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Should Recycled Content Standards be Raised in Response to Privatization?

Jiunn-Rong Chiou and Hung-Yi Chen*

This study analyzes the government's optimal recycled content standards (RCS) policy in a downstream mixed duopoly and examines how the policy should be adjusted in response to privatization. Before privatization, when the upstream recycling market is perfectly competitive, no RCS is needed if the marginal damage from unrecycled waste is smaller than the cost increase caused by substituting recycled materials for virgin materials; otherwise, the government should adopt the most stringent RCS. After privatization, the optimal RCS may instead emerge as an interior solution between zero and one. If privatization expands total output and thereby increases environmental damage, the optimal RCS should become more stringent. Conversely, if privatization reduces total output, the optimal RCS should be relaxed. We also consider the case of an upstream monopoly and show that the main qualitative results regarding the optimal RCS continue to hold. A comparison across upstream market structures further indicates that the optimal RCS tends to be higher under upstream monopoly than under perfect competition.

Keywords: optimal recycled content standards, recyclable markets, mixed duopoly, privatization
JEL classification: L33, Q28, Q55

*The authors are Professors in the Department of Economics, National Central University, and the Department of International Business, Soochow University, respectively. Corresponding author: Hung-Yi Chen, E-mail: hychen@scu.edu.tw. We would like to thank the editor and two anonymous referees for their valuable comments and suggestions, which significantly improved the paper. Any remaining errors are our own. Hung-Yi Chen gratefully acknowledges financial support from the Ministry of Science and Technology (MOST), Taiwan, under Grant No. MOST 110-2410-H-031-071.

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1 Introduction

In recent years, the issue of the circular economy has gained significant attention from governments around the world. The severe pollution resulting from improper waste disposal underscores the vital role of recycling, disposal, and reuse, particularly in the latter stages of a product's life cycle. One pressing challenge is the management of waste electrical and electronic equipment (WEEE), given the substantial volumes generated globally. According to the 2016 report by the European Union, WEEE has become the fastest-growing category of waste, with an annual growth rate of around 3–5%, while less than 40% is currently recycled (Tesar et al., 2021). Prominent Members of the European Parliament have noted that in 2017, approximately 44.7 million tons of e-waste were produced worldwide, yet only about 20% was properly recycled (European Parliament, 2020),

To address such concerns, governments have implemented a range of policy instruments aimed at reducing waste and promoting sustainable resource use, including taxes on virgin materials, subsidies for recycling activities, deposit-refund systems, and recycled content standards (RCS). Among these, RCS stands out as a market-based instrument that directly links firms' production decisions to environmental performance. By requiring producers to incorporate a minimum proportion of recycled materials into final products, RCS policies internalize part of the environmental externality associated with waste generation. For instance, Japan's Home Appliances Recycling Law, which came into effect in April 2001, mandates that electronics manufacturers achieve a recycling rate of at least 50% (Higashida and Jinji, 2006).

Similar mandates are emerging worldwide. Beginning January 1, 2023, plastics laws in Washington State (U.S.) require manufacturers of various consumer products to meet minimum recycled-content thresholds, such as 10% for garbage bags and 15% for beverage bottles.[1] Mexico's proposed legislation mandates that plastic products contain 20% recycled content by 2025 and 30% by 2030 (Plastics News, 2021), while Canada's Zero Plastic

[1] Other covered products will be required to meet post-consumer recycled content minimums at later dates. For details, please see "Recycled Content Minimums," Washington State Department of Ecology, U.S.A., https://ecology.wa.gov/Waste-Toxics/Reducing-recycling-waste/Waste-reduction-programs/Plastics/2021-plastic-pollution-laws/Recycled-content-minimums.

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Waste Action Plan targets 50% recycled content by 2030.[2] In the aviation sector, the EU's ReFuelEU Aviation regulation, which is part of the Fit for 55 package, sets a blending mandate requiring sustainable aviation fuel (SAF) shares of at least 2% by 2025, 6% by 2030, and 70% by 2050. These SAF mandates are structurally analogous to RCS, as both policies compel firms to replace conventional inputs with more sustainable alternatives.[3]

Parallel to these environmental initiatives, the global wave of privatization that began in the 1990s has reshaped many pollution-intensive industries, including solid waste, oil, steel, cement, power, and coal. According to Australia's Minderoo Foundation, twenty plastic companies account for 55% of the world's single-use plastic waste, a group that includes major state-owned and multinational oil and chemical enterprises (The Guardian, 2021).[4] Understanding how privatization interacts with environmental policies such as RCS therefore holds important policy implications.

Previous studies on recycling policies have largely focused on achieving efficiency under perfect competition, aiming to identify which instruments most effectively reduce waste. Sigman (1995) analyzes four types of recycling policies, including RCS, virgin-material taxes, deposit-refund systems, and recycling subsidies, while Palmer and Walls (1997) show that RCS alone cannot achieve a socially optimal allocation without complementary input or output taxes. These studies, however, primarily address efficiency and

[2]For details, please see "Development of Minimum Recycled Content Requirements for Plastic Items—Overview," Plastics Regulatory Affairs Division, Environment and Climate Change Canada,
https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/reduce-plastic-waste/recycle-content.html.

[3]For details, please see "AF Policy Around the World" https://worldenergy.net/resource/saf-policy-around-the-world/?utm_source=chatgpt.com.

[4]Within the above plastic industry, some leading plastic and petrochemical companies that originated as state-owned enterprises have undertaken partial privatization to improve efficiency, attract private capital, and enhance global competitiveness. PetroChina, the listed subsidiary of CNPC, conducted a landmark IPO in 2000, offering about 10% of its shares to investors such as BP as part of broader SOE reforms. Similarly, Saudi Aramco sold 1.5% of its equity in a record-setting 2019 IPO under Vision 2030, aimed at diversifying the economy and reducing reliance on oil revenues. These cases illustrate how major state-owned petrochemical firms adopt privatization strategy to expand financial capacity, strengthen governance, and align with long-term national reform objectives.

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waste reduction rather than the strategic design of RCS itself.[5]

Recent research explores RCS under imperfect competition. Notable contributions include Higashida and Jinji (2006), Iida (2011), Sugeta and Shinkuma (2012), and Sugiyama and Koonsed (2017) and Sugiyama and Koonsed (2019). Higashida and Jinji (2006) analyze international duopoly with trade in recycled materials, while Iida (2011) investigates optimal RCS under vertical and horizontal product differentiation, showing that stricter standards arise when products are less horizontally differentiated. Sugeta and Shinkuma (2012) develop a two-country model that links trade liberalization to environmental outcomes and find that welfare depends on cross-country differences in recovery rates. Sugiyama and Koonsed (2017) construct a model with an upstream monopoly recycler and a downstream duopoly engaging in environmental R&D, showing that stricter RCS can reduce both the degree of green design and firm profitability. Extending this framework, Sugiyama and Koonsed (2019) incorporate excise taxes and demonstrate that recycling standards can stimulate southern economies, whereas taxes effectively reduce total waste.

Although these studies provide valuable insights, they focus on private downstream oligopolies and largely neglect the case of mixed oligopolies, where public and private firms coexist and pursue different objectives. The implementation of environmental policies in mixed markets has been analyzed in related contexts, such as Ohori (2006), Bárcena-Ruiz and Garzón (2006), Pal and Saha (2014), Tsai, Wang, and Chiou (2016), and Chen, Yang, and Hu (2023), which collectively show that privatization and environmental regulation interact in complex ways, affecting welfare and pollution outcomes. Yet, the role of RCS under mixed market structures remains largely unexplored.

This study bridges these strands of research by examining how the optimal RCS is jointly shaped by the structure of the upstream recycling market and the nature of downstream competition and ownership. We begin by an-

[5] Some papers focus on recycling targets set by the government rather than recycled content standards. For example, Calcott and Walls (2005), Shinkuma (2003), Eichner (2005), and Aalbers and Vollebergh (2008) explore the implications and effectiveness of government-imposed recycling targets. Additionally,Tsai, Wu, and Hwang (2013), Sugeta and Shinkuma (2012), and Dubois and Eyckmans (2015) investigate take-back requirements and various product taxes based on recyclability or waste content to achieve socially optimal outcomes. These studies highlight different approaches and policies aimed at improving recycling rates and environmental sustainability.

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alyzing a benchmark case in which the government sets the optimal RCS in a mixed duopoly downstream market with a perfectly competitive upstream recycling sector. We then investigate how the optimal RCS is affected by privatization in the downstream market. Next, we examine how the RCS adjusts when the upstream market structure changes from perfect competition to monopoly.[6]

The results reveal how government ownership of the downstream firm determine the optimal RCS, highlighting the welfare trade-offs among promoting recycling, mitigating environmental damage, and maintaining market efficiency in mixed economies. Under upstream perfect competition, the optimal RCS equals zero (one) in a mixed duopoly when the marginal damage of waste is small (large). In a private duopoly, an interior optimal RCS arises when the marginal damage lies within an intermediate range. Following privatization, the optimal RCS increases if privatization raises total output and environmental damage, and decreases if it lowers total output.

Under upstream monopoly, the optimal RCS equals one (zero) in a mixed duopoly when the marginal damage of waste exceeds (falls short of) the difference between the monopolist's recycling cost and the price of virgin materials. In a private duopoly, the optimal RCS equals zero (one) when the marginal damage of waste is small (large), while an interior optimal RCS emerges for intermediate damage levels. The adjustment pattern of the optimal RCS induced by privatization mirrors that under upstream perfect competition. A comparison across upstream market structures further shows that, at intermediate levels of marginal damage, the optimal RCS is generally higher under monopoly than under perfect competition, because the monopolist's higher input price reduces downstream output and waste.

The remainder of the paper is organized as follows. Section 2 examines the case of a perfectly competitive upstream recycling market. It derives equilibrium outputs, firm profits, the optimal RCS, and social welfare before and after privatization, as well as the RCS adjustments induced by privatization. Section 3 analyzes a monopolized upstream market in which the price of recycled materials is set by a foreign monopolist.[7] In this setting,

[6]We sincerely thank the referee for raising this important issue, which has helped us clarify and improve the analysis.

[7]For tractability, we model the recycler as a foreign monopolist in Section 3, assuming that recycled inputs are imported from a large global supplier. This approach allows us to isolate the role of input pricing without the added welfare complications of a powerful

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we derive equilibrium outputs, firm profits, the optimal input price, the optimal RCS, and social welfare under both ownership regimes, together with the corresponding RCS adjustments following privatization. We then compare the optimal RCS under upstream perfect competition and monopoly. Section 4 concludes.

2 Upstream recycling market under perfect competition

In this section, we examine the optimal RCS before and after privatization under the assumption of a perfectly competitive upstream recycling market, with the aim of assessing how privatization affects the optimal RCS. The analysis proceeds by first examining a mixed duopoly in the downstream market, then considering a private duopoly, and finally analyzing how the optimal RCS adjusts following privatization.

2.1 Mixed duopoly

Consider an economy comprising a public firm and a fully private firm engaged in Cournot competition for final goods. Let firm 0 represent the public firm, and firm 1 represent the fully private entity. The inverse market demand for the final goods is given by $p(Q) = a - Q$, where p denotes the market price, $Q(= q_0 + q_1)$ represents the total market output, and q_0 and q_1 denote the outputs of firms 0 and 1, respectively. Assume that final goods are recyclable after consumption in the economy.

Under the RCS requirement imposed by the government, each firm must use a minimum proportion of recycled materials in the production of final goods. The unit price of recycled materials charged by upstream recyclers is w_r, and the marginal cost of recycling is constant at c_r. The supply of recycled materials is assumed to take place in a perfectly competitive market. Virgin materials are imported from the rest of the world at a fixed price w_v, which is lower than the price of recycled materials, that is $w_v < w_r$. Because virgin materials are relatively cheaper than recycled materials, downstream firms have no incentive to use recycled materials beyond the minimum level mandated by the government. For simplicity, we assume that both firms incur no additional material or processing costs. Since the RCS is binding, each downstream firm uses one unit of a composite input

domestic recycler. It also maintains consistency with the welfare calculation in Section 2.

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consisting of recycled and virgin materials to produce one unit of the final good. Therefore, the marginal cost of producing one unit of the final good is $c = \theta w_r + (1-\theta)w_v$, where $\theta \in [0, 1]$ denotes the ratio of recycled content set by the government.

Once one unit of the final good is consumed at time t, failure to recycle results in one unit of waste. When a fraction θ of the consumed good is recycled, only the remaining $1-\theta$ is landfilled and generates environmental damage. Following Higashida and Jinji (2006) and Sugiyama and Koonsed (2017), we restrict attention to the steady-state equilibrium to simplify the analysis. In steady state, the total input of recyclable resources into the recycling sector equals the flow of recycled materials, and total landfilled waste corresponds to the non-recycled portion of consumption. Consistent with Eichner (2005), Higashida and Jinji (2006), and Sugiyama and Koonsed (2017), environmental damage is assumed to be linear in total landfilled waste and is represented by $\mathrm{ED} = gZ$,where $Z = (1-\theta)Q$ denotes total unrecycled waste and $g(\geq 0)$ captures the marginal damage of waste.

The strategic interaction among the two downstream firms and the government unfolds in three stages. In the first stage, the government determines the optimal level of the recycled content standards. In the second stage, the upstream recyclers set the price of recycled materials. In the third stage, two downstream firms simultaneously choose their output levels. The equilibrium outcomes are obtained through backward induction to derive the subgame perfect Nash equilibrium.

Based on previous setting, the profit functions of the public and private firms are defined as follows:

$$\begin{aligned}\pi_0(q_0, q_1; w_r, \theta) &= p(Q)q_0 - cq_0 = (a - q_0 - q_1)\, q_0 \\ &\quad - [\theta w_r + (1-\theta)w_v]\, q_0, \qquad (1)\\ \pi_1(q_0, q_1; w_r, \theta) &= p(Q)q_1 - cq_1 = (a - q_0 - q_1)\, q_1 \\ &\quad - [\theta w_r + (1-\theta)w_v]\, q_1. \qquad (2)\end{aligned}$$

Social welfare is conventionally defined as the sum of consumer surplus and profits of the public and private firms, minus environmental damage, as follows:[8]

$$SW(q_0, q_1; w_r, \theta) = \mathrm{CS} + \pi_0 + \pi_1 - \mathrm{ED}, \qquad (3)$$

[8]In our model, quantity produced is assumed to be the only decision variable for the two firms at the market stage. Although the public firm maximizes social welfare, it does so with respect to output choice and subject to the binding RCS set by the government, rather than

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where $CS = (Q^2/2)$ denotes consumer surplus.

In the third stage of the game, each firm chooses its output q_i to maximize its respective objective function. The first-order condition (FOC) for the public firm, which maximizes social welfare, is given by:

$$\frac{\partial SW}{\partial q_0} = a - q_0 - q_1 - [\theta w_r + (1-\theta)w_v] - g(1-\theta) = 0. \quad (4)$$

From Equation (4), we see that firm 0 internalizes environmental damage in a manner equivalent to an increase in its effective marginal cost. When the RCS (θ) equals one, environmental damage is fully eliminated. In this case, the only remaining factor affecting firm 0's output decision is the price of recycled inputs. Consequently, the first-order condition for the public firm reduces to the standard pricing rule in which price equals marginal cost.

For the downstream private firm, it chooses q_1 to maximize its profit as shown in Equation (2). The FOC for the private firm is given by:

$$\frac{\partial \pi_1}{\partial q_1} = a - q_0 - 2q_1 - [\theta w_r + (1-\theta)w_v] = 0. \quad (5)$$

Equation (5) shows that the FOC for the private firm is obtained when marginal revenue equals marginal cost. By solving Equations (4) and (5) simultaneously, we obtain the outputs of the public and private firms, as well as the total market output, as follows:

$$q_0^M(w_r, \theta) = a - [\theta w_r + (1-\theta)w_v] - 2(1-\theta)g, \quad (6)$$

$$q_1^M(\theta) = (1-\theta)g, \quad (7)$$

$$Q^M(w_v, \theta) = a - [\theta w_r + (1-\theta)w_v] - g(1-\theta), \quad (8)$$

where the superscript "M" denotes the case of mixed duopoly. By inspecting Equations (6) and (7), we observe that in the absence of environmental damage ($g = 0$), the model reduces to the standard mixed duopoly with constant marginal costs, in which the welfare-maximizing public firm serves the entire market. This outcome arises because the two firms share identical production costs, implying that the private firm cannot operate profitably

choosing its own recycled content share endogenously. This assumption reflects regulatory uniformity and the separation between policy determination and firm-level production decisions. Since the RCS is imposed as a common environmental regulation, both public and private firms are assumed to operate under the same recycled content requirement.

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when the public firm produces the welfare-maximizing output. Moreover, when the government imposes the strictest RCS ($\theta = 1$) so as to eliminate all waste, firm 0 no longer internalizes environmental damage. In this case, the model again reduces to the conventional mixed duopoly benchmark: the public firm produces up to the point where market price equals its marginal cost, while the private firm earns zero profit and therefore exits the market.

From Equations (6) to (8), we can derive the following comparative-static results. The impacts of the marginal damage of waste on the outputs of each firm and on the total market output, which are respectively given as:$(\partial q_0^M/\partial g) = -2(1-\theta) \leq 0$, $(\partial q_1^M/\partial g) = 1-\theta \geq 0$ and $(\partial Q^M/\partial g) = -(1-\theta) \leq 0$. Because firm 0 internalizes environmental damage, an increase in the marginal damage parameter (g) reduces firm 0's output (q_0^M), while it increases firm 1's output (q_1^M) through strategic response of the firm 0 under Cournot competition. Together, these effects imply that total market output decreases. Since q_0^M is decreasing in g, to ensure that the public firm produces a positive output, we assume that the marginal damage of waste satisfies the condition $g < \bar{g} \equiv (a - w_v - \theta(w_r - w_v)/2(1-\theta))$ through the whole paper.

The effects of RCS on the outputs of public and private firms and total market output are respectively given as $(\partial q_0^M/\partial\theta) = 2g - (w_r - w_v) > (<)0$, if $g > (<)(w_r - w_v)/2$, $(\partial q_1^M/\partial\theta) = -g < 0$, and $(\partial Q^M/\partial\theta) = g - (w_r - w_v) > (<)0$ if $g > (<)w_r - w_v$.

An increase in the degree of RCS affects the public firm's output through two opposing effects. The first is *the internalized effect*: a higher θ reduces environmental damage per unit of output, thereby weakening the externality internalized by the welfare-maximizing public firm and tending to increase its output. The second is *the cost-raising effect*: a higher θ raises the required share of recycled materials in production, forcing the firm to rely more heavily on the relatively expensive recycled input, which increases marginal cost and reduces output. When g is sufficiently large, the internalized effect outweighs the cost-raising effect, implying that a higher degree of RCS increases the public firm's output. By contrast, for the private firm, an increase in θ affects output only through the latter cost channel, leading unambiguously to a reduction in output. As a result, the effect of θ on total market output is in general ambiguous. When the marginal damage of waste is sufficiently large, the reduction in internalized environmental damage dominates, and an increase in θ may raise total output.

In addition, a higher recycled-material price reduces the public firm's

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output but does not affect the private firm's output, implying a decline in total market output, i.e., $(\partial q_0^M/\partial w_r) = -\theta < 0$, $(\partial q_1^M/\partial w_r) = 0$, and $(\partial Q^M/\partial w_r) = -\theta < 0$. Since the public firm maximizes social welfare, it expands production until price equals marginal cost, whereas the private firm can only serve a share of the residual demand when it possesses a cost advantage. Under identical cost conditions, however, the private firm lacks such an advantage and therefore won't alter its output.

From the above comparative-static results, we have Lemma 1.

Lemma 1. (Output effects). In a mixed duopoly with an upstream perfectly competitive recycling market:

(i) An increase in g lowers the public firm's output but raises the private firm's output, resulting in a decrease in total market output.

(ii) An increase in θ may expand the public firm's output and total output under sufficiently large g or a relatively low recycled-material price, but it reduces the private firm's output.

(iii) An increase in the price of recycled materials (W_r) reduces the public firm's output but does not affect the private firm's output, implying a reduction in total market output.

Substituting the equilibrium outputs of the public and private firms from Equations (6) and (7) into the profit functions of firms 0 and 1, as well as into the expressions for consumer surplus and environmental damage, yields $\pi_0^M(w_r,\theta) = g(1-\theta)[a-\theta w_r-(1-\theta)w_v-2g(1-\theta)]$, $\pi_1^M(w_r,\theta) = g^2(1-\theta)^2$, $v = \mathrm{CS}^M(w_r,\theta) = ([a-\theta w_r-(1-\theta)w_v-g(1-\theta)]^2/2)$, and $\mathrm{ED}^M(w_r,\theta) = g(1-\theta)[a-w_r-\theta\rho-g(1-\theta)]$.

The impacts of marginal damage of waste on the profits of firms 0 and 1 are respectively given as $(\partial\pi_0^M/\partial g) = (1-\theta)[a-w_v-4g(1-\theta)-\theta(w_r-w_v)] < (>)0$, if $g > (<)\tilde{g} \equiv (a-w_v+(1-2\theta)(w_r-w_v)/1-\theta)$ and $(\partial\pi_1^M/\partial g) = 2g(1-\theta)^2 \geq 0$ An increase in the marginal damage of waste (g) may either increase or decrease the public firm's profit, depending on the level of g, while it strictly increases the private firm's profit. The economic reasoning is as follows. When g is large, the public firm produces substantially less than the profit-maximizing output it would choose as a private firm, so a further increase in g exacerbates this distortion and has a diminishing marginal impact on profit. Conversely, when g is small, the public firm's output exceeds the profit-maximizing level, so an increase

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in g reduces its output and thereby enhances its profit. Since firm 1 does not internalize environmental damage, g affects its profit only through the strategic response of the public firm. In particular, a higher g induces the public firm to reduce its output q_0, thereby expanding firm 1's residual demand and increasing its profit, as indicated in Lemma 1.

Next, the impacts of RCS on the profits of firms 1 and 2 are given respectively by $(\partial\pi_0^M/\partial\theta) = -g[a-w_v-4g(1-\theta)+(1-2\theta)(w_r-w_v)] > (<)0$ if $g < (>)(a-w_v+(1-2\theta)(w_r-w_v)/4(1-\theta))$ and $(\partial\pi_1^M/\partial\theta) = -2g^2(1-\theta) \leq 0$. An increase in the RCS (θ) may either increase or decrease the public firm's profit, depending on the level of θ, while it strictly decreases the private firm's profit. Raising RCS (θ) may either increase or decrease the public firm's profit, depending on its stringency, whereas it strictly lowers the private firm's profit. The economic intuition is as follows. A higher θ reduces the public firm's environmental-damage component internalized concerns, which tends to raise π_0. However, a higher θ also increases reliance on relatively costly recycled inputs, which lowers π_0. When the marginal damage of waste g is small, the former effect is weak and the input-cost effect dominates, so π_0 decreases. When g is large, the reduction in the internalized environmental burden dominates, and π_0 increases.

The comparative-static effects of the recycled-material input price are summarized by $(\partial\pi_0^M/\partial w_r) = -g\theta(1-\theta) \leq 0$ and $(\partial\pi_1^M/\partial w_r) = 0$. From $(\partial q_0^M/\partial w_r) < 0$ (Lemma 1), an increase in W_r raises firm 0's effective marginal cost, causing its equilibrium output q_0^M to fall. This output contraction reduces firm 0's operating profit, implying $(\partial\pi_0^M/\partial w_r) \leq 0$. By contrast, Lemma 1 shows that W_r does not affect firm 1's output, i.e., $(\partial q_1^M/\partial w_r) = 0$, implying that W_r has no impact on firm 1's profit.

From the above comparative-static effects, we obtain Lemma 2.

Lemma 2. (Profit effects). In a mixed duopoly with an upstream perfectly competitive recycling market:

(i) An increase in g can increase the public firm's profit when g is sufficiently large and always increases the private firm's profit.

(ii) An increase in θ may increase the public firm's profit at sufficiently large g by alleviating the internalized environmental burden, but it reduces the private firm's profit.

(iii) An increase in W_r reduces the public firm's profit but has no effect on the private firm's profit.

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The comparative-static effects of g, θ, and w_r on consumer surplus are given as follows: $(\partial \mathrm{CS}/\partial g) = a - w_v + (1-2\theta)(w_r - w_v) - 2g(1-\theta) < 0$, $(\partial \mathrm{CS}/\partial \theta) = (g - w_r - w_v)[a - w_v - \theta(w_r - w_v) - g + g\theta]$, and $(\partial \mathrm{CS}/\partial w_r) = -\theta[a - 2w_v + w_r - 2g + 2g\theta - 2\theta(w_r - w_v)] < 0$. The direction of the above comparative-static effects are intuitively identical to the impacts of g, θ, and w_r on total market output. We thus have the Lemma 3.

Lemma 3. (Consumer surplus effects). In a mixed duopoly with an upstream perfectly competitive recycling market:

(i) An increase in g reduces consumer surplus.

(ii) An increase in θ may increase consumer surplus when g is sufficiently large or when the recycled-material price is relatively low.

(iii) An increase in W_r reduces consumer surplus.

We next conduct comparative-static analyses of increases in g, θ, and w_r on environmental damage, which are summarized as follows: $(\partial \mathrm{ED}/\partial g) = (1-\theta)[a - w_v - 2g(1-\theta) - \theta(w_r - w_v)]$, $(\partial \mathrm{ED}/\partial \theta) = -g[a - 2w_v + w_r - 2g + 2g\theta - 2\theta(w_r - w_v)]$, and $(\partial \mathrm{ED}/\partial w_r) = -g\theta(1-\theta) < 0$. The impacts of g and θ on the environmental damage are not clear. Since $\mathrm{ED} = g(1-\theta)Q$, the components of ED include three parts: g, θ, and Q. As g increases, Q may increase or decrease. In addition, as θ increases, $(1-\theta)$ decreases but the impact on Q may increase or decrease. Interesting, as the degree of RCS becomes stringer, its impact on the environmental damage may increase. The impacts the recycled-material input price on environmental damage are straightforward negative. The impacts of g and θ on environmental damage are ambiguous. Since environmental damage is given by $\mathrm{ED} = g(1-\theta)Q$, it depends on three components: g, θ, and total output Q. As g increases, total output may either increase or decrease. Similarly, as θ increases, the factor $(1-\theta)$ declines, while its effect on total output may be positive or negative. Interestingly, when the degree of the RCS becomes sufficiently stringent, an increase in θ may raise environmental damage through its output-expansion effect. By contrast, the impact of the recycled-material input price on environmental damage is unambiguously negative. We thus have the Lemma 4.

Lemma 4. (Environmental damage effects). In a mixed duopoly with an upstream perfectly competitive recycling market:

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(i) An increase in the marginal damage of waste, g, has an ambiguous effect on environmental damage.

(ii) An increase in the degree of the RCS, θ, has an ambiguous effect on environmental damage and may increase environmental damage when its output-expansion effect dominates the direct waste-reduction effect.

(iii) An increase in the price of recycled materials, W_r, reduces environmental damage.

Substituting the equilibrium outputs of Equations (6) and (7) into the welfare function in Equation (3) yields

$$\begin{aligned} \mathrm{SW}^M(w_r, \theta) &= \frac{[a - \theta w_r - (1-\theta)w_v - g(1-\theta)]^2}{2} \\ &= \mathrm{CS}^M(w_r, \theta). \end{aligned} \tag{9}$$

Note that social welfare coincides with consumer surplus regardless of the level of the RCS and the value of g in the mixed duopoly. This result arises because the sum of two firms' profits net of environmental damage equals zero. In details, $\pi_0^M + \pi_1^M - \mathrm{ED}^M = [p - c - g(1-\theta)]Q$, the bracketed expression on the left-hand side of the equality equals zero, according to the public firm's first-order condition in Equation (4). The economic reasoning is as follows. When $g = 0$, environmental damage is zero, i.e., $\mathrm{ED}^M = 0$, $\pi_1^M = 0$, and $\pi_0^M = 0$. As g increases from zero but remains relatively small, environmental damage increases, private firm's profit increases, and public firm's profit decreases (see Lemma 2). When g increases further and becomes sufficiently large, environmental damage decreases, while the profits of both firms increase. Because the public firm internalizes environmental damage, the sum of environmental damage and producer surplus remains zero in equilibrium.

In the second stage of the game, given the assumption of perfectly competitive nature of the upstream recyclable market, the price of recycled materials charged by upstream recyclers quals to the marginal cost of recycling, i.e., $w_r = c_r$. Substituting $w_r = c_r$ into $\mathrm{SW}^M(w_r, \theta)$, the social welfare function becomes

$$\begin{aligned} \mathrm{SW}^M(\theta) = \mathrm{CS}^M(\theta) &= \frac{[a - \theta c_r - (1-\theta), w_v - g(1-\theta)]^2}{2} \\ &= \frac{[a - w_v - g + \theta(g-\rho)]^2}{2}, \end{aligned} \tag{10}$$

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where $\rho \equiv c_r - w_v$ denotes the difference between the recycler's marginal production cost and the unit cost of virgin materials, capturing the extent of the cost-raising effect.

We next proceed to the first stage of the game. The first-order derivatives of the welfare function in Equation (10) with respect to the RCS are obtained as follows:

$$\frac{\partial \mathrm{SW}^M(\theta)}{\partial \theta} = (g-\rho)\left[a - w_v - g + \theta(g-\rho)\right] > (<)0, \quad \text{if} \quad g > (<)\rho. \tag{11}$$

As $g > (<)\rho$, the social welfare function is convex and monotonically decreasing (increasing) in θ.[9] Therefore, we have

$$\mathrm{SW}^M = \begin{cases} \mathrm{SW}^M(\theta=0) = \frac{(a-w_v-g)^2}{2}, & \text{if } g < \rho, \\ \mathrm{SW}^M(\theta=1) = \frac{(a-w_v-\rho)^2}{2}, & \text{if } g > \rho. \end{cases} \tag{12}$$

Note that if $g = \rho$, the social welfare is constant and independent of θ; that is θ has no effect on the social welfare. From Equation (12), we conclude that the optimal RCS in the mixed duopoly market is as follows:

$$\theta^M = \begin{cases} 0, & \text{if } g < \rho, \\ 1, & \text{if } g > \rho. \end{cases} \tag{13}$$

In the mixed duopoly market, the optimal RCS is either zero or one, depending on the relative magnitude of marginal environmental damage and the cost differential between recycled and virgin materials and is shown as the following Proposition.

Proposition 1. When a public firm competes with a private firm and the upstream recycling market is perfectly competitive, the optimal RCS equals 0 (1) if the marginal damage of waste is smaller (greater) than the cost difference between recycled and virgin materials. Furthermore, when the optimal RCS is 1, the private firm does not produce.

The economic reasoning behind Proposition 1 goes as follows. Recall that $(\partial Q^M/\partial\theta) = \rho - g$, when g is small, the internalized effect is limited,

[9] First of all, for $\theta \in [0,1]$, social welfare varies monotonically with θ. Besides, the second-order derivatives of the welfare function with respect to θ is $(\partial^2 \mathrm{SW}^M(\theta)/\partial\theta^2) = (\partial^2 \mathrm{CS}^M(\theta)/\partial\theta^2) = (g-\rho)^2 > 0$.

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while the cost-raising effect is relatively large, implying that total output Q decreases as θ increases, and vice versa.

Under the optimal RCS, the equilibrium outputs for the public and private firms are $q_0^M = a - w_v - 2g$ and $q_1^M = g$ when $\theta = 0$; but when $\theta = 1$, the optimal outputs for two firms in the mixed duopoly are $q_0^M = a - w_v - \rho$ and $q_1^M = 0$. The environmental damage in the mixed duopoly is $\mathrm{ED}^M = g(a - w_v - g)$ when $\theta = 0$; and ED^M is zero when $\theta = 1$. We next discuss the case in which the public firm is privatized.

2.2 Private duopoly

In the context of market competition between two private firms, firm 0 now choose q_0 to maximize its profit shown in Equation (1) and the responding first-order condition is:

$$\frac{\partial \pi_0}{\partial q_0} = a - 2q_0 - q_1 - [\theta w_r + (1-\theta)w_v] = 0. \tag{14}$$

Solving the firstorder conditions in Equations (5) and (14), we have the outputs two firms and total market output as follows:

$$q_0^P = q_1^P = \frac{a - [\theta w_r + (1-\theta)w_v]}{3}, \tag{15}$$

$$Q^P = q_0^P + q_1^P = \frac{2\{a - [\theta w_r + (1-\theta)w_v]\}}{3}, \tag{16}$$

where the notation with superscript "P" represents the scenario of private duopoly The impacts of g, θ, and w_r on the output of private firm are as follows: $(\partial q_0^P/\partial\theta) = (\partial q_1^P/\partial\theta) = -(1/3)(w_r - w_v) < 0$, $(\partial q_0^P/\partial g) = (\partial q_1^P/\partial g) = 0$ and $(\partial q_0^P/\partial w_r) = (\partial q_1^P/\partial w_r) = -(1/3)\theta < 0$. The private firm's output is unaffected by the marginal damage of waste, while it decreases with both the RCS and the price of recycled materials. Now the impact of RCS on firm 0's output becomes unambiguously negative, since stricter RCS requirements increase production costs through greater reliance on recycled materials.

Substituting the equilibrium outputs given in Equation (15) into the profit functions of both firms, as well as into the consumer surplus and environmental damage functions, yields the corresponding equilibrium outcomes: $\pi_0^P = \pi_1^P = (\{a - [\theta w_r + (1-\theta)w_v]\}^2/9)$, $\mathrm{CS}^P = (2\{a - [\theta w_r + (1-\theta)w_v]\}^2/9)$, and $\mathrm{ED}^P = (2g(1-\theta)\{a - [\theta w_r + (1-\theta)w_v]\}/3)$

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The effects of g, θ, and w_r on each firm's profit and on consumer surplus follow the same qualitative patterns as their effects on firm outputs. That is, $(\partial\pi_i^P/\partial g)$, $(\partial\pi_i^P/\partial\theta)$, and $(\partial\pi_i^P/\partial w_r)$ share the same signs as $(\partial q_i^P/\partial g)$, $(\partial q_i^P/\partial\theta)$, and $(\partial q_i^P/\partial w_r)$, respectively; likewise, $(\partial \mathrm{CS}^P/\partial g)$, $(\partial \mathrm{CS}^P/\partial\theta)$, and $(\partial \mathrm{CS}^P/\partial w_r)$ share the same signs as $(\partial Q^P/\partial g)$, $(\partial Q^P/\partial\theta)$, and $(\partial Q^P/\partial w_r)$.

The impacts of g, θ, and w_r on the environmental damage are as follows: $(\partial \mathrm{ED}^P/\partial g) = (2(1-\theta)(a-w_v-\theta w_r+\theta w_v)/3) > 0$, $(\partial \mathrm{ED}^P/\partial\theta) = -(2g(a+w_r-2w_v-2\theta w_r+2\theta w_v)/3) < 0$, and $(\partial \mathrm{ED}^P/\partial w_r) = -(2g\theta(1-\theta)/3) < 0$. We thus have the Lemma 5.

Lemma 5. In a private duopoly with an upstream perfectly competitive recycling market, environmental damage increases with the marginal damage of waste, g, but decreases with both the degree of the RCS, θ, and the price of recycled materials, w_r.

In the second stage of the game, the equilibrium condition for the price of recycled materials ($w_r = c_r$) after privatization still holds under the perfectly competitive recycling market setting.

We now proceed to the first stage of the game. The social welfare function $\mathrm{SW}^P = \mathrm{CS}^P + \pi_0^P + \pi_1^P - \mathrm{ED}^P$, under private duopoly is

$$\mathrm{SW}^P(\theta) = \frac{2\,(a-w_v-\rho\theta)\,[2\,(a-w_v-\rho\theta)-3g(1-\theta)]}{9}. \quad (17)$$

The first-order derivative of social welfare with respect to the RCS is given by:[10]

$$\frac{\partial \mathrm{SW}^P}{\partial\theta} = \frac{2\,[3g\,(a-w_v+\rho-2\rho\theta)-4\rho\,(a-w_v-\rho\theta)]}{9}. \quad (18)$$

The second-order derivative with respect to θ is $(\partial^2 \mathrm{SW}^P/\partial\theta^2) = -(4\rho(3g-2\rho)/9) > (<)0$, if $g > (<)(2\rho/3)$. The second-order condition for welfare maximization in (17) on RCS does not hold when $g < 2\rho/3$ and thus the optimal RCS equals 0 or 1 We can easily verify that $\mathrm{SW}^P(\theta = 0) - \mathrm{SW}^P(\theta = 1) = (2(a-w_v)(2\rho-3g)+4\rho(a-w_v-\rho)/9) > 0$ when $g < (2\rho/3)$. It means that, if $g < (2\rho/3)$, then the optimal RCS equals 0.

[10] Although consumer surplus, each firm's profit, and environmental damage are all convex in θ, environmental damage is subtracted in the social welfare function; consequently, social welfare need not be convex in θ and may instead be concave when g is not sufficiently large.

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However, the second-order condition for welfare maximization in (17) on RCS holds when $g > 2\rho/3$. Setting (19) to zero and solving the interior RCS yields

$$\theta^* = \frac{3g\,(a - w_v + \rho) - 4\rho\,(a - w_v)}{2\rho(3g - 2\rho)}. \tag{19}$$

Note that the optimal RCS (θ^*) should satisfy the condition of $\theta \in [0, 1]$. From (19), we can see that θ^* is non-negative when $g \geq (4\rho(a-w_v)/3(a-w_v+\rho)) \equiv g_0(> (2\rho/3))$[11] Otherwise, θ^* is less than zero and the optimal RCS equals 0. Besides, the condition that θ^* cannot exceed 1 is $g \leq (4\rho/3)$. In other words, if $g \geq (4\rho/3)$, then the optimal RCS equals 1. This implies that the condition $g_0 < g < (4\rho/3)$ should be hold to guarantee the existence of an interior RCS.

From the above discussions, the optimal RCS when two private firms compete in the market is as follows:[12]

$$\theta^P = \begin{cases} 0, & \text{if } 0 < g \leq g_0, \\ \theta^*, & \text{if } g_0 < g < \frac{4\rho}{3}, \\ 1, & \text{if } g \geq \frac{4\rho}{3}. \end{cases} \tag{20}$$

Based on above outcomes, we have Proposition 2.

Proposition 2. When two private firms competing in the market, the optimal RCS should be set at zero (one) if the marginal damage of waste is small (large) and is $(3g(a - w_v + \rho) - 4(a - w_v)\rho/2\rho(3g - 2\rho)) \in (0, 1)$ if the marginal damage of waste is at an intermediate level.

The economic reasoning underlying Proposition 2 is as follows. As noted above, tightening the RCS reduces total market output; while this mitigates environmental damage, it also reduces the sum of two firms' profits and consumer surplus under a private duopoly. When the marginal damage of waste g is relatively small, the welfare loss arising from a stricter RCS, by forcing firms to rely more heavily on costly recycled materials, outweighs the benefit from reduced environmental damage. Consequently, the optimal RCS is zero. By contrast, when g is sufficiently large, the welfare gains from

[11] Note that $a - w_v > \rho$ since $a > c_r$. The condition $a - w_v > \rho$ ensures $g_0 > (2\rho/3)$.

[12] Higashida and Jinji (2006) assume that the marginal damage of waste equals 1, and their discussion on the optimal RCS focuses primarily on the conditions for the interior RCS. They do not give much attention to examining the two corner solutions considered in this paper.

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mitigating environmental damage dominate the associated production-cost distortion, implying that the optimal RCS is one. For intermediate values of g, the optimal RCS is determined by the condition that the marginal benefit from reduced environmental damage equals the marginal welfare loss from higher production costs. Accordingly, as g increases, the optimal RCS becomes more stringent, inducing greater mitigation of environmental damage.

Substituting the equilibrium outputs of firms 0 and 1 in Equation (15) and the optimal RCS in Equation (20) into the welfare function given in Equation (3) yields:

$$\mathrm{SW}^P = \begin{cases} \mathrm{SW}_1^P = \frac{2(a-w_v)[2(a-w_v)-3g]}{9}, & \text{if } 0 < g \leq g_0, \\ \mathrm{SW}_2^P = \frac{g^2(a-w_v-\rho)^2}{2\rho(3g-2\rho)}, & \text{if } g_0 < g < \frac{4\rho}{3}, \\ \mathrm{SW}_3^P = \frac{4(a-w_v-\rho)^2}{9}, & \text{if } g \geq \frac{4\rho}{3}. \end{cases} \tag{21}$$

Note that SW^P is in decreasing in g when $g < (4\rho/3)$ and remains constant as $g \geq (4\rho/3)$. We next examine the optimal adjustment of RCS in response to the privatization policy.

2.3 The optimal RCS adjustment due to privatization

Recall that Equations (13) and (20) represent the optimal RCS before and after privatization, respectively. By directly comparing the ranges of g in Equations (13) and (20), we find $g_0 < 4\rho/3$. However, the sign of $\rho - g_0$ remains indeterminate. Since $g_0 \equiv (4\rho(a - w_v)/3(a - w_v + \rho))$, it follows that $g_0 < (>)\rho$ when $(a - w_v) < (>)3\rho$. Therefore, two scenarios arise: the optimal RCS adjustment after privatization when $g_0 < \rho$ and when $g_0 > \rho$. We first analyze the case where $g_0 < \rho$ holds.

Case 1. $g_0 < \rho$ (or $a - w_v < 3\rho$)

We can utilize Figure 1 to illustrate the potential adjustment of the optimal RCS following privatization when $g_0 < \rho$. The optimal RCS prior to privatization includes two horizontal lines at different levels of g, as described in Equation (13) and shown in Figure 1. After privatization, the optimal RCS, described in Equation (20), consists of three parts corresponding to different levels of g: two horizontal lines and one convex curve, also depicted in Figure 1. When privatization realizes, the optimal RCS should

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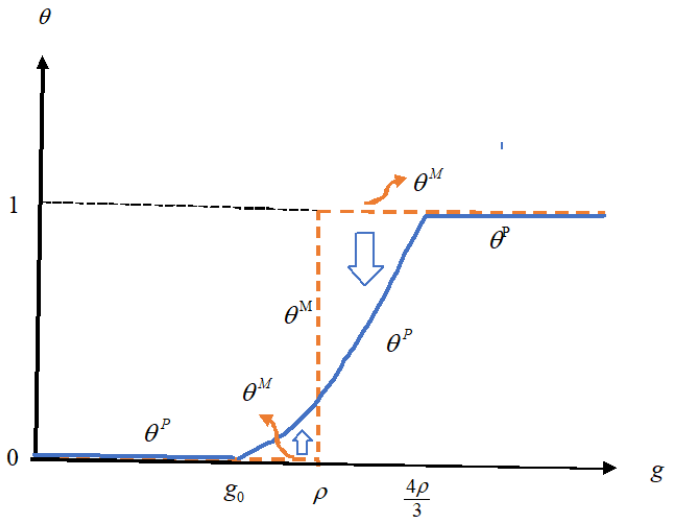
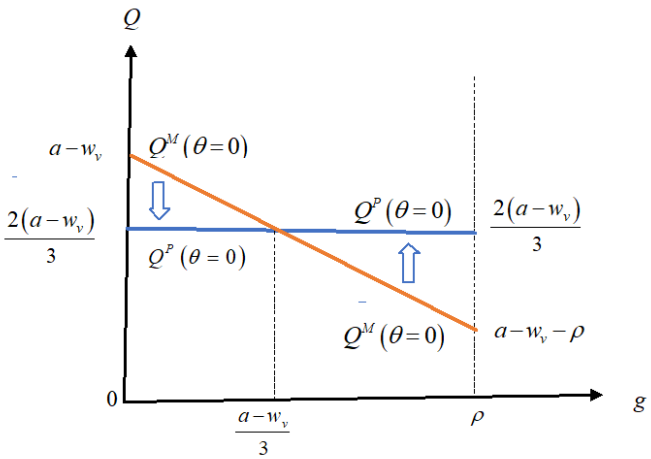


Figure 1: The optimal RCS when $g_0 < \rho$ under a perfectly competitive upstream market

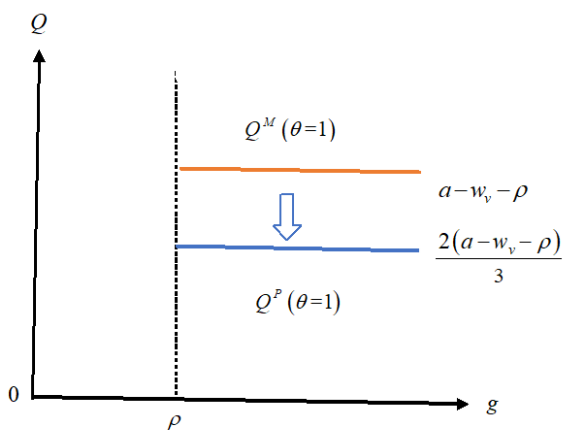
adjust accordingly, depending on the level of the marginal damage of waste. There are three possible possibilities. When the marginal damage of waste is small ($g \leq g_0$), the optimal RCS is zero both before and after privatization. There is no need to implement the RCS policy when the marginal damage of waste is small. When the marginal damage of waste is significantly large ($g \geq (4\rho/3)$, the optimal RCS is one both before and after privatization. When the marginal damage of waste falls into an intermediate range ($g_0 < g < (4\rho/3)$), the adjustment of the optimal RCS after privatization is not as straightforward. If $g_0 < g < \rho$, then the optimal RCS should increase due to privatization. However, if $\rho < g < (4\rho/3)$, then the optimal RCS should decrease due to privatization.

The economic reasoning behind the results in Figure 1 is as follows. Figures 2 illustrates the equilibrium market output at different levels of the marginal damage of waste, both before and after privatization, when the RCS equals zero and one, respectively. When there is no RCS, $\theta = 0$, before privatization, total market output decrease as the level of the marginal damage of waste increases, as shown in Figure 2(a). This occurs because the public firm takes environmental damage into account; thus, as g in-

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(a) RCS equals zero



(b) RCS equals one

Figure 2: The equilibrium market output with different level of g

creases, the public firm tends to reduce its output to mitigate the environmental impact. However, after privatization, as the public firm becomes a private firm, total market output becomes independent of the level of g, since private firms do not consider environmental damage in their output

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decisions. Therefore, the total market output in a mixed duopoly are not always larger than those in a private duopoly when the marginal damage of waste is considered. As the marginal damage of waste goes to a certain level ($(a - w_v/3) \leq g \leq \rho$), the total market output after privatization become larger.[13] Since the total market output increase after privatization in the intermediate interval ($(a-w_v/3) \leq g \leq \rho$), resulting in increased in the total environmental damage, the adjustment of the optimal RCS should increase following privatization.

However, when the marginal damage of waste is large ($\rho < g \leq (a - w_v/3)$), the government adopts the strictest RCS, $\theta = 1$, before privatization. In this scenario, the environmental damage is effectively mitigated by the strict RCS policy. Consequently, the total market output decrease after privatization when $\theta = 1$ as shown in Figure 2(b). This is because the public firm's environmental considerations are already addressed by the stringent RCS, allowing it to produce more outputs in mixed duopoly than in the private duopoly. Since the total market output decrease after privatization, leading to a decrease in the environmental damage, the optimal RCS after privatization should decrease.

Case 2. $g_0 > \rho$ (or $a - w_v > 3\rho$)

Figure 3 shows the adjustment of the optimal RCS after privatization when $g_0 > \rho$. It shows that when the marginal damage of waste is small ($g \leq \rho$), the optimal RCS is zero. Conversely, when the marginal damage of waste is large enough ($g \geq (4\rho/3)$, the optimal RCS is one. The optimal RCS remains unchanged when the marginal damage of waste is small or large enough. However, if the marginal damage of waste is intermediate ($\rho < g < (4\rho/3)$), then the adjustment of the optimal RCS after privatization should decrease. The economic reasoning is the same as in the Section 2.2 when the marginal damage of waste is intermediate ($\rho < g < (4\rho/3)$).

Based on the results of Figures 1 and 3, we propose Proposition 3 as follows

Proposition 3. The adjustment of the optimal RCS after privatization is as follows. If the marginal damage of waste is small (significantly large),

[13]This occurs because private firms, focusing solely on profit maximization, do not reduce output in response to environmental concerns, unlike the public firm in a mixed duopoly which does consider environmental damage.

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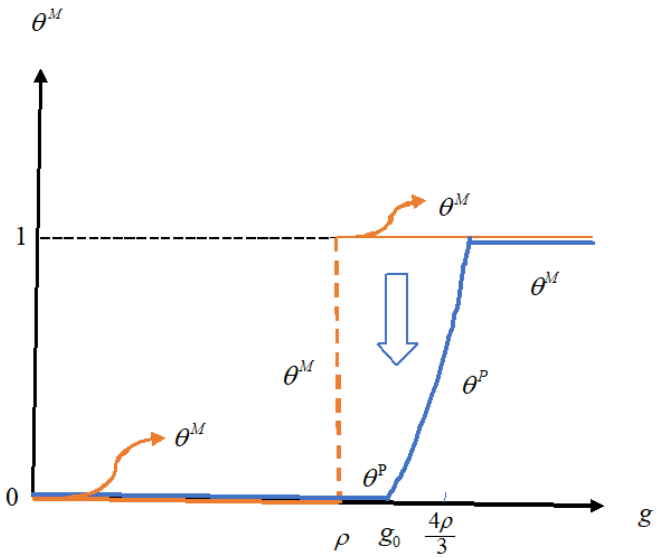


Figure 3: The optimal RCS when $g_0 > \rho$ under a perfectly competitive upstream

then the optimal RCS remains 0 (1) after privatization. However, when the marginal damage of waste falls at an intermediate level, the optimal RCS should be lower (higher) if privatization leads to a decrease (an increase) in total output.

3 The upstream recycler is a monopolist

In Section 2, an upstream perfectly competitive recycling market is considered. It is natural to ask whether a different upstream market structure alters the effect of the RCS. To explore this, in this section we consider the case where the upstream recycler is a monopolist. For simplicity, we model the upstream recycling sector as being operated by a foreign monopolist.[14]

[14]To simplify the analysis, the upstream recycler is modeled as a foreign monopolist, thereby avoiding additional welfare-accounting complications associated with the profits of a domestic upstream firm with market power. This treatment is consistent with the welfare specification in Section 2 and allows us to focus on how recycled-input pricing under alternative upstream market structures affects the optimal RCS ratio. This assumption is also

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Since each downstream firm uses 1 unit of a mixture of recycled and virgin materials to produce 1 unit of final good Q, the derived demand for recycled materials becomes θQ as the RCS establishes this minimum mixing ratio. The third-stage equilibrium outputs of the two firms are given by Equations (5) and (6). The profit function of the foreign upstream recycler is:

$$\hat{\pi}^R(w_r) = (w_r - c_r)\,\theta Q(w_r), \tag{22}$$

where upper "^" denotes the case in which upstream recycler is a monopolist. We first analyze the case of a mixed duopoly, and then turn to the case of a private duopoly.

3.1 Mixed duopoly

In the second stage, by substituting the equilibrium outputs of the public and private firms from Equations (6) and (7) into the profit function of the upstream recycler, and solving the first-order condition, we obtain the optimal price of recycled materials as:

$$\begin{aligned}\hat{w}_r^M(\theta) &= \frac{a-(1-\theta)w_v - g(1-\theta) + c_r\theta}{2\theta} \\ &= \frac{a - w_v + 2w_v\theta - g(1-\theta) + \rho\theta}{2\theta}.\end{aligned} \tag{23}$$

Differentiating Equation (23) with respect to θ, we obtain the impact of RCS on the price of recycled materials as:

$$\frac{\partial \hat{w}_r^M}{\partial \theta} = \frac{g-(a-w_v)}{2\theta^2} < 0. \tag{24}$$

The economic intuition is as follows. Using Equation (7), the inverse derived demand for recycled materials can be rewritten as $w_r(\theta) = ((a - w_v + g/\theta) + w_v - g) - (Q/\theta)$. This expression shows that an increase in θ affects w_r through two channels. First, a higher θ raises downstream firms' marginal cost, which shifts the derived demand downward by reducing its intercept. Second, a higher θ flattens the derived demand, i.e., it reduces

consistent with Sugiyama and Koonsed (2019), who analyze a Southern economy in which a Northern-owned recycler may monopolize the recycled-material market when the Southern recycler is sufficiently inefficient; otherwise, the Northern and Southern recyclers may compete or form an international recycling-firm joint venture.

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its slope in absolute value. Together, these effects imply that a stricter RCS lowers the equilibrium price of the intermediate input.[15] Substituting the optimal price of recycled materials from Equation (27) into the outputs, profits, consumer surplus, and environmental damage yields: $\hat{q}_0^M(\theta) = (a - w_v - 3g(1-\theta) - \rho\theta/2)$, $\hat{q}_1^M(\theta) = g(1-\theta)$, $\hat{\pi}_0^M(\theta) = g(1-\theta)[a - w_v - 3g(1-\theta) - \rho\theta]$, $\hat{\pi}_1^M(\theta) = g^2(1-\theta)^2$, $\widehat{\mathrm{CS}}^M(\theta) = ([a - w_v - g(1-\theta) - \rho\theta]^2/8)$, and $\widehat{\mathrm{ED}}_0^M(\theta) = (g(1-\theta)[a - w_v - g(1-\theta) - \rho\theta]/2)$. Again, as the RCS increases, the impacts on market output, firm 0's profit, consumer surplus, and environmental damage are unambiguous in a mixed duopoly when the upstream recycling market is monopolized.

The social welfare function under mixed duopoly becomes:[16]

$$\widehat{\mathrm{SW}}^M(\theta) = \widehat{\mathrm{CS}}^M(\theta) = \frac{[a - w_v - g(1-\theta) - \rho\theta]^2}{8}. \tag{25}$$

We next move to the first stage. The first-order derivative of social welfare with respect to RCS are

$$\frac{\partial \widehat{\mathrm{SW}}^M}{\partial \hat{\theta}} = \frac{(g-\rho)(a - w_v - g + g\theta - \rho\theta)}{4} > (<)0, \quad \text{if} \quad g > (<)\rho.^{17} \tag{26}$$

As in Section 2.1, we next evaluate social welfare when the RCS equals 1 and 0. Evaluating Equation (26) at $\theta = 0$ and $\theta = 1$, we have $\widehat{\mathrm{SW}}_0^M(\hat{\theta} = 0) = ((a - w_v - g)^2/8)$ and $\widehat{\mathrm{SW}}_1^M(\hat{\theta} = 1) = ((a - w_v - \rho)^2/8)$, respectively. We thus conclude the following optimal RCS in a mixed duopoly when the upstream market is a monopoly as follows.

$$\hat{\theta}^M = \begin{cases} 0, & \text{if } g < \rho, \\ 1, & \text{if } g > \rho. \end{cases} \tag{27}$$

The social welfare in a mixed duopoly with an upstream foreign monopoly

[15] In a typical vertically related market, the second effect is irrelevant for the determination of the optimal intermediate input price.

[16] Recall that in a mixed oligopoly, $\pi_0^M + \pi_1^M - \mathrm{ED}^M$ is always zero regardless of the values of g, θ, and w_r. Even when the upstream market is characterized by a foreign monopoly, welfare continues to coincide with consumer surplus in the mixed oligopoly, implying that producer surplus net of environmental damage is zero.

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is:

$$\widehat{\mathrm{SW}}^M = \begin{cases} \widehat{\mathrm{SW}}_0^M = \frac{(a-w_v-g)^2}{8}, & \text{if } g < \rho, \\ \widehat{\mathrm{SW}}_1^M = \frac{(a-w_v-\rho)^2}{8}, & \text{if } g > \rho. \end{cases} \tag{28}$$

Again, when $g = \rho$, the RCS has no impact on social welfare, as Equation (28) does not contain the θ term. Based on Equation (28) and the above discussion, we obtain the following proposition.

Proposition 4. In a mixed duopoly with an upstream foreign monopoly, the optimal RCS equals one (zero) when the marginal damage of waste exceeds (falls short of) the difference between the upstream marginal cost of recycling and the price of virgin materials.

3.2 Private duopoly

After privatization of the public firm, the profit of the two domestic private firms is the same as Equations (1) and (2). Next, we go back to the second stage, the upstream foreign firm decides the price of recyclable materials. Substituting Equations (1) and (2) into Equation (23) and taking a first-order derivatives with respect to the price of recyclable materials, the equilibrium price of recyclable materials can be solved as:

$$\hat{w}_r^P(\theta) = \frac{a-(1-\theta)w_v+\theta c_r}{2\theta} = \frac{a-w_v+2w_v\theta+\rho\theta}{2\theta}. \tag{29}$$

Substituting $\rho \equiv c_r - w_v$ into Equation (29) the equilibrium price of recyclable materials can be expressed as $\hat{w}_r^P(\theta) = (a - w_v + 2w_v\theta + \rho\theta/2\theta)$. The effect of the RCS on the price of recycled materials in a private duopoly is given by $(\partial\hat{w}_r^P/\partial\theta) = (-(a - w_v)/2\theta^2) < 0$. The underlying economic reasoning is analogous to that in the mixed duopoly case presented in Section 3.1.

After privatization, the price of recyclable materials of the foreign upstream monopoly will increase, that is $\hat{w}_r^P - \hat{w}_r^M = g(1-\theta) \geq 0$. In a mixed duopoly, firm 0 internalizes environmental damage when choosing its output, which gives rise to an internalization effect that reduces its production. Although firm 1 increases its output in response, total market output still falls. Consequently, derived demand shifts downward, which lowers $\hat{w}_r^P$. Therefore, the price of recycled materials increases after privatization.

Substituting the optimal price of recycled materials under downstream private duopoly from Equation (29) into the outputs, profits, consumer surplus, and environmental damage yields: $\hat{q}_0^P(\theta) = \hat{q}_1^P(\theta) = (a - w_v -$

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$\rho\theta/6)$, $\hat{\pi}_0^P(\theta) = \hat{\pi}_1^P(\theta) = ((a - w_v - \rho\theta)^2/36)$, $\widehat{\mathrm{CS}}^P(\theta) = ((a - w_v - \rho\theta)^2/18)$, and $\widehat{\mathrm{ED}}^P(\theta) = (g(1-\theta)(a - w_v - \rho\theta)/3)$. Note that environmental damage also decreases as the RCS increases after privatization when the upstream recycling market is monopolized. Comparing the impacts of the RCS on environmental damage between mixed duopoly and private duopoly under both perfectly competitive and monopolized upstream recycling markets, we obtain Proposition 5 as follows.

Proposition 5. A stricter RCS does not necessarily reduce environmental damage in a mixed duopoly, but it unambiguously reduces environmental damage in a private duopoly, regardless of whether the upstream recycling market is perfectly competitive or monopolized.

The welfare function with an upstream foreign monopoly after privatization thus becomes:

$$\widehat{\mathrm{SW}}^P = \frac{(a - w_v - \rho\theta)\,[a - w_v - \rho\theta - 3g(1-\theta)]}{9}. \tag{30}$$

The first- and second-order derivatives of social welfare with respect to θ can be derived as follows:

$$\frac{\partial \widehat{\mathrm{SW}}^P}{\partial \theta} = \frac{3g\,(a - w_v + \rho - 2\rho\theta) - 2\rho\,(a - w_v - \rho\theta)}{9}, \tag{31}$$

$$\frac{\partial^2 \widehat{\mathrm{SW}}^P}{\partial \theta^2} = -\frac{2\rho(3g - \rho)}{9} < (>)0 \ \text{ if } \ g > (<)\frac{\rho}{3}. \tag{32}$$

Setting Equation (31) equal to zero and solving for the interior RCS yields:

$$\hat{\theta}^{**} = \frac{(3g - 2\rho)\,(a - w_v) + 3g\rho}{2\rho(3g - \rho)}. \tag{33}$$

From Equation (33), we can see that $\hat{\theta}^{**}$ is non-negative when $g \geq (2\rho(a - w_v)/3(a - w_v + \rho)) \equiv g_1$. Finally, following the same method as in Section 2.2, the optimal RCS is:

$$\hat{\theta}^P = \begin{cases} 0, & \text{if } \ g \leq g_1, \\ \hat{\theta}^{**} = \frac{(3g-2\rho)(a-w_v)+3g\rho}{2\rho(3g-\rho)} & \text{if } \ g_1 < g < \frac{2\rho}{3}, \\ 1, & \text{if } \ g \geq \frac{2\rho}{3}. \end{cases} \tag{34}$$

From the above discussion, we get Proposition 6

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Proposition 6. After privatization, the market becomes two private firms competing in the downstream market and one foreign upstream monopoly. The optimal RCS is zero (one) if the marginal damage of waste is small (large); the optimal RCS is $\hat{\theta}^{**}$ if the marginal damage of waste is at an intermediate level.

The result in Proposition 6 is analogous to that in Proposition 4, except that the optimal RCS differs. Similarly, we express social welfare as follows:

$$\widehat{\mathrm{SW}}^{P} = \begin{cases} \widehat{\mathrm{SW}}_1^{P} = \frac{(a-w_v)^2-3g(a-w_v)}{9}, & \text{if } g \le g_1, \\ \widehat{\mathrm{SW}}_2^{P} = \frac{g^2(a-w_v-\rho)^2}{4\rho(3g-\rho)}, & \text{if } g_1 < g < \frac{2\rho}{3}, \\ \widehat{\mathrm{SW}}_3^{P} = \frac{(a-w_v-\rho)^2}{9}, & \text{if } g \ge \frac{2\rho}{3}. \end{cases} \tag{35}$$

3.3 The optimal RCS adjustment due to privatization under upstream monopoly

The adjustment of the optimal RCS resulting from privatization under an upstream monopoly is illustrated in Figure 4. Before privatization, the optimal RCS consists of two horizontal segments corresponding to different levels of g, as shown in Equation (27). After privatization, the optimal RCS characterized in Equation (34), comprises three segments associated with different levels of g: two horizontal lines and one convex curve. When privatization occurs, the adjustment pattern of the optimal RCS resembles that under an upstream perfect competition. As the marginal damage of waste reaches a certain threshold ($g_1 \le g \le \rho$), total market output after privatization becomes larger than before privatization. Since total market output increases with an intermediate range of $g(g_1 \le g \le \rho)$, leading to higher total environmental damage, the optimal RCS should therefore increase following privatization. Overall, privatization under an upstream monopoly leads to a higher optimal RCS in the intermediate range of g, as the government strengthens environmental regulation to offset the increase in total output and associated environmental damage.

3.4 Comparison of optimal RCS under upstream perfect competition and monopoly

We next compare the optimal RCS under an upstream perfectly competitive market and a monopolistic market structure. From the comparison of

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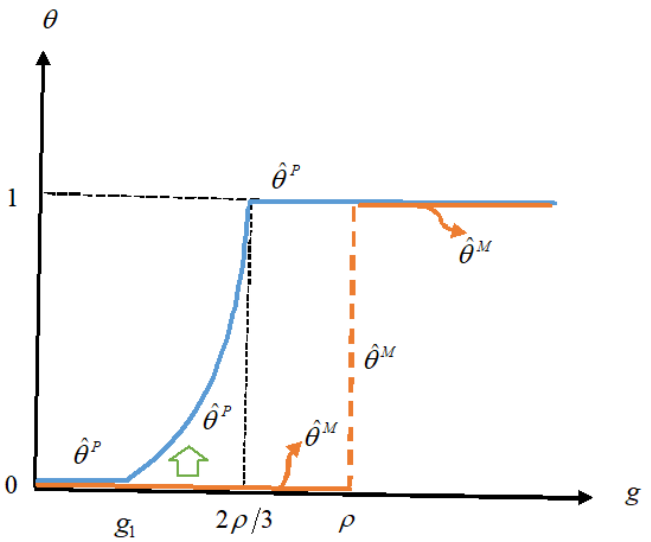


Figure 4: Optimal RCSs under upstream monopoly

the optimal welfare levels in Equations (12) and (28) for the mixed duopoly case, and Equations (21) and (35) for the private duopoly case, we summarize the results as follows. In a mixed duopoly, the optimal RCS equals 1 (0) when the marginal damage of waste exceeds (falls short of) the difference between the marginal recycling cost and the price of virgin materials, regardless of whether the upstream market is characterized by perfect competition or monopoly. In a private duopoly, the optimal RCS equals 0 (1) when the marginal damage of waste is lower (higher) than the threshold value for the cases of upstream perfect competition and monopoly. Otherwise, when the marginal damage of waste takes an intermediate value, the optimal RCS is higher under upstream monopoly than under perfect competition.

The intuition behind the latter result is as follows. Under upstream monopoly, the price of recycled materials is higher than under perfect competition, which raises production costs for downstream firms. Unlike the upstream perfectly competitive case, the foreign monopolistic recycler earns its profit by extracting surplus from domestic firms. This creates an incentive for the domestic government to adopt profit-shifting policies targeting the foreign monopolist. Based on the foregoing comparative-static result $(\partial \hat{w}_r^P / \partial \theta) < 0$, an increase in the RCS serves precisely this purpose, as the

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domestic government can raise the RCS to transfer profits from the foreign recycler to the domestic economy.

4 Concluding remarks

This paper examines the optimal design of recycled content standards in a downstream mixed duopoly and how such policies should be adjusted in response to privatization under alternative upstream market structures. Two upstream environments are considered: a perfectly competitive recycling market with an exogenous input price and a monopolized recycling market in which the price of recycled materials is endogenously determined.

Under upstream perfect competition, the optimal RCS in a mixed duopoly exhibits a corner solution that depends on the magnitude of the marginal damage of unrecycled waste. When the marginal damage is sufficiently small, no RCS is required. When it is sufficiently large, the strictest RCS is optimal, leading to a public monopoly outcome. By contrast, after privatization, the optimal RCS generally becomes interior, reflecting the absence of environmental internalization by private firms and the resulting need for policy intervention.

The adjustment of the optimal RCS following privatization depends critically on how privatization affects total market output. If privatization expands output and thereby increases environmental damage, the optimal RCS should be tightened. Conversely, if privatization reduces total output, the optimal RCS should be relaxed. When the marginal damage is either very small or very large, the optimal RCS remains at the boundary and is unaffected by privatization.

When the upstream recycling sector is monopolized, the main qualitative results continue to hold. In particular, the optimal RCS in a mixed duopoly still exhibits corner solutions prior to privatization and tends to become interior afterward. However, upstream monopoly introduces an additional distortion through a higher recycled input price, which suppresses downstream output and reduces waste generation.

A comparison across upstream market structures shows that, in general, the optimal RCS is higher under upstream monopoly than under perfect competition. Unlike the competitive case, a foreign monopolistic recycler extracts surplus from domestic firms, giving the domestic government an incentive to adopt profit-shifting policies. Since a stricter RCS reduces the foreign recycler's profit, the government can use the RCS to transfer surplus

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to the domestic economy.

Overall, the analysis shows that the optimal RCS policy depends jointly on the marginal damage of waste, the ownership structure of downstream firms, and the degree of upstream market power. These findings highlight the importance of coordinating environmental regulation with privatization policy and upstream market conditions in the design of recycling policies.

Before concluding the paper, it is worth noting that Sugiyama and Koonsed (2017) show that, in a private duopoly, a stricter RCS reduces environmental damage. The present paper confirms this result. However, when the downstream market is characterized by a mixed duopoly, a stricter RCS does not necessarily reduce environmental damage, regardless of whether the upstream recycling market is perfectly competitive or monopolized.

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最適回收成分標準應隨民營化政策而調整嗎?

邱俊榮
國立中央大學經濟學系
陳宏易
東吳大學國際經營與貿易學系

本文分析在下游混合寡占市場中的政府最適回收成分標準政策 (recycled content standards, RCS), 並探討其應如何因應可能的民營化政策而調整。民營化前, 在上游回收市場為完全競爭的情況下, 若未回收廢棄物的邊際損害小於以回收料取代原生料所造成的成本增加, 則政府無需實施 RCS; 反之, 則應採取最嚴格的 RCS。民營化後, 最適的 RCS 將可能存在介於 0 與 1 之間的內解。若民營化會擴大總產出並增加環境總損害, 則最適 RCS 應隨民營化而趨於嚴格; 反之, 若民營化減少總產出, 則最適 RCS 應隨民營化而放鬆。本文亦考慮上游獨占的情形, 並發現最適 RCS 的主要結果在質性上仍然成立。進一步比較不同上游市場結構可知, 一般而言, 最適 RCS 在上游獨占時會較完全競爭下為高。

關鍵詞: 最適回收成分標準, 可回收市場, 混合寡占, 民營化
JEL 分類代號: L33, Q28, Q55

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