 0$. $\frac{\partial \pi_{Ri}^{HL*}}{\partial b} = \frac{\partial \pi_{R(3-i)}^{LH*}}{\partial b} = \frac{Q^2(1+\eta)^2}{4} > 0$. $\frac{\partial \pi_{Ri}^{HH*}}{\partial Q} = \frac{\partial \pi_{R(3-i)}^{HH*}}{\partial Q} = \frac{r+bQ-a-e}{2} > 0$. $\frac{\partial \pi_{Ri}^{LL*}}{\partial Q} = \frac{\partial \pi_{R(3-i)}^{LL*}}{\partial Q} = \frac{r+bQ-a}{2} > 0$. $\frac{\partial \pi_{Ri}^{HL*}}{\partial Q} = \frac{\partial \pi_{R(3-i)}^{LH*}}{\partial Q} = \frac{(1+\eta)(r-a-e+bQ(1+\eta))}{2} > 0$. $\frac{\partial \pi_{Ri}^{LH*}}{\partial Q} = \frac{\partial \pi_{R(3-i)}^{HL*}}{\partial Q} = \frac{(1-\eta)(r-a+bQ(1-\eta))}{2} > 0$.

Furthermore, $\frac{\partial q_{Ri}^*}{\partial b} = 0$, $\frac{\partial q_{Ri}^*}{\partial Q} = 1/2 > 0$ \square

Proof of Lemma 3. We solve the problem using backward induction for symmetric and asymmetric choices of recycling standards.

(H,H) and (L,L) Equilibria. For the collector's problem, we write the Lagrangians as $L_{C1} = \pi_{C1} + \gamma_5 \phi_1^I + \gamma_6(1 - \phi_1^I) + \gamma_1 \phi_1^{II} + \gamma_2(1 - \phi_1^{II})$ and $L_{C2} = \pi_{C2} + \gamma_7 \phi_2^I + \gamma_8(1 - \phi_2^I) + \gamma_3 \phi_2^{II} + \gamma_4(1 - \phi_2^{II})$. We find that the Hessian is negative definite in (ϕ_i^I, ϕ_i^{II}) . At the optimality, the FOCs should hold:

$$\frac{\partial L_{C1}}{\partial \phi_1^I} = \frac{2Q\tau\beta(\kappa - w_1) - Q^2\tau^2\beta^2(2\phi_1^I + \phi_2^I) - Q^2\tau^2\alpha\beta(2\phi_1^{II} + \phi_2^{II})(1 - \beta) + 4\gamma_5 - 4\gamma_6}{4} = 0 \quad (\text{A.1})$$

$$\frac{\partial L_{C1}}{\partial \phi_1^{II}} = \frac{2Q\tau(1 - \beta)(\alpha\kappa - w_1) - Q^2\tau^2\alpha\beta(1 - \beta)(2\phi_1^I + \phi_2^I) - Q^2\tau^2\alpha(1 - \beta)^2(2\phi_1^{II} + \phi_2^{II}) + 4\gamma_1 - 4\gamma_2}{4} = 0 \quad (\text{A.2})$$

$$\frac{\partial L_{C2}}{\partial \phi_2^I} = \frac{2Q\tau\beta(\kappa - w_2) - Q^2\tau^2\beta^2(\phi_1^I + 2\phi_2^I) - Q^2\tau^2\alpha\beta(\phi_1^{II} + 2\phi_2^{II})(1 - \beta) + 4\gamma_7 - 4\gamma_8}{4} = 0 \quad (\text{A.3})$$

$$\frac{\partial L_{C2}}{\partial \phi_2^{II}} = \frac{2Q\tau(1 - \beta)(\alpha\kappa - w_2) - Q^2\tau^2\alpha\beta(1 - \beta)(\phi_1^I + 2\phi_2^I) - Q^2\tau^2\alpha(1 - \beta)^2(\phi_1^{II} + 2\phi_2^{II}) + 4\gamma_3 - 4\gamma_4}{4} = 0 \quad (\text{A.4})$$

In addition, the complementary slackness conditions (i.e., $\gamma_5 \phi_1^I = 0$, $\gamma_6(1 - \phi_1^I) = 0$, $\gamma_1 \phi_1^{II} = 0$, $\gamma_2(1 - \phi_1^{II}) = 0$, $\gamma_7 \phi_2^I = 0$, $\gamma_8(1 - \phi_2^I) = 0$, $\gamma_3 \phi_2^{II} = 0$, $\gamma_4(1 - \phi_2^{II}) = 0$) should hold too. Solving these OCs we find that there are 81 possible solutions. Specifically, any combination of solutions 1-9 from Table 2 with solutions a-i from Table 3 is possible. In the remainder of this proof, we refer to possible solutions using the names given in Tables 2-3. For example, solution 5(a) refers to $0 < \{\phi_1^I, \phi_2^I\} < 1$, $\phi_1^{II} = \phi_2^{II} = 0$. Next, we show that some of these solutions can never be feasible. Note that, from FOCs the following equalities should hold at the optimality:

$$\beta \frac{\partial L_{C1}}{\partial \phi_1^{II}} - \alpha(1 - \beta) \frac{\partial L_{C1}}{\partial \phi_1^I} = -Q\tau\beta(1 - \beta)(1 - \alpha) [Q\tau\alpha(1 - \beta)(2\phi_1^{II} + \phi_2^{II}) + 2w_1] - 4\alpha(1 - \beta)(\gamma_5 - \gamma_6) + 4\beta(\gamma_1 - \gamma_2) = 0 \quad (\text{A.5})$$

$$\beta \frac{\partial L_{C2}}{\partial \phi_2^{II}} - \alpha(1 - \beta) \frac{\partial L_{C2}}{\partial \phi_2^I} = -Q\tau\beta(1 - \beta)(1 - \alpha) [Q\tau\alpha(1 - \beta)(\phi_1^{II} + 2\phi_2^{II}) + 2w_2] - 4\alpha(1 - \beta)(\gamma_7 - \gamma_8) + 4\beta(\gamma_3 - \gamma_4) = 0 \quad (\text{A.6})$$

Consider solutions where $\phi_1^{I*} = 0$, i.e. solutions 1(a-i)-3(a-i). Here, from OCs $\gamma_6^* = 0$ and $\gamma_5^* > 0$. Then, (A.5) can never be satisfied if $\gamma_1^* \leq \gamma_2^*$, which holds only when $\gamma_1^* = 0$ and $\gamma_2^* \geq 0$. This implies that $\phi_1^{II*} > 0$ (solutions with d-i from Table 3) can never be feasible. Solutions where $\phi_1^{II*} = 0$, on the other hand, imply that the collectors do not sell in the secondary market at all (because recall that here $\phi_1^{I*} = 0$ too) and we analyze this case separately in Benchmark 2 in § 4.2.

Soln	ϕ_1^I	ϕ_2^I
1	0	0
2	0	+
3	0	1
4	+	0
5	+	+
6	+	1
7	1	0
8	1	+
9	1	1

Table 2: Possible solutions for (ϕ_1^I, ϕ_2^I) for the collectors' problem under recovery channel competition

Soln	ϕ_1^{II}	ϕ_2^{II}
a	0	0
b	0	+
c	0	1
d	+	0
e	+	+
f	+	1
g	1	0
h	1	+
i	1	1

Table 3: Possible solutions for $(\phi_1^{II}, \phi_2^{II})$ for the collectors' problem under recovery channel competition

Therefore, solutions 1(a-i)-3(a-i) are eliminated here. Using similar arguments and (A.6), we show that solutions with $\phi_2^{I*} = 0$, i.e. 4(a-i) and 7(a-i), are eliminated too.

Note that the first term in the right hand side of (A.5) is negative. Therefore, for the equality to hold the last two terms, i.e. $-4\alpha(1-\beta)(\gamma_5 - \gamma_6) + 4\beta(\gamma_1 - \gamma_2)$, should be positive. Therefore, if $\gamma_5 \geq \gamma_6$ then $\gamma_1 > \gamma_2$ should hold. This implies that if $\phi_1^{I*} < 1$ then $\phi_1^{II*} = 0$. Similarly, the first term in the right hand side of (A.6) is negative. Therefore, for the equality to hold the last two terms, i.e. $-4\alpha(1-\beta)(\gamma_7 - \gamma_8) + 4\beta(\gamma_3 - \gamma_4)$, should be positive. Therefore, if $\gamma_7 \geq \gamma_8$ then $\gamma_3 > \gamma_4$ should hold. This implies that if $\phi_2^{I*} < 1$ then $\phi_2^{II*} = 0$. Also, when $\phi_i^{I*} = \phi_i^{II*} = 0$, collector i does not sell to his recycler and this leaves recyclers outside of our model. These cases are not relevant for our research as we analyze the recycler's choice of standards. Furthermore, when $\phi_i^{I*} = \phi_i^{II*} = 1$, collector i does not sell in the secondary market and we analyze this case not here, but separately as Benchmark 1 in § 4.1. In sum, from the remaining solutions (i.e., 5,6,8,9), only 5(a), 6(a,b),8(a,d), 9(a,b,d,e) are possible or relevant.

(H,L) and (L,H) Equilibria. Here we give the proof for (L,H) equilibrium. The analysis for (H,L) equilibrium is similar and omitted for brevity. We again write the Lagrangians for each collector's problem as $L_{C1} = \pi_{C1} + \gamma_5\phi_1^I + \gamma_6(1 - \phi_1^I) + \gamma_1\phi_1^{II} + \gamma_2(1 - \phi_1^{II})$ and $L_{C2} = \pi_{C2} + \gamma_7\phi_2^I + \gamma_8(1 - \phi_2^I) + \gamma_3\phi_2^{II} + \gamma_4(1 - \phi_2^{II})$. We find that the Hessian is negative definite in (ϕ_i^I, ϕ_i^{II}) . At the optimality, the FOCs should hold:

$$\frac{\partial L_{C1}}{\partial \phi_1^I} = \frac{Q^2\tau^2\beta^2(1-\eta)(2\eta\phi_1^I - \eta\phi_2^I - 2\phi_1^I - \phi_2^I) + Q^2\tau^2\alpha\beta(\eta-1)(\beta-1)(2\eta\phi_1^{II} - \eta\phi_2^{II} - 2\phi_1^{II} - \phi_2^{II}) - 2\beta Q\tau(\kappa - w_1)(\eta-1) + 4(\gamma_5 - \gamma_6)}{4} = 0 \quad (\text{A.7})$$

$$\frac{\partial L_{C1}}{\partial \phi_1^{II}} = \frac{(1-\eta)(1-\beta)Q\tau(Q\tau\alpha\beta(2\eta\phi_1^I - \eta\phi_2^I - 2\phi_1^I - \phi_2^I) + Q\tau\alpha(1-\beta)(2\eta\phi_1^{II} - \eta\phi_2^{II} - 2\phi_1^{II} - \phi_2^{II}) + 2(\alpha\kappa - w_1)) + 4(\gamma_1 - \gamma_2)}{4} = 0 \quad (\text{A.8})$$

$$\frac{\partial L_{C2}}{\partial \phi_2^I} = \frac{Q^2\tau^2\beta^2(1-\eta)(2\eta\phi_1^I - \eta\phi_2^I - 2\phi_1^I - \phi_2^I) + Q^2\tau^2\alpha\beta(\eta-1)(\beta-1)(2\eta\phi_1^{II} - \eta\phi_2^{II} - 2\phi_1^{II} - \phi_2^{II}) - 2\beta Q\tau(\kappa - w_1)(\eta-1) + 4(\gamma_5 - \gamma_6)}{4} = 0 \quad (\text{A.9})$$

$$\frac{\partial L_{C2}}{\partial \phi_2^{II}} = \frac{(1+\eta)(1-\beta)\tau Q(Q\alpha\beta\tau(\eta\phi_1^I - 2\eta\phi_2^I - \phi_1^I - 2\phi_2^I) + Q\alpha(1-\beta)\tau(\eta\phi_1^{II} - 2\eta\phi_2^{II} - \phi_1^{II} - 2\phi_2^{II}) + 2(\alpha\kappa - w_2)) + 4(\gamma_3 - \gamma_4)}{4} = 0 \quad (\text{A.10})$$

In addition, the complementary slackness conditions (i.e., $\gamma_5\phi_1^I = 0$, $\gamma_6(1 - \phi_1^I) = 0$, $\gamma_1\phi_1^{II} = 0$, $\gamma_2(1 - \phi_1^{II}) = 0$, $\gamma_7\phi_2^I = 0$, $\gamma_8(1 - \phi_2^I) = 0$, $\gamma_3\phi_2^{II} = 0$, $\gamma_4(1 - \phi_2^{II}) = 0$) should hold too. Solving these OCs, we again find that there are 81 possible solutions. Specifically, any combination of solutions 1-9 from Table 2 with solutions a-i from Table 3 is possible. Next, we show some of these solutions that can never be feasible. Note that, from FOCs, the following equalities should hold at the optimality:

$$\beta \frac{\partial L_{C1}}{\partial \phi_1^{II}} - \alpha(1-\beta) \frac{\partial L_{C1}}{\partial \phi_1^I} = -Q\tau\beta(1-\beta)(1-\alpha)(1-\eta)[Q\tau\alpha(1-\beta)(2(1-\eta)\phi_1^{II} + (1+\eta)\phi_2^{II}) + 2w_1] - 4\alpha(1-\beta)(\gamma_5 - \gamma_6) + 4\beta(\gamma_1 - \gamma_2) = 0 \quad (\text{A.11})$$

$$\beta \frac{\partial LC2}{\partial \phi_2^{II}} - \alpha(1-\beta) \frac{\partial LC2}{\partial \phi_2^I} = -Q\tau\beta(1-\beta)(1-\alpha)(1+\eta)[Q\tau\alpha(1-\beta)((1-\eta)\phi_1^{II} + 2(1+\eta)\phi_2^{II}) + 2w_2] - 4\alpha(1-\beta)(\gamma_7 - \gamma_8) + 4\beta(\gamma_3 - \gamma_4) = 0 \quad (\text{A.12})$$

Consider solutions where $\phi_1^{I*} = 0$, i.e. solutions 1(a-i)-3(a-i). Here, from OCs $\gamma_6^* = 0$ and $\gamma_5^* > 0$. Then, (A.11) can never be satisfied if $\gamma_1^* \leq \gamma_2^*$, which holds only when $\gamma_1^* = 0$ and $\gamma_2^* \geq 0$. This implies that $\phi_1^{II*} > 0$ (solutions with d-i from Table 3) can never be feasible. Solutions where $\phi_1^{II*} = 0$, on the other hand, imply that the collectors do not sell in the secondary market at all (recall that, here, $\phi_1^{I*} = 0$ too) and we analyze this case separately in Benchmark 2 in § 4.2. Therefore, solutions 1(a-i)-3(a-i) are eliminated here. Using similar arguments and (A.12), we show that solutions with $\phi_2^{I*} = 0$, i.e. 4(a-i) and 7(a-i), can be eliminated too.

Note that the first term in the right-hand side of (A.11) is negative. Therefore, for the equality to hold the last two terms, i.e., $-4\alpha(1-\beta)(\gamma_5 - \gamma_6) + 4\beta(\gamma_1 - \gamma_2)$, should be positive. Therefore, if $\gamma_5 \geq \gamma_6$ then $\gamma_1 > \gamma_2$ should hold. This implies that if $\phi_1^{I*} < 1$ then $\phi_1^{II*} = 0$. Similarly, the first term in the right-hand side of (A.12) is negative. Therefore, for the equality to hold the last two terms, i.e., $-4\alpha(1-\beta)(\gamma_7 - \gamma_8) + 4\beta(\gamma_3 - \gamma_4)$, should be positive. Then, if $\gamma_7 \geq \gamma_8$ then $\gamma_3 > \gamma_4$ should hold. This implies that if $\phi_2^{I*} < 1$ then $\phi_2^{II*} = 0$. Also, when $\phi_i^I = \phi_i^{II*} = 0$, collector i does not sell to his recycler, leaving recyclers outside of our model. As such, these cases are not relevant for our research, given that we analyze the recycler's choice of standards. Furthermore, when $\phi_i^{I*} = \phi_i^{II*} = 1$, collector i does not sell in the secondary market; we analyze this case not here, but separately as Benchmark 1 in § 4.1. To sum up, from the remaining solutions (i.e., 5,6,8,9), only 5(a), 6(a,b),8(a,d), 9(a,b,d,e) are possible or relevant.

In § 5 we focus on the case 5(a) so we need to find the sufficient condition to ensure that case 5(a) is the unique relevant outcome. This is achieved by finding the sufficient condition that renders infeasible all the other cases, 6(a,b), 8(a,d) and 9(a,b,d,e). For example, for case 6(a) in the (H,L) outcome, the equilibrium is $\phi_1^I = \frac{2(\kappa - w_1) - (1-\eta)Q\beta\tau}{2Q\beta\tau(1+\eta)}$ and $\phi_2^I = 1$. This solution is feasible only if $\phi_1^I > 0$, which is equivalent to $w_1 < k - \frac{1}{2}Q\beta\tau(1-\eta)$. In other words, this solution would be infeasible if $\kappa - \frac{1}{2}Q\beta\tau(1-\eta) < 0$ (since $w_1 \geq 0$), or equivalently, $Q > \frac{2\kappa}{\beta\tau(1-\eta)}$. We apply the similar approach to find the sufficient condition for infeasibility of (H,H), (L,L), (H,L), (L,H) outcomes under cases 6(a,b),8(a,d) and 9(a,b,d,e). Comparing those conditions reveals that $Q > \frac{2\kappa}{\beta\tau(1-\eta)}$ renders infeasible all of those cases except for 5(a).□

Proof of Proposition 3. We analyze symmetric and asymmetric equilibria separately:

i. Consider the case when $t_1 = t_2$ and both recyclers choose the same recycling standard, i.e., (H,H) or (L,L) is equilibrium. Following backward induction, we first obtain the optimal fraction of e-waste quantity to sell in the secondary market. Under the assumption $Q > \frac{2\kappa}{\beta\tau(1-\eta)}$, only 5(a) is feasible, i.e., $\phi_1^{I*}(w_1, w_2) = \frac{2(w_2 - 2w_1 + \kappa)}{3Q\beta\tau}$, $\phi_2^{I*}(w_1, w_2) = \frac{2(w_1 - 2w_2 + \kappa)}{3Q\beta\tau}$ and $\phi_1^{II*} = \phi_2^{II*} = 0$. Substituting $\phi_i^k(w_i, w_{3-i})$ into recycler i 's objective function, given in Equation (6), we obtain each recycler's profit as: $\pi_{R1}(w_1, w_2) = \frac{1}{36}(2\kappa - 3Q - 4w_1 + 2w_2)(6a + 6\epsilon_i - 6r + 6w_1 + b(2\kappa - 3Q - 4w_1 + 2w_2))$ and $\pi_{R2}(w_1, w_2) = \frac{1}{36}(2\kappa - 3Q + 2w_1 - 4w_2)(6a + 6\epsilon_i - 6r + 6w_2 + b(2\kappa - 3Q + 2w_1 - 4w_2))$. We have $\frac{\partial^2 \pi_{Ri}(w_i)}{\partial w_i^2} = \frac{4(-3+2b)}{9} < 0$ (because $b < 3/2$ by assumption). Thus the optimal wholesale prices are obtained by solving the FOCs $\frac{\partial \pi_{Ri}(w_i)}{\partial w_i} = 0$ (for $i = 1, 2$) simultaneously. The unique equilibrium are given by $w_1^* = w_2^* = \frac{12(r-a-\epsilon_i) + (3-4b)(2\kappa-3Q)}{2(9-4b)}$. Substituting w_i^* and w_{3-i}^* into $\phi_i^{I*}(w_i, w_{3-i})$ for $i = 1, 2$, we obtain $\phi_1^{I*} = \phi_2^{I*} = \frac{4(a+\kappa+\epsilon_i-r) + (3-4b)Q}{(9-4b)Q\beta\tau}$, $q_{S1}^* = \phi_1^{I*}\beta\tau Q_1 + \phi_1^{II*}(1-\beta)\tau Q_1 = q_{S2}^* = \phi_2^{I*}\beta\tau Q_2 + \phi_2^{II*}(1-\beta)\tau Q_2 = \frac{4(a+\kappa+\epsilon_i-r) + (3-4b)Q}{2(9-4b)}$, $q_{R1}^* = (1-\tau)Q_1 + (1-\phi_1^{I*})\beta\tau Q_1 + (1-\phi_1^{II*})(1-\beta)\tau Q_1 = q_{R2}^* = (1-\tau)Q_2 + (1-\phi_2^{I*})\beta\tau Q_2 + (1-\phi_2^{II*})(1-\beta)\tau Q_2 = \frac{2(r-a-\kappa-\epsilon_i) + 3Q}{9-4b}$, $p^{I*} = \frac{4(r-a-\kappa-\epsilon_i) + (4b-3)Q - \kappa(4b-9)}{9-4b}$,

$$\pi_{R1}^* = \pi_{R2}^* = \frac{(3-2b)(2(r-a-\epsilon_i-\kappa)+3Q)^2}{2(9-4b)^2} \quad \text{and} \quad \pi_{C1}^* = \pi_{C2}^* = \frac{8(r-a-\epsilon_i-\kappa)^2 - 2Q(4b-21)(r-a-\epsilon_i-\kappa) - 4Q^2(4b-3)(b-3) + Q\kappa(4b-9)^2}{2(4b-9)^2},$$

where $\epsilon_i = e$ if $t_1=t_2=H$ and $\epsilon_i = 0$ if $t_1=t_2=L$. Therefore, $\pi_{R1}^{HH*} = \pi_{R2}^{HH*} = \frac{(3-2b)(2(r-a-e-\kappa)+3Q)^2}{2(9-4b)^2}$ and

$$\pi_{R1}^{LL*} = \pi_{R2}^{LL*} = \frac{(3-2b)(2(r-a-\kappa)+3Q)^2}{2(9-4b)^2}.$$

ii. Consider the asymmetric equilibrium when recycler i chooses the high standard ($t_i=H$) while recycler $3-i$ chooses the low standard ($t_{(3-i)}=L$), i.e., $\epsilon_i = e$ and $\epsilon_{(3-i)} = 0$, for $i = 1, 2$. Note that in this case, $Q_i = \frac{1+\eta}{2}Q$ and $Q_{(3-i)} = \frac{1-\eta}{2}Q$. From above, we know that only 5(a) is feasible (because $Q > \frac{\kappa}{2\beta(1-\eta)}$), i.e., $\phi_i^{I*}(w_i, w_{(3-i)}) = \frac{2(w_{(3-i)}-2w_i+\kappa)}{3Q\tau\beta(1+\eta)}$, $\phi_{(3-i)}^{I*}(w_i, w_{(3-i)}) = \frac{2(w_i-2w_{(3-i)}+\kappa)}{3Q\beta\tau(1-\eta)}$ and $\phi_i^{II*} = \phi_{(3-i)}^{II*} = 0$. We use backward induction, as explained above, for symmetric equilibrium. For brevity, we omit the details and provide the final solution: $w_i^* = \frac{\theta_1 - \theta_2 - 16(3-2b)e}{2(9-4b)(5-4b)}$, $w_{(3-i)}^* = \frac{\theta_1 + \theta_2 - 4(3-4b)e}{2(9-4b)(5-4b)}$, $\phi_i^{I*} = \frac{\theta_2 + \theta_3 + 4(7-4b)e}{((9-4b)(5-4b)Q\beta\tau(1+\eta))}$ and $\phi_{(3-i)}^{I*} = \frac{\theta_3 - \theta_2 - 8e}{(9-4b)(5-4b)Q\beta\tau(1-\eta)}$, where $\theta_1 = (5-4b)(12(r-a) - (3-4b)(3Q-2\kappa))$, $\theta_2 = (9-4b)(3-4b)Q\eta$, and $\theta_3 = (5-4b)(4(\kappa+a-r) + (3-4b)Q)$. Substituting these into $q_{Ri}(w_i, w_{(3-i)})$, we obtain $q_{Ri}^* = \frac{(9-4b)Q\eta + 2(5-4b)(r-a-\kappa) + 3Q(5-4b) + 2e(4b-7)}{(5-4b)(9-4b)}$, $q_{R(3-i)}^* = \frac{(4b-9)Q\eta + 2(5-4b)(r-a-\kappa) - 3Q(4b-5) + 4e}{(5-4b)(9-4b)}$, $q_{Si}^* = \phi_i^{I*}\beta\tau Q_i + \phi_i^{II*}(1-\beta)\tau Q_i$, $q_{S(3-i)}^* = \phi_{(3-i)}^{I*}\beta\tau Q_{(3-i)} + \phi_{(3-i)}^{II*}(1-\beta)\tau Q_{(3-i)}$, and secondary market price of high-quality product is $p^{I*} = \frac{4(r-a-\kappa) + (4b-3)Q - 2e - \kappa(4b-9)}{9-4b}$. Lastly, the recyclers' optimal profits are

$$\pi_{Ri}^* = \frac{(3-2b)(2(5-4b)(r-a-\kappa) - 2(7-4b)e + Q(9-4b)\eta + 3Q(5-4b))^2}{2(5-4b)^2(9-4b)^2}, \quad \pi_{R(3-i)}^* = \frac{(3-2b)(2(5-4b)(r-a-\kappa) - Q(9-4b)\eta + 3Q(5-4b) + 4e)^2}{2(5-4b)^2(9-4b)^2}.$$

We omit expressions for the collectors' profits as they are tedious. Using the optimal solutions provided in this proof, they can be easily calculated as $\pi_{Ci}^* = q_{Si}^*p^{I*} + q_{Si}^{II*}p^{II*} + q_{Ri}^*w_i^*$ for $i = 1, 2$ and are available from the authors. Therefore, $\pi_{R1}^{HL*} = \pi_{R2}^{HL*} = \frac{(3-2b)(2(5-4b)(r-a-\kappa) - 2(7-4b)e + Q(9-4b)\eta + 3Q(5-4b))^2}{2(5-4b)^2(9-4b)^2}$

$$\text{and } \pi_{R2}^{HL*} = \pi_{R1}^{HL*} = \frac{(3-2b)(2(5-4b)(r-a-\kappa) - Q(9-4b)\eta + 3Q(5-4b) + 4e)^2}{2(5-4b)^2(9-4b)^2}. \quad \square$$

Proof of Corollary 4. Taking the derivatives of w_i^* , q_{Ri}^* and $q_{R(3-i)}^*$, given in Proposition 3 (ii) and the Proof of Proposition 3, with respect to e , we find that: $\frac{\partial w_i^*}{\partial e} = \frac{16(3-2b)}{2(9-4b)(4b-5)} > 0$, $\frac{\partial q_{Ri}^*}{\partial e} = \frac{2(7-4b)}{(4b-5)(9-4b)} > 0$, whereas $\frac{\partial q_{R(3-i)}^*}{\partial e} = \frac{-4}{(4b-5)(9-4b)} < 0$, if and only if $b > \frac{5}{4}$. \square

Proof of Proposition 4. In order to find which recycling standard recycler i should choose, we need to consider all four possible equilibria: **a.** both recyclers choose the high standard, i.e., (H, H); **b.** recycler 1 chooses high standard, while recycler 2 chooses low standard, i.e., (H, L); **c.** recycler 1 chooses low standard, while recycler 2 chooses high standard, i.e., (L, H); **d.** both recyclers choose low standard, i.e., (L, L). Table 4 summarizes the recyclers' profits under each possible equilibrium. The expressions for optimal profits are provided in the proof of Proposition 3. Next we analyze the conditions required for each symmetric equilibrium to be optimal and show that an asymmetric equilibrium can never be optimal.

	R2 chooses H	R2 chooses L
R1 chooses H	$\frac{HH^*}{\pi_{R1}}, \frac{HH^*}{\pi_{R2}}$	$\frac{HL^*}{\pi_{R1}}, \frac{HL^*}{\pi_{R2}}$
R1 chooses L	$\frac{LH^*}{\pi_{R1}}, \frac{LH^*}{\pi_{R2}}$	$\frac{LL^*}{\pi_{R1}}, \frac{LL^*}{\pi_{R2}}$

Table 4: Summary of the Game

(H,H) Equilibrium: For (H,H) to be a unique equilibrium, the following conditions must hold: 1. $\frac{HH^*}{\pi_{R1}} - \frac{LH^*}{\pi_{R1}} > 0$, 2. $\frac{HL^*}{\pi_{R1}} - \frac{LL^*}{\pi_{R1}} > 0$, 3. $\frac{HH^*}{\pi_{R2}} - \frac{HL^*}{\pi_{R2}} > 0$, and 4. $\frac{LH^*}{\pi_{R2}} - \frac{LL^*}{\pi_{R2}} > 0$. Since the recyclers are symmetric, Conditions 1. and 2. will be the same as Conditions 3. and 4., respectively. Therefore, without loss of generality, we provide the analysis for recycler 1 and find

when Conditions 1. and 2. hold.

Condition 1. If recycler 2 chooses H, then recycler 1 chooses H if and only if

$$\begin{aligned}\Delta_1 &= \pi_{R1}^{HH*} - \pi_{R1}^{LH*} = \frac{(3-2b)(2(r-a-e-\kappa)+3Q)^2}{2(9-4b)^2} - \frac{(3-2b)(2(5-4b)(r-a-\kappa)-Q(9-4b)\eta+3Q(5-4b)+4e)^2}{2(5-4b)^2(9-4b)^2} \\ &= \frac{(3-2b)((9-4b)Q\eta-(14-8b)e)(4Qb\eta-24Qb-9Q\eta+16ab+8be+16b\kappa-16br+30Q-20a-6e-20\kappa+20r)}{2(4b-5)^2(4b-9)^2} > 0\end{aligned}$$

which can be equivalently written as

$$\Delta_1 = \frac{(3-2b)Q((9-4b)Q\eta-(14-8b)e)((1-\beta\tau\phi_1^{ILL*})(1-\eta)+(1-\beta\tau\phi_1^{IHH*}))}{4(5-4b)(9-4b)} > 0. \quad (\text{A.13})$$

Since $(1-\beta\tau\phi_1^{ILL*})(1-\eta)+(1-\beta\tau\phi_1^{IHH*}) > 0$ and $b < 3/2$ (by assumption), we conclude that $\Delta_1 > 0$ iff one of the following two conditions holds: 1.i.) $b < 5/4$ and $e < \bar{e}$; 1.ii.) $b > 5/4$ and $e > \bar{e}$, where $\bar{e} = \frac{(9-4b)Q\eta}{14-8b}$. Because the recyclers are symmetric, if recycler 1 chooses H then recycler 2 chooses H (when $\Delta_1 \geq 0$).

Condition 2. If recycler 2 chooses L, then recycler 1 chooses H if and only if $\Delta_2 = \pi_{R1}^{HL*} - \pi_{R1}^{LL*} = \frac{(3-2b)(4Qb\eta-9Q\eta-8be+14e)(4Qb\eta+24Qb-9Q\eta-16ab-8be-16b\kappa+16br-30Q+20a+14e+20\kappa-20r)}{2(4b-5)^2(4b-9)^2} > 0$ which can be rewritten as

$$\Delta_2 = \frac{(3-2b)Q((9-4b)Q\eta-(14-8b)e)((1-\beta\tau\phi_1^{IHL*})(1+\eta)+(1-\beta\tau\phi_1^{ILL*}))}{4(5-4b)(9-4b)} > 0. \quad (\text{A.14})$$

Since $(1-\beta\tau\phi_1^{IHL*})(1+\eta)+(1-\beta\tau\phi_1^{ILL*}) > 0$ and $b < 3/2$, comparing expressions for Δ_1 (see (A.13)) and Δ_2 , we conclude that $\text{sign } \Delta_1 = \text{sign } \Delta_2$. Thus, $\Delta_2 > 0$ iff Condition 1.i. or 1.ii. holds. This also proves that asymmetric equilibrium can never arise. That is because, for an asymmetric equilibrium, $\pi_{R1}^{LH*} - \pi_{R1}^{HH*} = -\Delta_1 > 0$ and $\pi_{R1}^{HL*} - \pi_{R1}^{LL*} = \Delta_2 > 0$ should hold simultaneously. However, this is not possible because $\text{sign } \Delta_1 = \text{sign } \Delta_2$.

(L,L) Equilibrium: For (L,L) to be the unique equilibrium, the following conditions must hold: 1. $\pi_{R1}^{LH*} - \pi_{R1}^{HH*} > 0$, 2. $\pi_{R1}^{LL*} - \pi_{R1}^{HL*} > 0$, 3. $\pi_{R2}^{HL*} - \pi_{R2}^{HH*} > 0$, and 4. $\pi_{R2}^{LL*} - \pi_{R2}^{LH*} > 0$. Because the recyclers are symmetric, conditions 1. and 2. again will be the same as conditions 3. and 4., respectively. We find that 1. $\pi_{R1}^{LH*} - \pi_{R1}^{HH*} = -\Delta_1$ and $\pi_{R1}^{LL*} - \pi_{R1}^{HL*} = -\Delta_2$. Therefore, (L,L) is a unique equilibrium if and only if 2.i.) $b < 5/4$ and $e > \bar{e}$; or if 2.ii.) $b > 5/4$ and $e < \bar{e}$. To sum up;

i. If $b < 5/4$, then the equilibrium is $(t_1^*, t_2^*) = \{(H,H) \text{ if } e < \bar{e} \text{ and } (L,L) \text{ if } e > \bar{e}\}$ and

ii. If $b > 5/4$, then the equilibrium is $(t_1^*, t_2^*) = \{(L,L) \text{ if } e < \bar{e} \text{ and } (H,H) \text{ if } e > \bar{e}\}$.

Note that if $e = \bar{e}$ then $\Delta_1 = \Delta_2$ and therefore there are multiple equilibria (i.e., $(t_1^*, t_2^*) = (t_1, t_2)$ where $t_1, t_2 \in H, L$). Finally, $\Delta = \pi_{R1}^{LL*} - \pi_{R1}^{HH*} = \frac{2(3-2b)e(2r+3Q-2a-e-2\kappa)}{(9-4b)^2} > 0$ (because $(2r+3Q-2a-e-2\kappa) > 0$ from $1-\beta\tau\phi_1^{IHH*} = \frac{2(2r+3Q-2a-e-2\kappa)}{Q(9-4b)} > 0$). Therefore, whenever (H,H) arises as equilibrium it creates a prisoner's dilemma. \square

Proof of Corollary 5. Taking the derivatives of the optimal solutions given in Proposition 3(i.) with respect to Q , we find that: (i) $\frac{\partial q_{Si}^*}{\partial Q} = \frac{3-4b}{2(9-4b)} > 0$ if and only if $b < \frac{3}{4}$, and $\frac{\partial q_{Ri}^*}{\partial Q} = \frac{3}{9-4b} > 0$; (ii) $\frac{\partial w_i^*}{\partial Q} = \frac{3(4b-3)}{2(9-4b)} < 0$ and $\frac{\partial p_i^*}{\partial Q} = \frac{4b-3}{9-4b} < 0$ if and only if $b < \frac{3}{4}$; (iii) $\frac{\partial \pi_{Ri}^*}{\partial Q} = \frac{3(3-2b)(2r+3Q-2a-2\epsilon_i-2\kappa)}{(9-4b)^2} > 0$ and $\frac{\partial \pi_{Ci}^*}{\partial Q} = \frac{8(4b-3)(3-b)Q+(4b-3)(4b-13)\kappa+2(4b-21)(a+\epsilon_i-r)}{2(9-4b)^2}$. Therefore, $\frac{\partial \pi_{Ci}^*}{\partial Q} \leq 0$ if and only if $b < \frac{3}{4}$ and $Q \geq \bar{Q} = \frac{(4b-3)(4b-13)\kappa+2(4b-21)(a+\epsilon_i-r)}{8(3-4b)(3-b)}$. \square

Proof of Corollary 6. Taking the derivatives of the optimal solutions provided in Proposition 3(ii.) with respect to b , we find that: (i) $\frac{\partial q_{Ri}^*}{\partial b} = \frac{4(2r+3Q-2a-2\epsilon_i-2\kappa)}{(9-4b)^2} > 0$ (this and the following inequalities hold because $\beta\phi_i^{I*} \in (0, 1)$ and therefore $2r+3Q-2a-2\epsilon_i-2\kappa > 0$ by assumption) and $\frac{\partial q_{Si}^{I*}}{\partial b} = \frac{-4(2r+3Q-2a-2\epsilon_i-2\kappa)}{(9-4b)^2} < 0$; (ii) $\frac{\partial w_i^*}{\partial b} = \frac{12(2r+3Q-2a-2\epsilon_i-2\kappa)}{(9-4b)^2} > 0$; and $\frac{\partial p^{I*}}{\partial b} = \frac{8(2r+3Q-2a-2\epsilon_i-2\kappa)}{(9-4b)^2} > 0$; (iii) $\frac{\partial \pi_{Ci}^*}{\partial b} = \frac{2(Q(9-4b)+4(2r+3Q-2a-2\epsilon_i-2\kappa))(2r+3Q-2a-2\epsilon_i-2\kappa)}{(9-4b)^3} > 0$ and $\frac{\partial \pi_{Ri}^*}{\partial b} = \frac{(3-4b)(2r+3Q-2a-2\epsilon_i-2\kappa)^2}{(9-4b)^3}$. Therefore, $\frac{\partial \pi_{Ri}^*}{\partial b} < 0$ if and only if $b > 3/4$. \square

Proof of Lemma 4. The difference between the total environmental impacts is $\Delta_E = E^{LL} - E^{HH} = (\lambda_L \sum_{i=1}^2 q_{Ri}^{LL*} + \lambda_S \sum_{i=1}^2 q_{Si}^{LL*}) - (\lambda_H \sum_{i=1}^2 q_{Ri}^{HH*} + \lambda_S \sum_{i=1}^2 q_{Si}^{HH*})$, where $q_{Si}^* = q_{Si}^{I*} + q_{Si}^{II*}$. Here, we substitute in the expressions of q_{Si}^* and q_{Ri}^* , given in the proof of Proposition 3i. and ii. for (H,H) and (L,L) equilibria, respectively, and find $\Delta_E = \frac{2(2(\lambda_L - \lambda_S)e - (3Q - 2a - 2\kappa + 2r - 2e)(\lambda_H - \lambda_L))}{9-4b}$. Note that $(3Q - 2a - 2\kappa + 2r - 2e) = q_{Ri}^{HH*}(9 - 4b) > 0$ and $\lambda_H > \lambda_L$ (by assumption). Therefore, $\Delta_E > 0$ if and only if $2e(\lambda_L - \lambda_S) > (\lambda_H - \lambda_L)(3Q - 2a - 2\kappa + 2r - 2e)$. \square

Proof of Lemma 5. The difference between the surplus under (L,L) and (H,H) equilibria is $\Delta_S = S^{LL} - S^{HH} = \frac{4e(4Qb - 3Q - 4a - 2e - 4\kappa + 4r)}{(9-4b)^2} = \frac{-4e \sum_{i=1}^2 q_{Si}^{I*}(\epsilon=0) - 8e^2}{(9-4b)^2} < 0$. The difference between the total collector profits is $\sum_{i=1}^2 \pi_{Ci}^{LL*} - \sum_{i=1}^2 \pi_{Ci}^{HH*} = \frac{2e(21Q - 4Qb - 8a - 4e - 8\kappa + 8r)}{(9-4b)^2} = \frac{4e \sum_{i=1}^2 q_{Ri}^*(\epsilon=e) + 2e(9Q - 4Qb + 4e)}{(9-4b)^2} > 0$. From the proof of Proposition 3, we know that $\sum_{i=1}^2 \pi_{Ri}^{LL*} - \sum_{i=1}^2 \pi_{Ri}^{HH*} > 0$. Therefore, $\Delta_P = \sum_{i \in \{1,2\}} (\pi_{Ci}^{LL*} + \pi_{Ri}^{LL*}) - \sum_{i \in \{1,2\}} (\pi_{Ci}^{HH*} + \pi_{Ri}^{HH*}) > 0$. To sum up, the recovery channel achieves higher profit under the low standard whereas secondary-market customers achieve lower surplus. Therefore, the sign of $\Delta_P + \Delta_S = \frac{2e((33Q - 8Qb + 8ab + 4be - 8br - 28a - 14e + 28r) - 4(7-2b)\kappa)}{(9-4b)^2}$ depends on how the difference in the sum of profits compares with the difference in surpluses. If the potential secondary-market size is small, i.e., $\kappa < \frac{(33Q - 8Qb + 8ab + 4be - 8br - 28a - 14e + 28r)}{4(7-2b)}$, then $\Delta_P + \Delta_S > 0$. \square

Proof of Proposition 5. The difference between the total welfare achieved under (L,L) and (H,H) equilibria is $\Delta_W = W^{LL} - W^{HH} = \frac{4e(\lambda_L - \lambda_S) - 2(3Q - 2a - 2\kappa + 2r - 2e)(\lambda_H - \lambda_L) + (9-4b)(\Delta_P + \Delta_S)}{9-4b}$. Recall that $\lambda_H > \lambda_L$ and $(3Q - 2a - 2\kappa + 2r - 2e) > 0$. Therefore, $\Delta_W > 0$ iff $2e(\lambda_L - \lambda_S) > (\lambda_H - \lambda_L)(3Q - 2a - 2\kappa + 2r - 2e) - \frac{(9-4b)}{2}(\Delta_S + \Delta_P)$. \square

B. Each Recycler Working with Multiple Collectors

We consider the case where each recycler works with a mutually exclusive set of n collectors. Define Q_{ij} as the amount of e-waste collector j , who works with recycler i , receives from donors. Since donors are indifferent between the n identical collectors of recycler i , collector j receives $Q_{ij} = \frac{Q_i}{n}$ units of e-waste, for $i = 1, 2$ and $j = 1, 2, \dots, n$. We denote π_{Cij} as the profit of collector j , working with recycler i . To optimize his profit, collector j chooses the fraction of e-waste of each resalable quality level to sell in the secondary market, denoted by $\phi_{ij}^k \in [0, 1]$ for $i = 1, 2$, $j = 1, 2, \dots, n$ and $k = I, II$. Thus, the amount of high (low) quality e-waste collector j sells in the secondary market is $q_{Sij}^I = \phi_{ij}^I \beta \tau Q_{ij}$ ($q_{Sij}^{II} = \phi_{ij}^{II} (1 - \beta) \tau Q_{ij}$). Then the total amount of high- (low-) quality e-waste sold in the secondary market by collectors working with recycler i is $q_{Si}^I = \sum_{j=1}^n q_{Sij}^I$ ($q_{Si}^{II} = \sum_{j=1}^n q_{Sij}^{II}$), for $i = 1, 2$. The structures of the inverse demand functions p^I and p^{II} for high- and low- quality e-waste remain the same as in (1)-(2), respectively. Lastly, collector j sells the remaining e-waste, $q_{Rij} = (1 - \phi_{ij}^I) \beta \tau Q_{ij} + (1 - \phi_{ij}^{II})(1 - \beta) \tau Q_{ij} + (1 - \tau) Q_{ij}$, to recycler i at a wholesale price w_{ij} . The profit functions of the collectors and recyclers are given as follows:

$$\pi_{Cij}(\phi_{ij}^I, \phi_{ij}^{II}) = p^I q_{Sij}^I + p^{II} q_{Sij}^{II} + w_{ij} q_{Rij}, \text{ for } i = 1, 2, j = 1, 2, \dots, n$$

$$\pi_{Ri} = \sum_{j=1}^n (r - w_{ij}) q_{Rij} - \int_0^{\sum_{j=1}^n q_{Rij}} g(x) dx, \text{ for } i = 1, 2$$