Scrap collection for recycling how far should we go?

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Abstract

This paper examines the interaction between the extraction and the recycling industries in a simple two-period model, facing different scraps collection system organized by the government. Analyzing different market structure in the recycling industries, I show that, due to the strategic interaction of the extractor, a full circular economy can only be attained if (*i*) there are enough recycling firms relative to the number of extraction firms, the higher the cost of recycling, the higher number of recyclers required (*ii*) the cost of recycling is lower enough relative to the cost of extraction, (*iii*) the environmental impact of extraction is higher than a certain threshold and (*iv*) the cost of the collection system is cheap enough. Would one of these conditions be violated, the scraps collection rate that maximizes social welfare is significantly lower than 100%.

Key words: Recycling, extraction, strategic reaction, entry, monopoly, municipal solid waste

JEL: D43, L13, Q30

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1 Introduction

The rising consciousness about the environment has been resulting in an increasing recycling rate in many countries. Particularly, recycling of municipal solid waste has been becoming more and more common. The total municipal solid waste recycling and composting in the USA has increased from 10.1% in 1985 to 89.4% in 2014 (U.S. EPA, 2016) . Nowadays, the recycling rate is over 62% in Germany and 55% in Belgium, but it is as low as 1% in some other countries like Turkey and Serbia (EEA, 2016). Governments have been favoring municipal solid waste recycling by investing heavily in improving curbside collection and encouraging third parties firms and NGOs to participate in the collection system through regulation and heavy subsidies. Some developed countries set really ambitious target for municipal recycling to reach ”zero waste” society. The European Commission hopes to boost the recycling of municipal solid waste to 70% by 2030, aiming for the full circular economy in the future. California (USA) targets 70% of municipal solid waste recycled in 2020. The Netherlands even goes further with the target of 100% recycling rate in 2050 with 27 million investment.

Are these recycling rates too high? More precisely, are they socially desired? Is more recycling always better than less recycling? How far should we go in recycling so that the society is not hurt? To answer these questions, Kinnaman et al. (2014) use data in Japan to estimate the average social cost of recycling as a function of the recycling rate. They find that the optimal recycling rate in Japan should only be 10%. While a recycling rate up to 10% appears to reduce social costs, a rate higher than that costs the environment and the economy more than it helps. Dijkgraaf and Gradus (2014) estimate the cost function resulted by different policies in waste recycling in the Netherlands and find that it seems nearly impossible for the Netherlands to reach the EU-goal of 70% recycling rate. These studies[1], however, focus on the collection

[1] In this stream of the literature, we can also cite, for e.g, Callan and Thomas (2001), Kinnaman and Fullerton (2000) , Kinnaman (2006), Bohm et al. (2010), Kinnaman (2010), Ongondo and Williams (2011), Hamilton et al. (2013) and Ferrão et al. (2014)

and waste disposal system and ignore the extraction and recycling sectors. They only study the cost function of recycling and look for the recycling rate that minimizes the average cost of the recycling system. Ignoring the market structure of the extraction and recycling industries, they implicitly assumed perfect competition in those sectors.

But the extraction and recycling industries have known many regimes of competition and are different from one type of material to another. Martin E. (1982) recognizes that "many of the industries currently practicing recycling are highly concentrated". This claim still remains true until our days. We can cite, for example, the extraction of rare earths. Until 1948, rare earths were mainly extracted in Brazil and India, then in South Africa in the 1950s and in California, the USA in 1960s. Nowadays, China produces over 95% of rare earths used in the world and Beijing has announced to close some of their mines in recent years. The recycling sector of rare earths from electronics devices has been established in Japan, France and India. But due to the high cost of advanced technology, the recycling sector is still ill-organized with very few active agents. Another interesting example is phosphate extraction together with phosphorus recycling. While the extraction is concentrated in Morocco, the recycling of phosphate, mainly based on the reuse of nutrient flows stemming from food production and consumption, is undertaken in many developed countries.The extraction and recycling of Aluminum is also a typical example that has been studied in the literature. The Alcoa case in 1945 has initiated a large literature of Industrial Organization on the interaction between the extraction and the recycling industries. The case was concluded by the judgment of Judge Learned Hand that Alcoa constituted an illegal monopoly by virtue of its control over 90% of virgin aluminum output, which can limit the competitiveness of the recycling industry. Starting in the mid-70s, the literature studied, both theoretically and empirically, the correctness of the judgment. Theses studies analyze the market power of the extractor when it face a competitive recycling sector. The main question is whether the existence of the competitive recycling sector can push the price down to the marginal cost of production. The literature was lately enlarged into the analysis of the interaction between the extraction and the recycling sectors, its impact on the market power of firms and on social welfare[2].

The majority of this literature, however, focuses on the analysis of welfare without considering the environmental impact of extraction activities and the social cost of the collection system. Only a few papers such as Hoel (1978) and Ba and Mahenc (2016) consider the environmental impact of the industry and study the optimal scheme of recycling.

Also, most of the theoretical papers in this literature endogenized the inefficiency of recycling activities into the recycling sector. In reality, this inefficiency is caused not only in (i) the reprocess phase, but also in (ii) the collection system. While (i) depends on technological progress, improved mostly by the effort of private firms that conduct recycling, (ii) depends on the effort of the collection system, which cost depends on the type of product, the scrap processing technology and the society's commitment to collect end-of-life products of the specific industry. This effort comes not only from private sector but also from municipalities, households and various levels of institution. The two factors deciding the recycling rate, therefore, depend both on the effort made by the recycling firms and the society, which are decided independently in most of the cases. In the classical setting, the effort of the recycling sector alone decides both loss during the collection phase and the shrinkage during the recycling phase. This setting is particularly incorrect in a B2C industry where the collection phase requires a complex system depending on municipalities' effort and intervention of third-party organizations more than recyclers themselves. Very few papers have provided an alternative to this recycler-centric point of view. Martin E. (1982) analyzes the profit-maximizing scrap recovery sector, considering the recycling sector as competitive. Baksi and Long (2009) proposes a consumer-centric approach by endogenizing consumers' incentive in participating in recycling with the network effect among heterogeneous consumers. These approach are suitable for the B2B or even some B2C economies where scraps are

[2]See for e.g. Schulze (1974), Swan (1980), Hoel (1981), Hoel (1983), Hollander and Lasserre (1988), Grant (1999), Gaudet and Long (1999), Gaudet and Van Long (2003), Eichner (2005) and Honma and Chang (2010)

of high value and the participation of private profit-maximizing firms are significant. However, with municipal solid waste recycling, most of the time, the collection system is organized by municipality or other non-profit institutes who are heavily subsidized by the government. In this case, the interaction between the extractor and the recycler are linked by an exogenous collection system which target of collection is more or less decided in advance by the government.

This paper aims to contribute to fill the gap of the literature by studying theoretically the interaction between the extractor and the recycling industry, and its influence on the optimal recycling rate. In the model, the efficiency of the collection system is not decided by the recycler but by an exogenous agent[3]. The efficiency of the recycling process is explicated through the recycling cost, which is the result of effort in research and development of the firm, conducted before entering the industry. If the recycling cost is high, the recycler cannot reprocess all the resource, the rest of collected scraps must be disposed of. Otherwise, I assume that the recycler has a 1:1 technology of recycling, i.e. one unit of scraps is reprocessed into one unit of recycled material. So the loss occurs if the technology does not allow the recycler to recycle everything.

The analysis is organized as followed. Section 2 characterizes the model and the analysis of the strategic interaction between the two sectors and the outcomes. Section 3 analyzes social welfare and investigates the optimal collection rate. Section 4 discusses and concludes.

2 The Model

2.1 Setting

I consider a simple two-period model in which there are one profit-maximizing firm extracting the resource and m recyclers who enter the industry and compete with

[3] This can be the municipal service, the curbside recycling program sponsored by local governments or a volunteer program in order to clean savage waste, etc.

the extractor on the same final good market in the second period. Firms then follow a leader-follower game: the quantity extracted in the first period by the extractor decides the volume of raw material the recyclers have in the second period, when firms compete à la Cournot.

Without loss of generality, I normalize the cost of resource extraction to zero, i.e. the extractor bears no cost of extraction and transportation. The marginal cost of recycling is assumed to be constant and is referred as c. Because the extraction cost is assumed to be zero, c can be interpreted as the relative marginal cost of recycling over extraction. In line with the reality, I assume a positive c, which represents the situation that recycling is more expensive than extraction.

For the sake of simplicity, I assume that recycling firms are perfectly symmetric. I also assume a linear inverse demand function of the final product that is produced by the virgin or the recycled material $p = 1 - q$. In addition, I assume no discounting factor between periods for both consumers and firms. Assuming no discounting and no differentiation[4] puts the incumbent in the worst case scenario as far as entry is concerned. If products were (horizontally or vertically) differentiated or if the extractor had a stronger preference for the present, entry would be less of a threat, so these assumption would not alter the results in any meaningful way (it would just reduce the threat of entry).

In the beginning of the first period, the government sets the target for the collection rate α. Assuming that the government can perfectly realize its commitment, all agents know with certainty the collection rate α that they will face in the second period. After receiving the target of the government, the extractor extracts a quantity q_1 of virgin resource. Assuming all resources in use becomes useless after one period and a recycling procedure is needed to bring them back to market in the second period, otherwise they are disposed of.

[4]The assumption of no differentiation is generally correct in the case of metals recycling, the quality of aluminum, cooper, iron after the recycler process is considered at the same level as the original metal.

In the beginning of the second period, used resource are collected to be used as raw material and given to the recyclers at price zero [5]. The collection of scrap is assumed exogenous. Depending on the efficiency of the collection activities, there is only a proportion $\alpha \in [0, 1]$ of used resource is collected[6] The recyclers then enter and compete with the extractor à la Cournot, knowing that they only have in total αq_1 units of scrap as input for the recycling process, or $\frac{\alpha q_1}{m}$ for each firm as they are perfectly symmetric.

I assume a 1:1 technology in recycling, which means 1 unit of scrap in input gives 1 unit of recycled material in output. Assuming a 1:1 recycling technology does not mean that their is no shrinkage effect, the source of loss in the recycling process is due to the recycling cost c[7]. If the cost is too high, the recycler cannot recycle all the scrap collected, the rest becomes waste and is disposed of to the environment. If the recycling cost is low enough, then the recyclers can reprocess all the input, i.e. αq_1 to make the same amount of secondary resource.

I use backward induction to get to the Subgame Perfect Nash Equilibrium.

2.2 Analysis

The extractor chooses extraction q_1 and q_2 to maximize its profit throughout the two periods

[5]This can be interpreted by the fact that the collection system is organized by benevolent municipals, or the collection institutes are subsidized by the government. This setting is generally correct in municipal solid waste collection system

[6]This loss can be explained by many reasons. For the case of aluminum cans in the beverage industry, for example, it is hard to collect all the used cans due to the sparsity of consumption and disposal. For high-tech devices like mobile phones and computers, many of them stay in garages or drawers for years without the attention of their owners. Metals are oxidized during using and plastic get burnt or damaged are also reasons of the loss.

[7]this recycling cost includes also the cost that the firm bears for each unit of scrap shrinks during the process of recycling

$$\max_{q_1,q_2} \pi^E = q_1\Big(1 - q_1\Big) + q_2\Big(1 - q_2 - \sum_k^m r_k\Big)$$

with r_k the quantity of recycled material produced by the recycler k in the second period.

In the second period, each recycler k maximizes its profit, subject to the resource constraint of scraps collected

$$\max_r \pi_k^R = r_k(1 - q_2 - r_k - \sum_{l \neq k} r_l - c)$$

$$\text{s.t} \quad r_k \leq \alpha q_1 - \sum_{l \neq k} r_l$$

In the second period, due to the constraint of raw material, the production of the recycler is limited to the amount of scrap collected. Hence the best response function of the recycler is defined as

$$\begin{cases} r_k = \dfrac{1 - q_2 - \sum_{l \neq k} r_l - c}{2} & \text{if} \quad r_k < \dfrac{\alpha q_1}{m} \\ r = \alpha q_1 - \displaystyle\sum_{l \neq k} r_l & \text{otherwise} \end{cases} \tag{1}$$

If the recyclers are not efficient enough to recycle all the scrap collected, or in other word, the unconstrained profit-maximizing quantity of recycling is smaller than the quantity of scrap collected, the market clearing is the solution of the system of the n best response functions

$$\begin{cases} r(q_2) = \dfrac{1 - c - q_2}{m + 1} \\ q_2(r) = \dfrac{1 - m r_k}{2} \end{cases} \tag{2}$$

Define r_k^{NE} and q_2^{NE} respectively the Nash Equilibrium quantity of recycling and extraction absent any constraint in the second period, $(r_k^{NE},\ q_2^{NE})$ is therefore the solution of system (2).

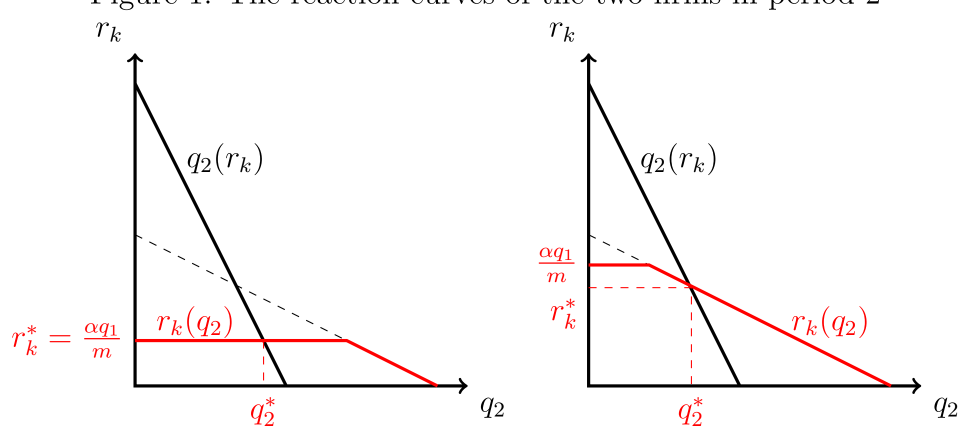
$$\begin{cases} r_k^{NE} = \dfrac{1 - 2c}{m + 2} \\ q_2^{NE} = \dfrac{1 + mc}{m + 2} \end{cases} \tag{3}$$

The recycling quantity $r^{NE} = \dfrac{1-2c}{m+2}$ becomes negative if $c > \dfrac{1}{2}$, i.e. the recyclers can only enter the market when the cost of recycling is not too high relative to the cost of extraction. Therefore, we exclude the case $c > \frac{1}{2}$ where there is no recycling activities whatever the collection rate.

This is the Subgame Perfect Nash Equilibrium provided that $r_k^{NE} < \dfrac{\alpha q_1}{m}$, this equilibrium is illustrated in the right-hand side of Figure 1. Otherwise, the best the recyclers can do is to recycle all the scrap available, $r_k^* = \dfrac{\alpha q_1}{m}$. We then receive a corner solution corresponding to the left-hand side of Figure 1. Knowing $r_k^* = \dfrac{\alpha q_1}{m}$, the extractor maximizes it profit in period 2 with respect to q_2. We receive therefore another subgame equilibrium of the market in the second period

$$\begin{cases} r_k^* = \dfrac{\alpha q_1}{m} \\ q_2^* = \dfrac{1-\alpha q_1}{n+1} \end{cases} \tag{4}$$

Figure 1: The reaction curves of the two firms in period 2



So, given a recycling cost and a quantity of scrap available, there exists a threshold of the collection rate α below which the recyclers recycle all the amount of raw material and we obtain a corner solution independent of c. If α is above this threshold, we obtain a standard Cournot equilibrium in the second period.

In the first period, the extractor chooses q_1 to maximize its total profit over the two periods. It has two options: to extract a monopolistic quantity or to reduce the extraction to soften competition in the second period.

When the recyclers cannot reprocess all the scrap αq_1, corresponding to System (3) and the right-hand-side graph of Figure 1, the extractor has no incentive to reduce prior-extraction. Therefore, it maintains the prior extraction $q_1^{NE} = \dfrac{1}{2}$ and the corresponding profit

$$\pi^E(q_1^{NE}, q_2^{NE}, r_k^{NE}) = \frac{(4c^2+1)\,m^2 + (8c+4)m + 8}{4(m+2)^2}$$

This result is the equilibrium as long as the amount of scraps collected is bigger than the quantity of recycled resources, i.e. $\dfrac{\alpha}{2} > m\dfrac{1-2c}{m+2}$, equivalent to

$$\alpha > \frac{2m(1-2c)}{m+2} \tag{5}$$

When the recyclers can reprocess all the scraps collected, corresponding to System (3) and the left-hand-side of Figure 1, the volume of material recycled is increasing with the extraction in the first period. Hence the extractor has motivation to reduce the quantity of extraction in the first period to soften competition in the second period. In this situation, the extractor maximizes its profit over the two periods with respect to q_1:

$$\max_{q_1} \pi^E = q_1\Big(1 - q_1\Big) + q_2^*\Big(1 - q_2^* - mr_k^*\Big)$$

Replacing r^* and q_2^* from (4), we can compute respectively the extraction in the first period

$$q_1^* = \frac{1}{\alpha+2}$$

the extraction in the second period

$$q_2^* = \frac{1}{\alpha+2}$$

and the corresponding profit of the extractor

$$\pi_k^E(q_1^*, q_2^*, r_k^*) = \frac{1}{\alpha+2}$$

In this case, the recycler k's profit is

$$\pi_k^E(q_1^*, q_2^*, r_k^*) = \frac{\alpha(1-\alpha c-2c)}{m(\alpha+2)^2}$$

which is positive when $c < \frac{1}{\alpha+2}$. Combining with the condition above, we restrict the cost of recycling to $c \in [0, \frac{1}{\alpha+2}]$ so that recyclers always find it profitable to enter the market.

Given a recycling cost c, facing each collection rate α, the extractor chooses the strategy between ignoring and accommodating the new entries to maximize their profit. Therefore, the extractor chooses to ignore the entry if

$$\pi^E(q_1^{NE}, q_2^{NE}, r_k^{NE}) < \pi^E(q_1^*, q_2^*, r_k^*)$$

which give

$$\alpha > \frac{-8c^2m^2 - 16cm + 2m^2 + 8m}{4c^2m^2 + 8cm + m^2 + 4m + 8} \equiv \tilde{\alpha} \tag{6}$$

$\tilde{\alpha} > \frac{2m(1-2c)}{m+2}$, so condition (5) is satisfied.

From the expression above, we can deduce that $\tilde{\alpha} > 1$ if $m > \frac{8\sqrt{3}c}{1-12c^2}$ and $c < \frac{1}{2\sqrt{3}}$. Under these two conditions, the extraction always accommodate the new entries for all value of the collection rate $\alpha \in [0, 1]$.If $c = 0$, we only need $m > 1.46$, i.e. 2 recyclers. However, this threshold increases convexly in the recycling cost, for $c = \frac{1}{2\sqrt{3}}$, we need $m > 90$ in order to have no discontinuity. Otherwise, there always exist a threshold $\tilde{\alpha}$, below which the extractor prefers reducing extraction in the first period to accommodate the new entries in the second period; and above which the extractor chooses to ignore the new entries and maintain extraction in the first period as if there is no entry. The switch in strategy is due to changes in the "cost of accommodation". When α is low, the recyclers reprocess all the scraps collected, so every less unit of extraction in the first period softens competition in the second period. When α is high, because the recyclers cannot economically reprocess all the scraps collected, to soften competition in the second period, the extractor has to take into account also the surplus of the scraps collected, which causes a too high "cost of accommodation". Therefore, if α is bigger than a certain threshold, the extractor prefers ignoring to accommodating. When there are many recyclers and the recycling cost is low enough, the economic capacity of the recyclers increases push the threshold of α closer to 1. If there are enough recyclers with a low enough recycling cost, there will be full recycling for all $\alpha \in [0,1]$. In this case, the extractor has no motivation to switch to ignoring. Therefore, the extractor always accommodates the new entries by reducing extraction in the first period and there is no discontinuity in the reaction function.

Since $\frac{\partial\tilde{\alpha}}{\partial c} = -\frac{32m(m+2)^2(cm+1)}{((4c^2+1)m^2+(8c+4)m+8)^2} < 0$ for all m, the threshold $\tilde{\alpha}$ is decreasing with c, i.e. when the cost of recycling decreases, the range of the collection rate that makes the extractor reduces it prior-extraction is larger. Because facing a smaller cost of recycling means that the extractor faces a stronger competition from the recycling. So it will have more incentive to accommodate the recycler to maintain its profit.

Also, $\tilde{\alpha} < 0$ when $c > \frac{1}{2}$ and $\tilde{\alpha} = \frac{10}{13} < 1$ when $c = 0$. Reminding that the recycler will not find it profitable to enter if $c > \frac{1}{2}$ and the assumption that recycling is more costly than extraction, we can perfectly limit $c \in [0, \frac{1}{2}]$ for the analysis. Because $\tilde{\alpha} < 1$ for all $c \in [0, \frac{1}{2}]$, with m smaller than the threshold or c higher than $\frac{1}{2\sqrt{3}}$, there always exists a discontinuity in the extractor's reaction function along the range of possible collection rate.

Hence, if there is the discontinuity in the reaction function of the extractor, its profit function is

$$\pi^E = \begin{cases} \dfrac{1}{\alpha+2} & \text{if} \quad \alpha \leq \tilde{\alpha} \\ \dfrac{(4c^2+1)\,m^2+(8c+4)m+8}{4(m+2)^2} & \text{if} \quad \alpha > \tilde{\alpha} \end{cases} \tag{7}$$

otherwise, its profit function is

$$\pi^E = \frac{(4c^2+1)\,m^2+(8c+4)m+8}{4(m+2)^2} \tag{8}$$

When there exists the discontinuity in the reaction function of the extractor, the outcomes can be summarized in Figure (3). In the other case, only the left-hand side of Figure (3) can occur.

Figure 2: condition to have no discontinuity in the extractor's reaction function

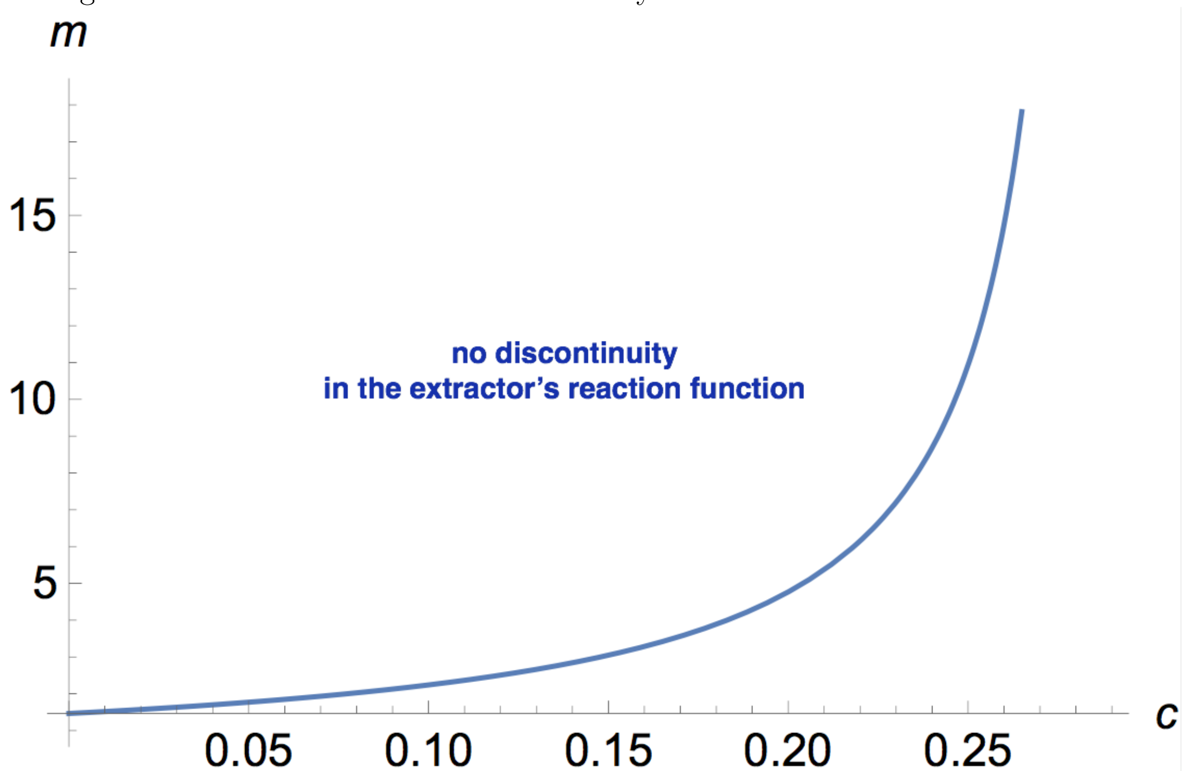
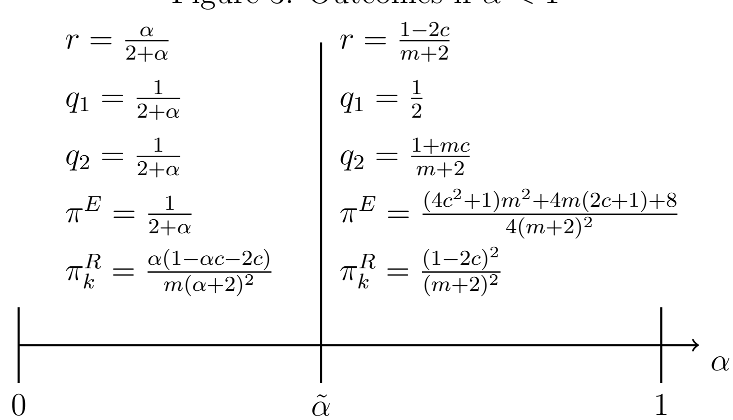


Figure 3: Outcomes if $\tilde{\alpha} < 1$



3 The analysis of social welfare

To conduct the analysis, I define social welfare as the sum of consumer surplus and firms' profit minus the environmental impact of virgin-resource extraction and the social cost of the collection system[8]

$$SW = CS + \pi_E + m\pi_R - eV - \theta\alpha$$

The environmental impact e of extraction includes various source of environmental bad. The direct impact is the destruction of the nature at the mine, physical impact of the extraction on the site include the use of dynamite, the deforestation to serve the mines, etc. The impact also comes from transportation and infrastructure to serve the transport line, pollution caused by trucks and the destruction of nature to build roads play a major role in the environmental impact of extraction. Another impact can be counted in is the energy used in extraction. Some metal requires a huge mass of energy in the extraction and metallurgical progress. Chemical treatments of virgin resource and leakage of chemical substances during the metallurgical process can pollute the earth and source of water. There exists also an indirect impact, because resource are exhaustible, extraction today reduces the stock of resource in the future, I also count this in the environmental impact of extraction. V is the quantity of virgin resource extracted, and $\theta\alpha$ the social cost of the collection system. The environmental impact and the cost of the collection system are assumed to be linear for the sake of simplicity[9]. This cost of collection is not only the economic cost but includes also

[8]In reality, there are also environmental impacts caused by landfill and incineration, which are the solution for non-recycled material. However, it is increasing recognized that the environmental impact of extraction is much more significant than the one of landfill, especially under modern landfill condition (UNEP, 2010)

[9]A higher degree of the environmental and social cost (such as eV^2 and $\theta\alpha^2$, which are the common assumptions in the literature) will lead to worse cases, where the social welfare decreases faster. Hence, the linear assumption will not alter the meaning of the analysis, which corresponds to the most optimistic scenario.

other social cost attached with the improvement of the collection system such as the cost of sorting the used material for consumers, the environmental impact coming from sorting, transporting and storing the scraps, the environmental and economic cost of disposing-of unused collected scraps, or the cost of management of the system. For materials like plastics, the cost of sorting is extremely high. Scraps such as end-of-life cars or electronic devices are combination of many types of plastics which are chemically incompatible among them. Therefore the sorting procedure is complex and requires many effort to purify the resource to recycling. In the case of WEEE, because products are diversified (from fridge to smartphone), of diverse composition of plastic, the deposits of scraps are of low density, which requires a cost of collection which is sometime too expensive. With this setting, I assume that there exists not only the environmental impact of extraction but also the social, economic and environmental cost of the collection system, which can be also a proxy to tackle the externalities caused by recycling. Without any further assumption, this setting does not restrict to the assumption that recycling causes less harm to environment and the society than extraction.

If $\tilde{\alpha} < 1$, the social welfare function is

$$SW = \begin{cases} \dfrac{(12c^2 - 8c + 7)\, m^2 + 4\,(8c^2 - 6c + 7)\, m + 24}{8(m+2)^2} - \dfrac{e(2cm + m + 4)}{2m + 4} - \alpha\theta & \text{if} \quad \alpha > \tilde{\alpha} \\ \dfrac{\alpha^2(1-2c) + \alpha(6-4c) + 6}{2(\alpha+2)^2} - \dfrac{2e}{\alpha+2} - \alpha\theta & \text{if} \quad \alpha < \tilde{\alpha} \end{cases} \tag{9}$$

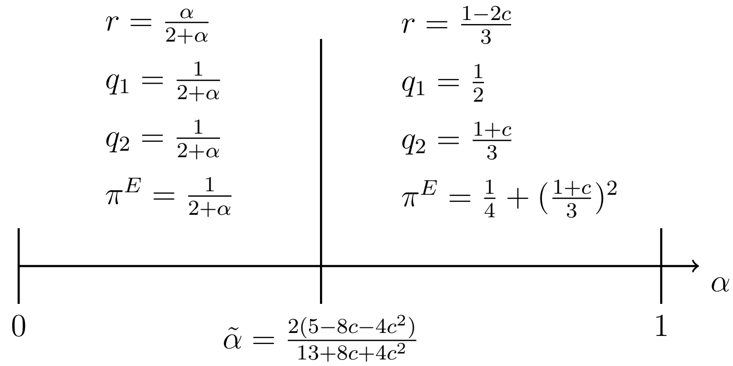
Otherwise, it is

$$SW = \frac{\alpha^2(1-2c) + \alpha(6-4c) + 6}{2(\alpha+2)^2} - \frac{2e}{\alpha+2} - \alpha\theta \tag{10}$$

3.1 When $\tilde{\alpha} < 1$

For this section, I investigate the case where there is discontinuity in the reaction function of the extractor.

Figure 4: Outcomes in the monopolistic case



From the social welfare function above, we can observe that the social welfare function when $\alpha < \tilde{\alpha}$ is independent of the number of recyclers m the number of recyclers. Also, when there exists the discontinuity in the reaction function of the extractor, as firms compete à la Cournot in the second period when the extractor chooses to ignore new entries, a smaller number of recyclers leads to a higher deadweight loss then $\alpha > \tilde{\alpha}$. Therefore, the analysis when $m = 1$ is the worst case analysis and the pattern of variables in interest will not change with m as long as $m < \frac{8\sqrt{3}c}{1-12c^2}$ or $c > \frac{1}{2\sqrt{3}}$. Therefore, for the sake of simplicity, in this section, I focus only on the situation where both the extraction and the recycling industries are monopolies. The outcomes of this situation are given in Figure (4).

Firstly, to match with the classical literature on recycling, I conduct a static comparison of three variables: the quantity of virgin resource extracted, consumer surplus and the material-related social welfare without taking into account the environmental impact of extraction and the cost of improving the collection system.

If there is no recycling, the extractor will maintain in both two periods the monopolistic quantity of extraction, which is $q_1 = q_2 = q^m = \frac{1}{2}$, so the total amount of resource extracted is $q_1 + q_2 = 2q^m = 1$. In the presence of recycling, if $\alpha < \tilde{\alpha}$, the extractor extracts $\frac{1}{2+\alpha}$ in both periods. The total amount of virgin resource extracted is $\frac{2}{2+\alpha}$. If $\alpha > \tilde{\alpha}$, the extractor extracts $\frac{5+c}{6}$ in the first period and $\frac{1+2c}{6}$ in the second period. The total amount of virgin resource extracted is then $\frac{2+c}{2}$. Because $\alpha \in [0, 1)$

and $c \in [0, \frac{1}{2}]$, the quantity of virgin resource extracted in the presence of the recycler is always smaller than without recycling. Even when $\alpha > \tilde{\alpha}$, the extractor ignores the new entry and extracts the monopolistic quantity in period 1 but in period 2, it extracts less virgin resource due to the competition of the recycler.

Concerning consumer surplus, the utility function of consumers is $U(q) = q - \frac{q^2}{2}$. Then the consumer surplus in each period facing q total quantity of virgin and recycled resource is:

$$CS(Q) = U(Q) - p(Q)Q = \frac{Q^2}{2}$$

with $Q = q_1 + q_2 + r$ the total amount of resource existed in the market over the 2 periods. Because the demand function is linear, it is evident that consumer surplus increases with the quantity of resource available.

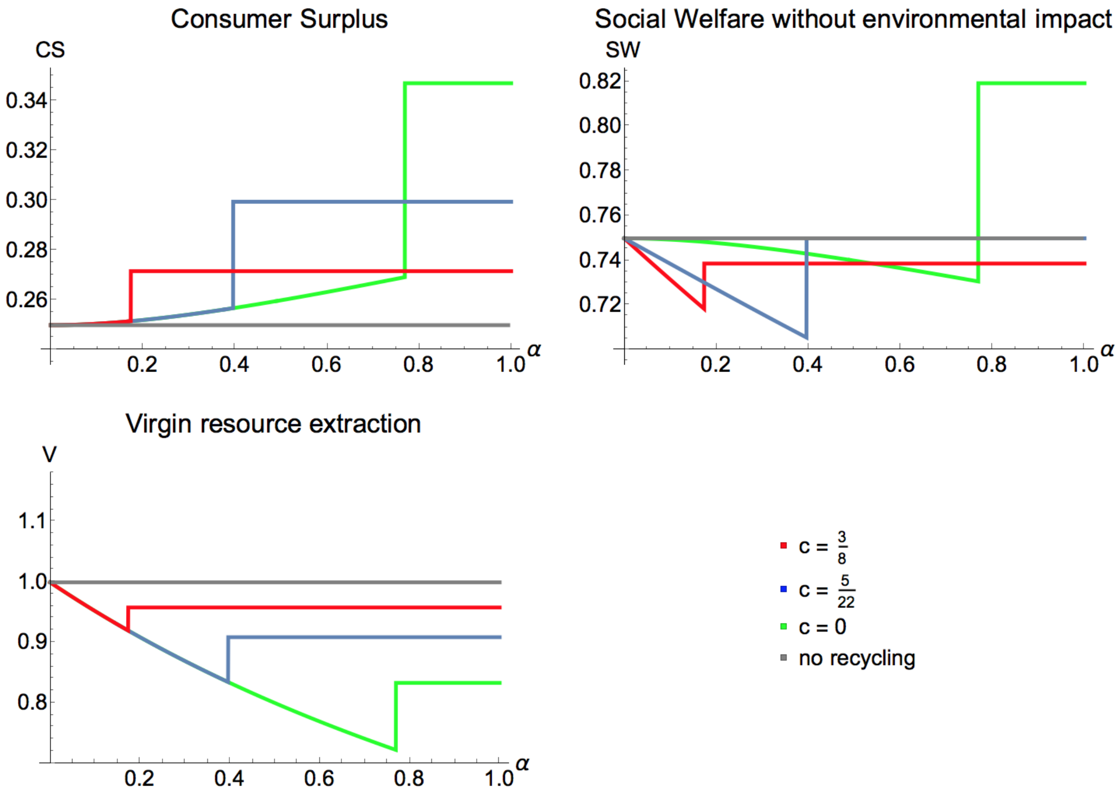
Without recycling, $q_1 = q_2 = \frac{1}{2}$, leading to the total consumer surplus $CS = \frac{1}{4}$. With recycling, a decrease in quantity in the first period increases the price, causing a decrease in consumer surplus. However, in the second period, the entry of the recycler increases the quantity of material on the market and lowers the price, which leads to an increase in consumer surplus. The total variation of consumer surplus depends then on the difference between the loss in period 1 and the gain in period 2. The total consumer surplus is :

$$CS = \begin{cases} \dfrac{\alpha^2 + 2\alpha + 2}{2(\alpha+2)^2} & \text{if } \alpha < \tilde{\alpha} \\ \dfrac{1}{72}(41 - 46c + 50c^2) & \text{if } \alpha > \tilde{\alpha} \end{cases} \tag{11}$$

Then the material-related social welfare is simply defined as the sum of consumer surplus and producer surplus, $SW = CS + \pi_E + \pi_R$. Limiting prior-extraction and the entry of the recycler harms the profit of the extractor. However the net variation of the total welfare in biases due to the participation of the recycler in the second period which can improve consumer surplus.

$$SW = \begin{cases} \dfrac{\alpha^2(1-2c) + \alpha(6-4c) + 6}{2(\alpha+2)^2} & \text{if } \alpha < \tilde{\alpha} \\ \dfrac{1}{72}(44c^2 - 32c + 59) & \text{if } \alpha > \tilde{\alpha} \end{cases} \tag{12}$$

Figure 5: Static comparison of variables of interest



The variation of consumer surplus, social welfare, and the quantity of virgin resource extracted for three given values of the recycling cost $c = 0, c = \frac{5}{22}, c = \frac{3}{8}$ is presented in Figure 5. The non-recycling case is represented by the gray line.

The quantity of virgin resource extracted is unsurprisingly always smaller in the existence of recycling relative to the non-recycling case. Although there is a jump of this quantity when α is higher than the benchmark, this quantity stays below the extraction in the absence of recycling. The lower the recycling cost, the better the recycler can do in the second period, the smaller the extraction is.

Because there are more resource in the industry over the two periods with the entry of the recycler, consumers are always better off with the existence of recycling relative to the non-recycling case. The jump at the discontinuity threshold gives a greater level of consumer surplus, which stay constant while the collection rate increases over the threshold.

Considering the social welfare without environmental impact, when $\alpha < \tilde{\alpha}$, social welfare is smaller in the existence of recycling relative to the non-recycling case because the gain of consumer surplus cannot offset the loss in firms' profit. Also, because the extraction of virgin resource decrease with the collection rate, the material-related social welfare also decreases with the collection rate. When the cost of recycling decreases, the threshold of the collection rate increases, enlarge the range of α that makes the society worse off relative to the non-recycling case. The minimum social welfare at $\tilde{\alpha}$, however, is not monotonic in the cost of recycling c. At first, it decreases with c, because a small cost of recycling enhances the competitiveness of the market, leads to low profit of the extractor. But when the cost of recycling is small enough, consumer surplus will increase faster than the loss in firms' profit, which reduce the speed of reduction in social welfare and also a higher minimum social welfare.

When $\alpha > \tilde{\alpha}$, the jump in quantity of resource leads to a jump in social welfare. The margin of this jump depends on the recycling cost c. This stems to some interesting results. First, if $c > \frac{5}{22}$, the social welfare will always be smaller relative to the non-recycling case even after the jump. Those value of the recycling cost make the society always worse off no matter how good is the collection system. Second, even with $c < \frac{5}{22}$, the collection rate must be higher than the benchmark to have a higher material-related social welfare.

We see clearly here the trade-off between the material-related social welfare and the quantity of virgin-resource extraction. If the government cares more about reducing extraction than about profit of firms, it is reasonable to keep a low collection rate. In this scenario, consumers still gain from the entry of the recycler and the reduction in extraction is significant when the collection rate is close to the threshold $\tilde{\alpha}$. If the government cares more about the firms' profit, and improvement in consumer surplus with less attention on the quantity of virgin resource extracted, a collection rate higher than the threshold $\tilde{\alpha}$ is clearly preferred.

In the classical literature on recycling, the discussion stops here with the analysis of the monopolist's market power. Many authors argue that the monopolist restrains its output to soften the competition of the recycler in the latter period. This activity is considered anti-competitive and has negative effect on social welfare. Without considering the environmental impact of extraction and the social cost of collection, we can observe the same situation here when the collection rate is smaller than a certain threshold $\tilde{\alpha}$. When the collection rate is higher than this threshold, the monopolist ignores the new entry. As a consequence, social welfare increases. Thus this situation is considered better for the society in the classical literature.

The social welfare function is then defined as:

$$SW = \begin{cases} \dfrac{\alpha^2(1-2c)+\alpha(6-4c)+6}{2(\alpha+2)^2} - \dfrac{2e}{\alpha+2} - \theta\alpha & \text{if} \quad \alpha < \tilde{\alpha} \\ \dfrac{1}{72}\left[c^2(58-18e) - 2c(36e+31) - 72e + 67\right] & \text{if} \quad \alpha \geq \tilde{\alpha} \end{cases} \tag{13}$$

Proposition 1 *There exists a threshold of e, denoted $\tilde{e}$ such that if $e < \tilde{e}$, the optimal collection is $\tilde{\alpha}$, independent of the collection rate*

The society is better off when $\alpha \geq \tilde{\alpha}$ if

$$\frac{1}{72}\left[c^2(58-18e) - 2c(36e+31) - 72e + 67\right] \geq \frac{\alpha^2(1-2c)+\alpha(6-4c)+6}{2(\alpha+2)^2} - \frac{2e}{\alpha+2} - \alpha\theta$$

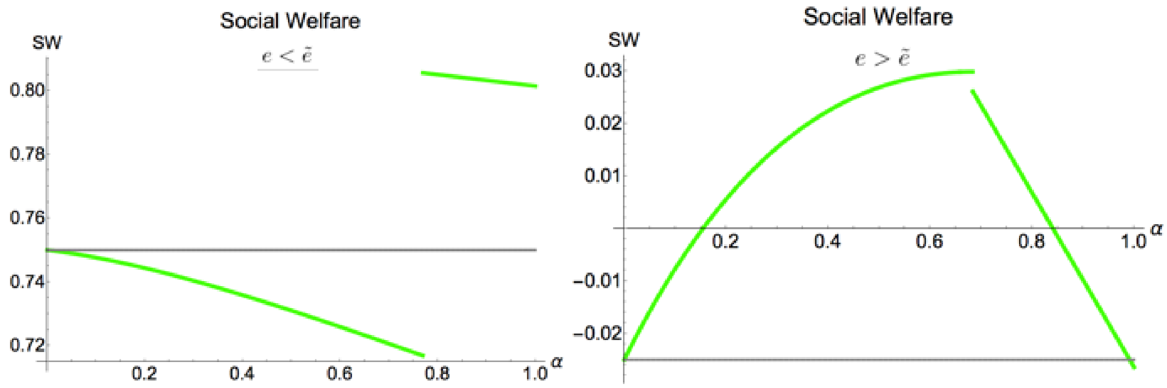
which gives

$$e \leq \frac{-8c^3+108c^2-66c+115}{144(c+1)} \equiv \tilde{e}$$

In Figure 6, I compare the variation of social welfare along the value of the collection rate α, with the same cost θ of the collection system, when $e < \tilde{e}$ on the left-hand side and when $e > \tilde{e}$ on the right-hand side. The gray line represents social welfare without recycling.

When $e < \tilde{e}$, the jump in the reaction function of the extractor leads to a jump upward in the social welfare function. Before the jump, if the cost of collection is high, social welfare is decreasing with the collection rate and is smaller than social welfare in the case without recycling. After the jump, because the environmental impact is small, the gain in consumer surplus and firms' profit from the jump upward in the

Figure 6: The two scenarios of social welfare with different e



quantity of virgin resource extracted can offset the environmental impact. Hence, social welfare after the jump is higher than before the jump and is higher than social welfare without recycling. When the collection rate increases after the jump, because addition collection are wasted due to the fact that the recycler already reaches its profit-maximizing recycled output, social welfare decreases in the collection rate because of the cost of collection. Thus, when $e < \tilde{e}$ the optimal collection rate is right at the threshold $\tilde{\alpha}$.

Proposition 2 *When $e > \tilde{e}$, the optimal collection rate is $\tilde{\alpha}$ if $\theta < \tilde{\theta}$ and decreases with θ if $\theta > \tilde{\theta}$*

When $e > \tilde{e}$, because the social welfare function has a jump downward when α crosses $\tilde{\alpha}$, the optimal collection rate α^* must be smaller than the threshold $\tilde{\alpha}$.

Therefore, the optimal α^* is such that

$$\alpha^* = min\Big[\tilde{\alpha}, \text{argmax}\{\frac{\alpha^2(1-2c)+\alpha(6-4c)+6}{2(\alpha+2)^2} - \frac{2e}{\alpha+2} - \theta\alpha\}\Big]$$

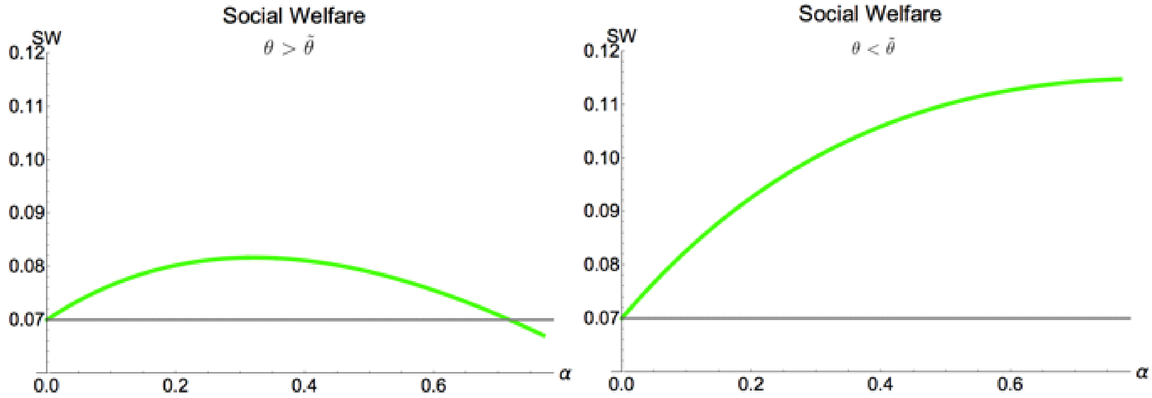
Then $\alpha^* < \tilde{\alpha}$ if

$$\theta > \frac{(4c^2+8c+13)^2\,(4c^2-28c+36e-5)}{23328} \equiv \tilde{\theta}$$

So, the optimal collection rate decreases with θ, and if $\theta > 1/2(e-c)$, it is better for the society to have no recycling, with a collection rate of zero.

The result is illustrated in Figure 7.

Figure 7: The social welfare when $e > \tilde{e}$ with different θ



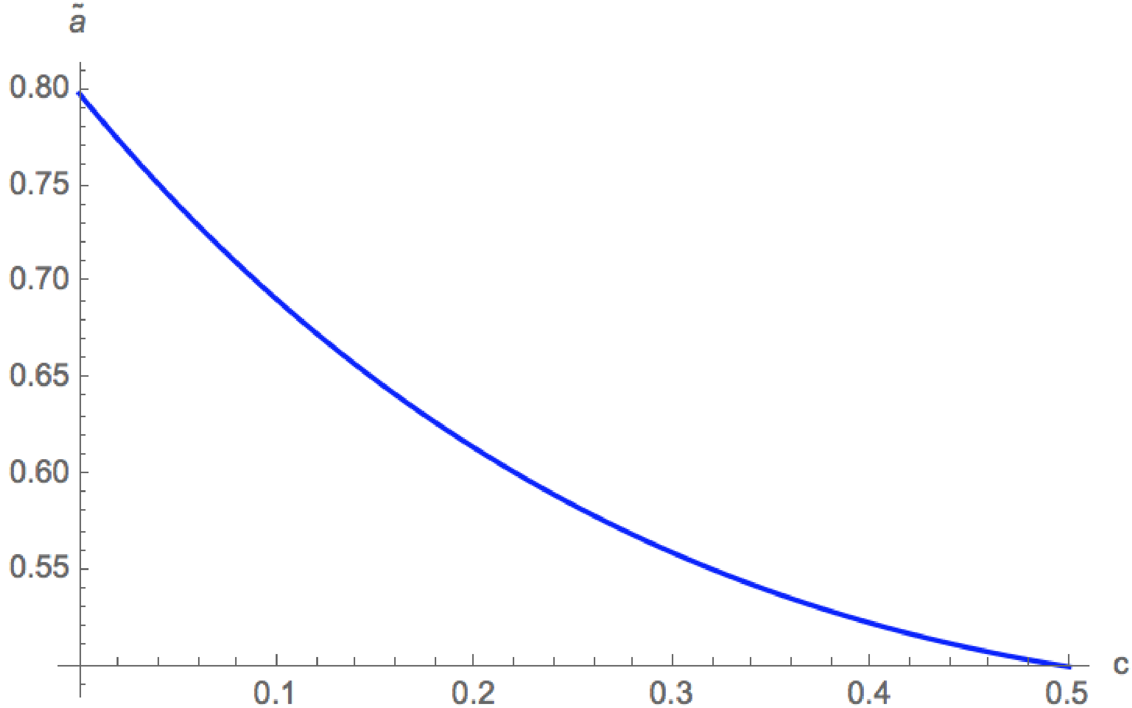
Proposition 2 *When $e < \tilde{e}$, the optimal collection rate, which is $\tilde{\alpha}$ is strictly smaller than 100% as long as recycling is not cheaper than extraction.*

The two propositions above suggests an interesting contribution of this paper. In the presence of the discontinuity in the extractor's reaction function, $\tilde{\alpha}$ can be used as a benchmark to determine the range of candidates for the optimal collection rate. If $e < \tilde{e}$, any collection rate smaller than $\tilde{\alpha}$ actually makes the society worse off, hence the government should set the collection target as least as high as $\tilde{\alpha}$ to avoid the case that the target minimizes social welfare instead of maximizing it. If $e > \tilde{e}$, $\tilde{\alpha}$ becomes the highest collection rate that the government should aim to, because any collection higher than that will lead to a jump downward in social welfare. Figure 8 represents the variation of $\tilde{\alpha}$ with respect to c.

3.2 When $\tilde{\alpha} > 1$

In this section, we discuss the situation when $m > \frac{8\sqrt{3}c}{1-12c^2}$ and $c < \frac{1}{2\sqrt{3}}$, which leads to no discontinuity in the reaction function of the extractor along the possible collection rate. In this case, because the recycler always recycle all the scraps collected, the collection rate is also the recycling rate. An interesting outcome of full recycling is that the number of recyclers does not play any role in the social welfare. As m recyclers share equally the total input, output and profit of the recycling sector, when sum up their

Figure 8: The variation of $\tilde{\alpha}$ with respect to c when there is one recycler



profit into the social welfare function, the number of recycling firm disappears. The social welfare function in then

$$SW = \frac{\alpha^2(1-2c) + \alpha(6-4c) + 6}{2(\alpha+2)^2} - \frac{2e}{\alpha+2} - \alpha\theta \tag{14}$$

The recycling rate that maximizes social welfare is defined as

$$\alpha^* = \frac{6c\theta - 6e\theta + 3\theta - \left(\sqrt{(6c\theta - 6e\theta + 3\theta)^3 + 729\theta^4} - 27\theta^2\right)^{2/3}}{3\theta\sqrt[3]{\sqrt{(6c\theta - 6e\theta + 3\theta)^3 + 729\theta^4} - 27\theta^2}} - 2 \tag{15}$$

So whenever $\alpha^* \geq 1$, a full circular economy will be socially optimal. Otherwise, the optimal recycling rate will be smaller than 100%. The condition for $\alpha^* \geq 1$ is that

$$e > \frac{6c+1}{6} \tag{16}$$

$$\theta < \frac{6e - 6c - 1}{27} \tag{17}$$

Would the environmental impact of extraction and the cost of the collection system violate on of these two conditions or both, then a full circular economy is not optimal. Condition (16) is to make sure that the benefit of reducing extraction is high enough to cover the loss in the extractor's profit when accommodating the new entry. Condition (17) assures that the collection system does not cost the society too much in conducting the recycling activity. If the collection system is too expensive, then recycling cannot be socially profitable.

To the extreme, if $e < c$ or $e > c$ and $\theta > \frac{e-c}{2}$, a recycling rate of zero will be optimal for the society, which means in those conditions, no recycling is socially optimal. Here again, we observe that if the environmental impact is smaller than the cost of recycling, then recycling is not profitable even when it costs nothing to collect the scraps.

4 Concluding remarks

This paper raises the concern of the market structure while study the optimal recycling rate. In a simple two-period model, it shows that the optimal recycling rate depends on the strategic interaction between the extractor and recycling industry, facing different efficiency of the collection system. While extraction decreases with the collection rate at the beginning, there might exist a threshold of the latter, above which the extractor ignores the new entries and return to the initial level of prior-extraction. This discontinuity always exists if the cost of recycling is too high, or there are not enough recycling firms in the industry. It causes a jump upward in the quantity of resource extracted, leading to a jump upward in consumer surplus and material-related social welfare just before and after the threshold.

Considering the environmental impact of extraction in the social welfare function, the discontinuity causes a jump upward of social welfare if the environmental impact is small and a jump downward if the environmental impact is above a certain threshold. This non-monotonic variation is caused by the different magnitude of the environment impact of a jump in extraction and the gain in material-related social surplus. When the environmental impact of extraction is high, the gain in material-related social welfare cannot offset the impact caused by the jump upward in extraction, causing a decrease in social welfare and vice-versa.

The model shows that in the presence of the discontinuity in the reaction function of the extractor, the optimal scraps collection rate never reaches 100% as long as recycling is more costly than virgin resource extraction. When the environmental impact is small and the discontinuity causes a jump upward in the social welfare function, social welfare is maximized right at the threshold of the collection rate that cause the jump. This optimal collection rate is independent of the cost of collection, decreasing in the cost of recycling but cannot reach 100% even if recycling is as cheap as extraction. Also, because the optimal collection rate is at the discontinuity of the extractor's reaction function, a small variation of the collection rate influence dramatically the level of social welfare. When the environmental impact of extraction is bigger than the threshold, the optimal collection also depends on the cost of collection. If the cost of collection is above a certain threshold, the optimal collection rate decreases significantly.

A counterintuitive results of the model is that, facing a high cost of the collection system, a high environmental impact of the extraction procedure leads to a lower optimal collection rate than a lower environmental impact does. This paradoxical outcome is due to the strategic reaction of the extractor, when it has to choose between accommodating and ignoring the new entry. This result emphasizes the importance to consider the market structure of the extraction and recycling sectors when studying the recycling rate.

The model also points out the conditions for a full circular economy to be socially optimal: (*i*) there must be enough recyclers, depending on the cost of recycling, (*ii*) the cost of recycling must be low enough, (*iii*) a high environmental impact of extraction and (*iv*) the cost of the collection system must not exceed a certain threshold. Would one of them be violated, a collection rate significantly lower than 100% will be optimal for the society.

(*i*) and (*ii*) are necessary conditions, assuring that there is no discontinuity in the reaction function of the extractors, so that the always reduces their extraction in the first period to accommodate the new entries. Also, a circular economy only makes sense if (*iii*) is satisfied, i.e, the environmental benefit of reducing extraction is high enough to cover the loss in the extractors' profit for accommodating the new entries. Otherwise, a zero recycling rate is optimal for the society. (*iv*) assures that the social cost of the collection system is not too high, even though scrap collection and recycling is environmentally benefit, if it cost too much to the society or it is too annoying for the population, it will not be beneficial for the society in a whole. However, this cost needs not to be zero, it is sufficient to be lower than a certain threshold with respect to the environmental impact of extraction. Only if all of the four conditions above are satisfied that a full circular economy is socially beneficial.

Because different materials have different environmental impact from extraction and cost of collection, the optimal collection rate is also different from one industry to another. As a consequence, policy makers must also pay attention in setting the target for the scraps collection sector. Because social welfare is strongly sensitive to a small change in the collection rate, setting one unique collection target for many material can have a strong impact on social welfare.

While the estimation of the optimal recycling rate encounters many difficulties in the estimation of the environmental impact of extraction activities and the social cost of the collection system [10], this model show a possibility to restrict the rang of candidates for optimal recycling rate. If the environmental impact of extraction is expected to be small, then the government should not set a target lower than the threshold of the collection rate that cause the jump in social welfare function because the social welfare is much smaller before than after this threshold. On the other hand, if the environmental impact is expected to be high, then the government should not set any target higher than the threshold above because of the jump downward in the social welfare function. The estimation of this threshold can be easier than the estimation

[10] see the discussion of Kinnaman (2014) among others

of the optimal recycling rate because it only depends on information of the number of firms the recycling industry relative to the extraction industry, together with the relative economic cost of recycling relative to extraction. In practice, this constraint may help narrow down the estimation and lead to a more precise prediction of the optimal recycling rate.

Although this paper only tackles the case where the extraction industry is monopoly, it is relevant because the extraction industry is widely considered very concentrated due to many reasons. Therefore, the extractors enjoy a market power that leads to a similar strategic reaction as in this analysis. The analysis of a more competitive extraction sector will also be useful, but due to the difficulties in computation, I will leave that for further research.

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