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The effect of recycling over a mining oligopoly

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Abstract

In a view of switching from a linear to a circular economy, recycling plays a fundamental role. While the literature on the effect of recycling over the mining activity is focused on a monopoly, here we only deal with a mining oligopoly, which better reflects realistic market conditions. Our results show a decreasing mining output with the presence of recycling and unexpectidly a greater market power. Nevertheless, we point out the need for recylers to benefit from a minimum recycling efficiency technology to enter the market. A second technologic threshold also allows the recyclers to lower the oligopolistic market power. In this case of extreme foreclosure, since the mining output rises with the number of firms, a cooperation is necessary to prevent the entry of recycling. In terms of strategy, an horizontal integration could strengthen their position in the upstream industrial process and would also represent a good way to step forward to the so-called circular economy.

Keywords: oligopoly, market power, recycling, Alcoa case, iron and steel industry

JEL Classification: L13, L72, D43, Q40, Q53

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Introduction

In a view of switching from a linear to a circular economy, recycling plays a fundamental role. Beyond the interesting issue dealing with how recycling interfere the traditional take-make-dispose economy, our purpose focuses on the upstream extraction stage. As recycling yields a substitute to the virgin resource, prior extraction is potentially the source of later competition between the sectors of extraction and recycling. In this perspective, the mining firms have the advantage to determine both what remains to be extracted and what could be recycled in the next period. The magnitude of this future competition relies on few factors such as the marginal cost of the mining and the recycling firms, the level of intrinsic competition in the primary and secondary sectors, the level of purity reached by the recycled material which rises the possibility of substitution between the both primary and secondary materials, and the time delay between primary production and recycling.

In the non abundant literature about the influence of recycling over a non competitive primary sector , Grant (1999) refered it as the ≪recycling problem ≫and stated that ≪the market power of the dominant firm will continually erode as the amount of material available for recycling increases over time ≫. But this economic literature began a while ago with the famous Alcoa antitrust case [1]. In 1945, Alcoa was found in a monopolistic position with around 90% of the market share, in violation with the Sherman Antitrust Act. To support its decision, the US Justice Department disregarded the recycling sector from the relevant market, by arguing this was also controlled by Alcoa's strategic behavior. In the economic literature, the issue reffers to, whether or not, the pro-competitive effect of the recycling sector will be sufficient enough to achieve a Pareto optimal result. If the competitive supply of secondary aluminum inexorably drives the price toward the competitive level, the court was wrong in its finding. Gaskins (1974) was the first to work on the price effect and indicated that the existence of the secondhand market makes things worse in the short run and that the dominance of the virgin producer in the long run, relies on the steady rate of the demand growth. Since product demand was increasing over time, he concluded that Alcoa would have considerable market power in the long run.[2]. Martin (1982) considered various forms of vertical integration by the monopolist.

[1] See e.g. Gaskins (1974), Swan (1980), Martin (1982) and Suslow (1986).

[2] His empirical findings show that the initial price practiced by the monopoly with a recycling sector is 6% higher than without the recycling and 3.5 times higher than the competitive price. In the long run, the price is estimated 14% lower with the recycling sector but sill 2.8 times higher than the competitive level. The simulation also indicates that the secondary sector entails a progressive decrease of the price, but 100 years would be necessary to see long run equilibrium value reduced by 5%.

His results confirmed the Judge Hand's decision, since ≪long run price will be strictly greater than the marginal cost of ingot virgin production, as long as any depreciation occurs in scrap recovery or any shrinkage occurs in secondary ingot production ≫. From this, Martin inferred that any improvement in the technology of scrap recovery or scrap conversion will lower monopoly rents and that any leakage of scrap into export markets will raise monopoly rents and lower industry output. More recently, Gaudet and Van Long (2003) dropped the assumption of a competitive market structure in the secondary sector. They confirmed the reducing steady-state output and profit of the sole virgin producer though. They also showed that the market power of the primary producer measured by the Lerner Index is a decreasing function of the time delay between primary production and recycling when the marginal cost of the primary producers is increasing.

While most of the papers took a monopoly in the primary production, here we only focus on an oligopolistic supply of primary materials facing a competitive recycling sector. Our paper aims at seeing how a recycling competitive sector affects a mining oligopoly output, its market power and the potential strategies that can be undertaken by the oligopolistic firms. As far as we know about minerals supplying and as Wan and Boyce (2014) show in their paper, the market structure in the extraction of non renewable resources is quite concentrated like for platinum, diamond or in the iron ore seaborne market. Despite several antitrust regulations in the Unites States and European Union, mineral world markets are systematically subject to cartelisation or controlled by only few companies, because of the large scale of these markets and the need to cover important fixed costs (Kesler and Simon (2015)). Unlike in the Alcoa case where the monopoly is vertically integrated (i.e. merger of extraction and melting activities), here we modelize the competition holding between the mining oligopoly and the recyclers based on the iron and steel sector where three firms hold more than 70% of the market share in the iron ore seaborne market. As the following Figure 1 shows, both the mining firms and recyclers are willing to provide steel producers with inputs. The steelmaking industry is horizontally integrated so that the firms can produce steel either with iron ore through the so-called ≪oxygen route ≫, or with steel scrap through the ≪electric route ≫.

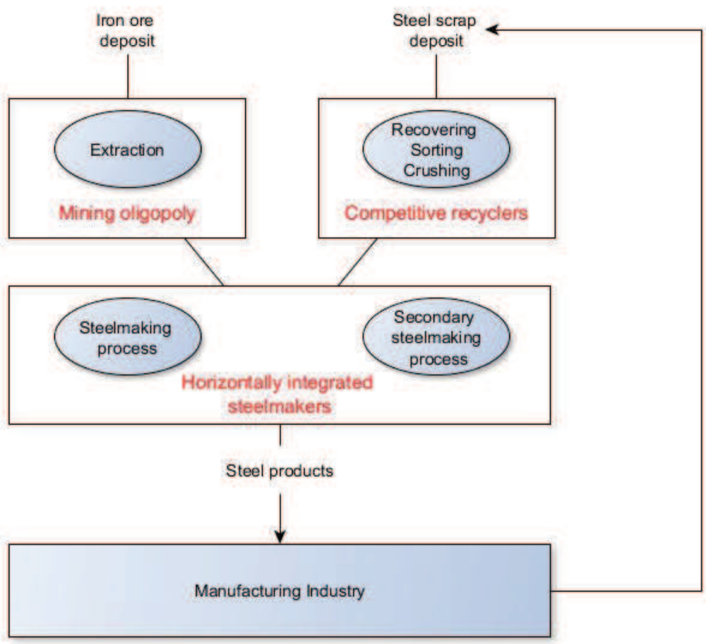

Figure 1: **The market structure of the iron and steel industry**

This context also highlights the market power hold by the mining firms towards the steelmaking industry, that can indirectly be applied to face the future competition from the recyclers. Indeed, since the recycling loop makes the mining firms also suppliers to their competitors, we might face here an «extreme»foreclosure case. Unlike the literature that links vertical integration and market foreclosures (see *e.g.* Hart and Tirole (1990), Gaudet and Van Long (1996), Reisinger and Tarantino (2015)), here the oligopolistic firms are not vertically integrated. Yet, they can limit the secondary sector to supply the steelmaking industry. Likewise, the downstream foreclosure here is not even caused by a potential contractual arrangement which would aim at rising the cost of recycling, but directly related to the potential reduced primary production.

We assume in our whole analysis that the both virgin and secondary materials are perfectly substituables. The oligopoly determines its output simultaneously through a *à la Cournot* model. Besides, since its output determines the quantities recycled in the next period, we consider that the oligopoly has a temporal and informational advantage over the recyclers. In our model, it makes them leader against the secondary producers which are the followers. In this context, our analysis shows how much the followers can affect the leader position in terms of reducing output and market power.

Quelques elements de conclusion...

The first section aims at showing how the output is affected by the presence of a secondary production. In the second section we dwell on the effect over the oligopoly's market power while our third section deals with the strategies that can come out from the oligopoly in response to the competition of the recycling sector.

1 The model

In our leader follower model [3], we assume that the n leader firms $i, j, (...)$ are symetrics with the same size and the same cost structure. They sell ore to the steelmaking industry while the secondary material processing lead to what we consider as an ore (and steel) equivalent. Indeed, the oligopoly competes with recyclers that collect and transform scrap to make a secondary material. We define a recycling function $r(z)$, where z is the recycling cost per unit of scrap (Swan (1980)). $0 < r(z) < 1$ shows that scrap recovery can never be greater than scrap stock and also illustrates a phenomenon of depreciation (*i.e.* leaks of materials) observed in the recycling process. We also consider a parameter θ representing the proportion of scrap that is available for recycling in the next period. So we have $0 < \theta < 1$ and $(1 - \theta)$ shows that a proportion of iron and steel is definetly lost or hold in products for a too long period to be recycled. The inverse demand function is linear and given by $p(Q_t) = 1 - Q_t$ where $Q_t = Q_t^Y + r(z_t)\theta Q_{t-1}$ showing that the whole production of materials, or ≪inputs≫for the steelmaking industry, is the result of a virgin production in t and a proportion of the production in $t-1$. Besides, as $Q_t^Y = \sum_{i=1}^{n} q_t^i$, we have $Q_t = q_t^i + Q_t^{Y-i} + r(z_t)\theta Q_{t-1}$.

1.1 The recycling sector

The profit function of the secondary sector is :

$$\Pi_t^S = (p_t r(z_t) - z_t)\bar{q} \tag{1}$$

where $\bar{q}$ is the stock of scrap available for recyclers and equal to θQ_{t-1}.
The FOC is therefore:

$$\Pi_t^{S'} = p_t r'(z_t) - 1 = 0 \Leftrightarrow r'(z_t) = \frac{1}{p_t}$$

Like Swan (1980) and Martin (1982), we assume $r(z)$ as concave such as $r(0) = 0$,

[3] The mining firms choose their optimal output by considering the existence of a competitive secondary supply as given. Hence, they face a residual demand which results from the total demand reduced by the secondary supply. Thereafter, the competitive recyclers equate their marginal cost to the given price.

$r'(z) > 0$ and $r''(z) < 0$. The diminishing returns reflect the increasing difficulty to recycle despite of higher expenses per ton of scrap. Like the mining firms, the recyclers focus first on the easiest and cheapest deposits.
We assume now $r(z_t) = 1 - e^{-kz_t}$(Swan (1980)) with the exogenous parameter k measuring the efficiency of the recycling technology. This functionnal form of $r(z)$ allows us to find the optimal solution $\hat{z}_t = \frac{lnk+lnp_t}{k}$ verifying $\Pi_t^{S'} = 0$.
With $\hat{z}$, we also infer the following optimal level of recycling :

$$r(\hat{z}_t) = 1 - \frac{1}{k(1 - Q_t)} \tag{2}$$

To allow recyclers to enter the market (*i.e.* $r(z_t) > 0$), the technology of recycling has to reach the threshold $\tilde{k} = \frac{1}{1-Q_t}$ which relies on the level of output before the arrival of recycling, so the threshold becomes $\tilde{k} = \frac{1}{1-Q_t^Y}$.It means that in addition to determine what is going to be recycled in the next period, the level of mining output is also a determinant to the minimum level of technology needed for recyclers to enter the market. For instance, assuming a very little proportion of scrap that is available for recylers (*i.e.* the parameter θ is closed to 0), we can fairly consider that the non cooperative mining firms do not take into consideration the existence of recycling in the profit maximisation. Therefore, the traditionnal output equilibrium at steady state is $Q^{O*} = \frac{n-c}{n+1}$. It implies the following technologic threshold:

$$\tilde{k} = \frac{n+1}{1+c} \tag{3}$$

This threshold $\tilde{k}$ grows with the number of firms in the oligopoly and decreases with a high marginal cost for the mining activity. A necessary level of technology but not enough though to ensure recyclers to compete with the virgin producers since θ is closed to 0.
Assuming now a greater θ which ensures that recyclers can benefit from a significant scrap deposit, we consider that the firms of the oligopoly take into account the future competition to fullfill the demand. We determine the new mining output equilibrium that still results from a Cournot competition holding between the n firms from the oligopoly. Considering the same cost structure, the intertemporal and simpliest profit function of firm i is:

$$\Pi^i = \sum_{\tau=0}^{\infty} \delta^{t+\tau}(1 - Q_{t+\tau} - c)q^i_{t+\tau} \tag{4}$$

with the rate of depreciation $\delta = \frac{1}{1+r}$. From the FOC and by aggregating the n firms from the oligopoly, we have:

$$Q_t^Y = n - nQ_t^Y - n\theta Q_{t-1} - nc - \sum_{\tau=1}^{T}(\delta\theta)^\tau Q_{t+\tau}^Y \tag{5}$$

At steady state, the equilibrium becomes:

$$Q^{Y*} = (n - nc)(1 + \frac{n}{1-\theta} + \frac{\delta\theta}{1-\delta\theta})^{-1} \tag{6}$$

This results with a new threshold of k:

$$\tilde{k} = \frac{1 + \frac{n-c}{1-\theta} + \frac{\delta\theta}{1-\delta\theta}}{1 + \frac{n\theta}{1-\theta} + \frac{\delta\theta}{1-\delta\theta} + \frac{c}{1-\theta}} \tag{7}$$

It confirms our previous results $\frac{\partial\tilde{k}}{\partial n} > 0$ and $\frac{\partial\tilde{k}}{\partial c} < 0$, and with $\frac{\partial\tilde{k}}{\partial\theta} < 0$, we also deduce the advantage for recyclers of a high θ. Indeed, we assume it allows them to benefit from a large deposit and no longer only rely on a strong efficiency of the recycling technology.

Proposition 1:*There is a minimum level of recycling efficiency (i.e. a technologic threshold) that allows recyclers to enter the market and compete with the virgin producers. This threshold increases with the number of firms in the oligopoly, and decreases with the marginal cost of the mining activity and with scrap availability.*

Besides, the form of $r(z)$ shows the cyclicity of the recycling activity since it is an increasing function of the price. It also implies that for any t, we have $\frac{\partial r(z_t)}{\partial Q_t} < 0$. This reflects that for instance, a rise of Q_t generates a negative effect on $r(z_t)$, which would tend to 0. Since the recycling sector is competitive, the recyclers are price takers and respond to a decreasing price by restraining their expenses to recycle z, hence the proportion to recycle $r(z)$.

1.2 The effect on the mining output

We assume now that a sufficient level of recycling efficiency is reached. It allows the recylers to enter the market with $r(z) > 0$, and we can focus on the effect on the oligopoly's output.

In the virgin sector, the intertemporal profit function of the firm i is:

$$\Pi^i = [(1-Q_t)q_t^i - cq_t^i] + \sum_{\tau=1}^{\infty} \delta^\tau (1-Q_{t+\tau})q_{t+\tau}^i - cq_{t+\tau}^i \tag{8}$$

with $Q_t = Q_t^{Y-i} + q_t^i + \theta r(z_t)Q_{t-1}$. This implies the following FOC (*see Appendix A*):

$$1 - Q_t^{Y-i} - 2q_t^i - \theta Q_{t-1}q_t^i \frac{\partial r(z_t)}{\partial Q_t} - \theta Q_{t-1}r(z_t) - c - \sum_{\tau=1}^{\infty} \delta^\tau q_{t+\tau}^i \frac{\partial Q_{t+\tau}}{\partial Q_t} = 0$$

From which we can aggregate with n firms:

$$1 + \theta Q_{t-1}\frac{\partial r(z_t)}{\partial Q_t} Q_t^Y = n - nQ_t^Y - n\theta Q_{t-1}r(z_t) - nc - \sum_{\tau=1}^{\infty} \delta^\tau Q_{t+\tau}^Y \frac{\partial Q_{t+\tau}}{\partial Q_t} \tag{9}$$

If we take $r(z_t) = 1$ like we implicitly supposed in the first section, the above equation is, as we expected, equals to (5).

At steady state, we have:

$$Q_t = Q^*$$

$$z_t = z^*$$

$$\frac{\partial r(z_t)}{\partial Q_t} = d^*$$

$$\frac{\partial Q_{t+\tau}}{\partial Q_t} = e_\tau$$

Hence, the production of the recycling sector becomes $r(z^*) = 1 - \frac{1}{k(1-Q^*)}$, and this implies (*see Appendix B for (10) and (11)*):

$$(n + 1 + d^*\theta Q^* + \sum_{\tau=1}^{\infty} \delta^\tau e_\tau)Q^{*Y} = n(1 - \frac{\theta Q^*(k(1-Q^*)-1)}{k(1-Q^*)} - c) \tag{10}$$

where

$$d^* = \frac{\partial r(z^*)}{\partial Q} = -\frac{1}{k(1-Q^*)^2} < 0$$

And

$$e_\tau = (A(Q^*))^\tau$$

Since

$$A(Q^*) = 0 < \frac{\theta r(z^*)}{1 - d^* \times \theta Q^*} < 1$$

we also have:

$$0 < (\frac{\theta r(z^*)}{1 - d^* \times \theta Q^*})^\tau < 1 \Longleftrightarrow 0 < e_\tau < 1 \tag{11}$$

From (11), we can see that except in a closed-loop system (*i.e.* both θ and $r(z^*)$ equal to 1), where the effect of a potential rise of the total output will become constant and equal to 1, higher is τ, lower will be e_τ. The effect of a potential rise of the total output in t is decreasing over time with what we can fairly suppose the depreciation effect (i.e. $0 < r(z^*) < 1$).

Although the explicit form of Q^{Y*} cannot be found here, by using (10) we observe that $(d^*\theta Q^* + \sum_{\tau=1}^{\infty} \delta^\tau e_\tau)$ is close to 0 and $0 < 1 - \frac{\theta Q^*(k(1-Q^*)-1)}{k(1-Q^*)} < 1$.Hence, considering the mining output equilibrium when the firms do not take into consideration the recycling sector being $Q^{O*} = \frac{n-c}{n+1}$, we have $Q^{Y*} < Q^{O*}$.

Proposition 2: *Like expected, the output equilibrium of the oligopoly is lower when the firms take into consideration the presence of recycling.*

This confirms what is intuitively perceptible since the firms face a residual demand whose the other part is fullfilled by the recycling sector.

Using the mining output equilibrium, we also can deduce whether the secondary production tends to more erode a monopoly's virgin production or the oligopoly's. Hence, we have:

$$\frac{\partial Q^{Y*}}{\partial n} > 0 \tag{12}$$

Proposition 3: *Like a situation without recycling and as we expect, the mining output rises with the number of firms, so that recycling better erodes the output of a monopoly than the oligopoly's.*

To face the recyclers, it seems that the whole mining activity should be more competitive. Through the induced decreasing price this would tend to reduce $r(z)$, and it would also imply for recyclers a higher threshold to enter the market. However, even though collectively a rise of n appears to be positive, individually the firms might loose a part of their rent and most of all, a better mining output gives a better stock of scrap to the recyclers in the next periods, hence, a better secondary supply to the detriment of the miners. Therefore, the firms of the oligopoly seem to be encouraged to reduce their output in order to limit the future competition with the recyclers and to prevent the new mining entrants in the market, like it occurs in a situation with a monopoly.

From now that we have observed the behavior of the steady state output of the oligopoly with the presence of recycling, we can have a look on the effect of few varying parameters:

$$\frac{\partial Q^{Y*}}{\partial \theta} < 0$$

With the same quantity of iron and steel products entering the market, a modification of θ implies a modification of the proportion of these products that go to scrap. For instance, a public policy which aims at fostering a longer product life, might unexpectidly be beneficial to the mining oligopoly by increasing the virgin output.

$$\frac{\partial Q^{Y*}}{\partial k} < 0$$

A better efficiency of the recycling process rises $r(\hat{z})$ and therefore lead to a decrease of the mining output. Like we show in the previous section about the recycling sector, no matter the fact that for a certain level of technology, the expenses per unit of scrap decrease or increase, the recycling level $r(\hat{z})$ becomes greater with a rising k.

$$\frac{\partial Q^{Y*}}{\partial \hat{z}} < 0$$

As expected, if the recyclers rise the expenses per unit of scrap, it implies a decrease of the mining output, because of the induced rising $r(\hat{z})$. Nonetheless, the effect on the mining oligopoly varies according to the level of recycling technology, hence, the weight of the outlays to rise recycling.

$$\frac{\partial Q^{Y*}}{\partial c} < 0$$

If this result stands to reason, here we highlight the possibility of a rising marginal cost that might arises with the depletion of the deposit and/or a lower ore quality.

Proposition 4: *A more efficient recycling technology and a better availability of scrap push the supply from the secondary production up, to the detriment of the oligopoly which cannot influence on these exegeneous factors.*

Now that we have observed the recycling sector and the effect on the mining output, we focus our analysis on the equilibrium price that results from both the primary and secondary sectors.

1.3 The equilibrium price

Since we defined the recycling function as $r(z_t) = 1 - \frac{1}{kp_t}$, we infer the following secondary supply in t:

$$S_t = \theta(1 - \frac{1}{kp_t})Q_{t-1} \tag{13}$$

That we can compare with the secondary demand:

$$\theta(1 - \frac{1}{kp_t})Q_{t-1} = 1 - p_t - Q_t^Y$$

This results with the following equilibrium price at steady state, with which we deduce the effect of the parameters θ and k on the price:

$$p^* = \frac{1 - Q^{Y*}(1-\theta)}{1 + k\theta Q^{Y*}} \tag{14}$$

Proposition 5: *At steady state, a more efficient recycling technology and a better availability of scrap tend to push the price of the output down, to the benefit of the downstream sector.*

Remark 1: By using the mining output expressed in (10) where with the implicit form of Q^{Y*} we find the implicit form of the equilibrium price:

$$p^* = \frac{\theta Q^*}{k[\theta Q^* - 1 + \frac{(n+1+d^*+\theta Q^*+\sum_{\tau=1}^{\infty}\delta^\tau e_\tau)Q^{*Y}}{n}]} \tag{15}$$

we confirm that $\frac{\partial p^*}{\partial k} < 0$, like in the above equation (14).
Before going into the potential strategies that might occur between the cooperative firms, we dwell on the effect of recycling on the market power of the oligopoly, through the analysis with the Lerner index.

2 The effect on the market power

In order to measure the market power of the oligopoly, we use the conventional Lerner index, which is the ratio of marginal markup $(p - c)$ to price p:

$$L = \frac{p - c}{p}$$

Here we aim at seeing how the recycling sector affect the market power of the oligopoly. In the absence of this secondary industry, the economic litterature gives the following market power (e.g. Cowling and Waterson (1976)) :

$$L = \frac{p - c}{p} = \alpha^i \frac{1}{n\eta}$$

where n is the number of firms, $\alpha^i = \frac{q^i}{Q}$ represents the market share of the firm i and $\eta(Q) = \frac{-p(Q)}{Qp'(Q)}$ is considered as the price elasticity of demand.
We now focus on the recycling sector embodied by $r(z) > 0$, and, as we know that at the steady state $\sum_{i=1}^{n} q_{i*} = Q^{Y*}$, we have $Q^{Y*} \neq Q^*$ and we can fairly assume:

$$L^{Q^{Y*}} = \frac{p(Q^*) - c(Q^{Y*})}{p(Q^*)} = (\frac{Q^{Y*}}{Q^*})\frac{1}{n\eta(Q^*)} \tag{16}$$

This contrasts with the Lerner measure of market power without recycling (i.e. $r(z) = 0$), where $Q^{Y*} = Q^* \equiv Q^{O*}$:

$$L^{Q^{O*}} = \frac{p(Q^{O*}) - c(Q^{O*})}{p(Q^{O*})} = \frac{1}{n\eta(Q^{O*})} \tag{17}$$

Before going into the effect of recycling on the market power, we need to dwell on the relationship between Q^{O*}, the steady-state output of the oligopoly without recycling, and Q^*, the steady-state output of the total industry in the presence of the recycling sector. For this, we base our demonstration on what has been done by Gaudet and Van Long (2003) with a monopoly. Suppose $Q^{O*} > Q^*$, hence, we note that $p(Q^*) > p(Q^{O*})$. Since it follows from $p'(Q) < 0$ that $\eta'(Q) < 0$ for all $Q > 0$, we have:

$$\frac{p(Q^*) - c(Q^{Y*})}{p(Q^*)} < \frac{p(Q^{O*}) - c(Q^{O*})}{p(Q^{O*})}$$

and

$$\frac{c(Q^{Y*})}{c(Q^{O*})} > \frac{p(Q^*)}{p(Q^{O*})} > 1 \tag{18}$$

Assuming $C'' \geq 0$, and like Gaudet and Van Long (2003) showed in their paper, here there is a contradiction and since (13) cannot hold, we draw the conclusion that $Q^{O*} \leq Q^*$.
Remark: The steady state output of the total industry in the presence of a recycling sector is greater or equal to the steady state output of the oligopoly without recycling. Since it follows from what we already showed that $Q^{Y*} < Q^{O*}$ with the presence of recycling (i.e. $r(z)\bar{q} > 0$), we have $Q^{Y*} < Q^{O*} \leq Q^*$.

Since recycling increases the materials supply and more than offsets the decreasing output of the oligopoly, with a constant demand the price tends to be pushed down, although we cannot conclude that it will reach its competitive level.
By now we shall see under which conditions, recycling tends to lower, or not, the market power of the oligopoly, and potentially, pushes the price to its competitive level. First, with $Q^{O*} \leq Q^*$, we have $p(Q^*) \leq p(Q^{O*})$ and since $\eta(Q^*) \leq \eta(Q^{O*})$, we deduce $\frac{1}{\eta(Q^*)} \geq \frac{1}{\eta(Q^{O*})}$.
Hence, if we assume a situation where $k \to \frac{1}{p}$, we have $r(z^*) \to 0^+$, and since $\frac{Q^{Y*}}{Q^*} \to 1^-$, we still have:

$$\frac{Q^{Y*}}{Q^*}\frac{1}{\eta(Q^*)} \geq \frac{1}{\eta(Q^{O*})} \equiv L^{Q^{Y*}} \geq L^{Q^{O*}} \tag{19}$$

With a very little proportion of recycling, the market power of the oligopoly is greater than without recycling.
Assuming the opposite case where $k \to +\infty$ and we have $r(z^*) \to 1^-$, the ratio $\frac{Q^{Y*}}{Q^*}$ tend to 0 and the Lerner index would become lower, such as:

$$\frac{Q^{Y*}}{Q^*}\frac{1}{\eta(Q^*)} \leq \frac{1}{\eta(Q^{O*})} \equiv L^{Q^{Y*}} \leq L^{Q^{O*}} \tag{20}$$

Hence, the level of recycling determines whether or not, the oligopoly maintains its rent.

Proposition 6: *While in the short run we expect a greater market power of the oligopoly with the arrival of recycling, the rise of the secondary production lowers this market power until pushing it to around* 0*, if the recycling loop tends to be closed.*

Remark 1: This proposition fits with what Martin (1982) concluded about the maintained rent of the monopoly as long as depreciation occurs. Alike, this unavoidable phenomenon in the recycling process is also the reason why the price cannot reach its competitive level.

Remark 2: The first statement giving a greater market power seems to be a short term result when the firms strategically restraint their output in order to prevent the future competition with the recyclers, like it has been explained by Gaskins (1974) or Martin (1982) in their respective paper about the Alcoa case with a monopoly, and Tirole (1988) in his textbook.

In the short run, this more than offsets the future competition price holding on the market with the arrival of recycling. A decreasing of the market power only occurs with a better recycling that we can fairly expect in the long run if the proportion of available scrap rises or with a better recycling technology. Hence, in the long run, the steelmaking industry would benefit from the existence of recycling.

Also, here we draw attention to the role of the parameter k. Indeed, (16) and (17) show through the ratio $\frac{Q^{Y*}}{Q^*}$ that there is a minimum market share of the oligopoly which ensures a maintaining rent compared to a situation where there is no recycling (*i.e.* $L^{Q^{Y*}} = L^{Q^{O*}}$). Therefore, it implies the presence of a recycling threshold $\bar{r}(z)$ leading to $L^{Q^{Y*}} = L^{Q^{O*}}$. Hence, we assume a minimal $\bar{k}$ under which recycling allows the oligopoly to maintain its market power. With (10), we have:

$$\frac{n(1 - \theta Q^* + \frac{\theta Q^*}{\bar{k}(1-Q^*)}) - c}{(n + 1 + d^*\theta Q^* + \sum_{\tau=1}^{\infty} \delta^\tau e_\tau)} = \frac{Q^*\eta(Q^*)}{\eta(Q^{O*})}$$

$$\bar{k} = \frac{n\eta(Q^{O*})\theta Q^*}{[Q^*\eta(Q^*)(n + 1 + d^*\theta Q^* + \sum_{\tau=1}^{\infty} \delta^\tau e_\tau) + n\eta(Q^O)(c + \theta Q^* - 1)](1 - Q^*)} \qquad (21)$$

This implicit form of $\bar{k}$ allows us to deduce few messages though. Like we show with the entering threshold $\tilde{k}$, here the value of $\bar{k}$ which equals the both market power with and without recycling, moves with the following exogeneous parameters.

First, we assume $\frac{\partial \bar{k}}{\partial n} > 0$. Since a rise in the number of oligopolistic firms logically pushes the market power down, the minimum level of recycling efficiency also has to rise because the intial market power of the oligopoly will be lower with the higher number of firms. In other words, more competitive is the primary sector, higher has to be the recycling efficiency to push the market power to the competitive level.

Second, as we might expect $\frac{\partial \bar{k}}{\partial c} < 0$. To face a potential decreasing marginal cost in the primary production, the efficiency of recycling has to rise in order to offset the induced greater market power.

Finally, we assume $\frac{\partial \bar{k}}{\partial \theta} < 0$. Considering a higher proportion of scrap available for recylers through a greater θ, we deduce a lower value of $\bar{k}$ needed to imply a decrease of the market power.

Proposition 7: *The threshold $\bar{k}$ above which the recycling sector makes the market power lower than a situation without recycling, rises with the number of firms of the oligopoly, decreases with the marginal cost of the primary sector and with the proportion of available scrap.*

Since the literature about the effect of recycling over a non competitive market structure focused on a mining monopoly, there was no need to look at the competition within the mining sector, unlike in our paper where we assume two competiting firms.

3 Discussion about strategies

First of all, since in realistic conditions the mining output is considered as homogeneous, a product differenciation strategy does not seem to be possible in our case. Second, we do not take into account a potential pricing strategy *à la Bertand* in our analyses because of the low price elasticity of ore supply that is related to the mining activity in general. Indeed, the firms cannot easily adjust their production capacities that would result from a decreasing price strategy and the induced rising demand. Hence, we consider the quantities as the most appropriate variable to set up a strategy, also for the reason that they can control what remains in the deposit [4] and most of all, what is going to be recycled in the next periods . This shows the ability for each miner to set a part of the production capacities of their common competitors: the recyclers. Assuming high production capacities, a strategy which consists in rising the mining output would be efficient only with a high fixed cost for the recycling sector, that we do not take into account in our paper. In this case though, the firms are incited to rise their output until pushing the price down enough to prevent the entry of recyclers. In addition, since we showed $\frac{\partial Q^{Y*}}{\partial n} > 0$ and in order to prevent the future competition, it seems that the firms are encouraged to decrease their ouptut. In the short run, a such strategy rises their market power and limits the supply of the recyclers in the long run. We consider it as an extreme downstream foreclosure strategy since the oligopolistic firms do not need to undertake a vertical integration or set up a contractual arrangement with the downstream sector. That said, we might wonder how a decreasing output strategy

[4]Though we assume an infinite ore deposit.

occurs between the mining firms and if this can be maintained in a longer term. For instance, it stands to reason that in a traditionnal oligopoly, the firms are encouraged to cooperate in order to decrease their output and benefit from the induced rising price [5]. Here with the presence of recycling, even with a lower mining output, the non cooperative firms will not benefit from a rising price since the demand is also fullfilled by recyclers (*i.e.* $p(Q^*) \leq p(Q^{O*})$). The rent is eroded and the firms aim now at limiting this erosion by taking into account the existence of recycling. In our leader follower model, the miners take their decision before the recyclers but in a simultaneous way. A decision to reduce the output and anticipate the entry of recyclers would not benefit to the first moving firm, unless it knows that the other firm does it too. Since the unilateral move is unexpected at any time, a cooperation might arises and seem to be the best solution for the mining firms. Nevertheless, a such cooperation they might be involved in, better looks like to a ≪defensive cooperation ≫to limit the future competition with recyclers and the potential entry of new miners, than a traditional improving profit looking.

The question we might have in mind is in which extent the firms would be motivated to stop the strategy, and logically put an end to the cooperation. Even though such a move would benefit to the first that stop, this will be followed by the mining competitors for the next period. Hence, this ending cooperation benefits to the recyclers. However, even if the oligopoly will still benefit of a market power as long as depreciation occurs, as we showed an improving recycling technology erodes the leaders position. In longer term it seems that they are only able to contain the erosion of their dominant position. This longer term perspective might lead to an end of the cooperation and each one of the firms could undertake an integration strategy. Either an horizontal integration over the recycling activity strengthens their position in the upstream industrial process, or considering a vertical integration over the steelmaking industry would also allow them to expand the potential of foreclosure strategies (*e.g.* making steel products more complex in term of resource composition, in order to rise the recycling marginal cost.).

Conclusion

As far as we know, the literature on the effect of recycling over the mining sector only focused on a monopoly, while most of the market structures in this sector seem to be

[5] Especially with a low price elasticity of demand which is the case in most of raw marerials market

oligopolistics. Therefore, this paper takes a symetric oligopoly as the main assumption to form a simple model and see the effect of recycling over the mining output, its market power and the potential strategies that arise with that kind of market structure. As we might expect, the main conclusion confirms the results drawn from the monopoly case and the related Alcoa literature. Since a part of the demand is captured by the secondary production, the mining firms face a residual demand once the recyclers enter the market. To do so, by focusing on the recycling activity we show that a minimum level of recycling efficiency is needed and can be more or less high according to the number of firms on the primary market and the marginal cost of the miners. Likewise, a second technologic threshold is needed to lower the oligopolistic market power comparing to a situation without recycling. This threshold also rises with the number of mining firms and decreases with the marginal cost of the oligopoly and the proportion of available scrap.

While without recycling a lower output results to a rising price, here it is not the case since the demand is also fullfilled by the recyclers, so that the firms are encouraged to cooperate to decrease their output. This is also motivated by the fact that the mining output rises with the number of firms. Like it has been illustrated in the literature about the monopoly, such a strategy rises the market power of the oligopoly in the short run and limit the future competition. However, it seems that this extreme foreclosure strategy cannot stand with a more efficient recycling technology. Hence, the initial leader position of the mining firms is in the long run challenged by the entry of recycling, with the (high) assumptions of a constant demand and a perfect substitution between the primary and secondary output. Hence, on the one hand the firms might consider a potential horizontal integration towards the recycling activity. In addition to strengthen their position in the upstream industrial process, this would represent a good way to step forward to the so-called circular economy. On the other hand, a vertical integration appears to be an other option in order to set up a foreclosure strategy.

References

Cowling, K. and Waterson, M. (1976). Price-costs margins and market structure. *Economica*, 43(267-274).

Gaskins, D. W. (1974). Alcoa revisited: The welfare implications of a secondhand market. *Journal of Economic Theory*, 7(254-271).

Gaudet, G. and Van Long, N. (1996). Vertical integration, foreclosure and profits in the presence of double marginalisation. *Journal of Economics and Management Strategy*, 5(409-432).

Gaudet, G. and Van Long, N. (2003). Recycling redux: A Nash-Cournot approach. *The Japanese Economic Review*, 54(409-419).

Grant, D. (1999). Recycling and market power: A more general model and re-evaluation of the evidence. *International Journal of Industrial Organization*, 17(59-80).

Hart, O. and Tirole, J. (1990). Vertical integration and market foreclosure. *Washington: Brookings Institution*, (205-286).

Kesler, S. E. and Simon, A. C. (2015). Mineral resources, economics and the environment.

Martin, R. E. (1982). Monopoly power and the recycling of raw materials. *The Journal of Industrial Economics*, 30(405-419).

Reisinger, M. and Tarantino, E. (2015). Vertical integration, foreclosure and productive efficiency. *The RAND Journal of Economics*, 46(461-479).

Suslow, V. Y. (1986). Estimating monopoly behavior with competitive recycling: An application to alcoa. *The RAND Journal of Economics*, 17(389-403).

Swan, P. L. (1980). The influence of recycling on monopoly power. *Journal of Political Economy*, 88(76-99).

Tirole, J. (1988). The theory of industrial organization. *Economica*, (155-157).

Wan, R. and Boyce, J. R. (2014). Non renewable resource Stackelberg games. *Resource and Energy Economics*, 37(102-121).

Appendix A: The general case

The FOC of $\frac{\partial \Pi^i}{\partial q^i}$ under the case where the output of the recycling sector is defined as $r(z_t)\theta Q_{t-1}$, is:

$$\begin{aligned}
\frac{\partial}{\partial q_t^i}\left((1-Q_t)q_t^i - cq_t^i\right) &= \frac{\partial}{\partial q_t^i}\left[\left(1-Q_t^{Y,-i} - q_t^i - \theta r(z_t)Q_{t-1}\right)q_t^i - cq_t^i\right] \\
&= (1-Q_t^{Y,-i}) - 2q_t^i - \theta Q_{t-1}q_t^i\frac{\partial r(z_t)}{\partial q_t^i} - \theta Q_{t-1}r(z_t) - c \\
&= (1-Q_t^{Y,-i}) - 2q_t^i - \theta Q_{t-1}q_t^i\frac{\partial r(z_t)}{\partial Q_t} \times \frac{\partial Q_t}{\partial q_t^i} - \theta Q_{t-1}r(z_t) - c \\
&= (1-Q_t^{Y,-i}) - 2q_t^i - \theta Q_{t-1}q_t^i\frac{\partial r(z_t)}{\partial Q_t} - \theta Q_{t-1}r(z_t) - c.
\end{aligned}$$

And

$$\begin{aligned}
\frac{\partial}{\partial q_t^i}\sum_{\tau=1}^{\infty}\delta^\tau(1-Q_{t+\tau})q_{t+\tau}^i - c(q_{t+\tau}^i) &= -\sum_{\tau=1}^{\infty}\delta^\tau q_{t+\tau}^i\frac{Q_{t+\tau}}{q_t^i} \\
&= -\sum_{\tau=1}^{\infty}\delta^\tau q_{t+\tau}^i\frac{\partial Q_{t+\tau}}{\partial Q_t} \times \frac{\partial Q_t}{\partial q_t^i} \\
&= -\sum_{\tau=1}^{\infty}\delta^\tau q_{t+\tau}^i\frac{\partial Q_{t+\tau}}{\partial Q_t}.
\end{aligned}$$

This leads to the following FOC:

$$(1-Q_t^{Y-i} - 2q_t^i - \theta Q_{t-1}q_t^i\frac{\partial r(z_t)}{\partial Q_t} - \theta Q_{t-1}r(z_t) - c - \sum_{\tau=1}^{\infty}\delta^\tau q_{t+\tau}^i\frac{\partial Q_{t+\tau}}{\partial Q_t} = 0 \tag{22}$$

As we know that a part of the total output of the industry in t is back on the market in $t+1$ through the recycling process, we observe that for any $\tau > 0$ we have:

$$\frac{\partial r(z_{t+\tau})}{\partial Q_t} = \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \frac{\partial Q_{t+\tau}}{\partial Q_t}$$

Since we know that $Q_{t+\tau} = Q_{t+\tau}^Y + \theta r(z_{t+\tau})Q_{t+\tau-1}$, this implies:

$$\frac{\partial Q_{t+\tau}}{\partial Q_t} = \theta r(z_{t+\tau})\frac{\partial Q_{t+\tau-1}}{\partial Q_t} + \theta Q_{t+\tau-1}\frac{\partial r(z_{t+\tau})}{\partial Q_t},$$

Hence

$$\begin{aligned}\frac{\partial r(z_{t+\tau})}{\partial Q_t} &= \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \frac{\partial Q_{t+\tau}}{\partial Q_t} \\ &= \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta r(z_{t+\tau}) \frac{\partial Q_{t+\tau-1}}{\partial Q_t} + \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta Q_{t+\tau-1} \frac{\partial r(z_{t+\tau})}{\partial Q_t}.\end{aligned}$$

This implies

$$\left(1 - \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta Q_{t+\tau-1}\right) \frac{\partial r(z_{t+\tau})}{\partial Q_t} = \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta r(z_{t+\tau}) \frac{\partial Q_{t+\tau-1}}{\partial Q_t}.$$

Hence

$$\frac{\partial r(z_{t+\tau})}{\partial Q_t} = \frac{\frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta r(z_{t+\tau})}{1 - \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta Q_{t+\tau-1}} \times \frac{\partial Q_{t+\tau-1}}{\partial Q_t}.$$

And we finally have:

$$\begin{aligned}\frac{\partial Q_{t+\tau}}{\partial Q_t} &= \theta r(z_{t+\tau}) \frac{\partial Q_{t+\tau-1}}{\partial Q_t} + \theta Q_{t+\tau-1} \frac{\partial r(z_{t+\tau})}{\partial Q_t} \\ &= \theta r(z_{t+\tau}) \frac{\partial Q_{t+\tau-1}}{\partial Q_t} + \theta Q_{t+\tau-1} \times \frac{\frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta r(z_{t+\tau})}{1 - \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta Q_{t+\tau-1}} \times \frac{\partial Q_{t+\tau-1}}{\partial Q_t} \\ &= \theta r(z_{t+\tau}) \left(1 + \frac{\frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta Q_{t+\tau-1}}{1 - \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta Q_{t+\tau-1}}\right) \frac{\partial Q_{t+\tau-1}}{\partial Q_t} \\ &= \frac{\theta r(z_{t+\tau})}{1 - \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta Q_{t+\tau-1}} \frac{\partial Q_{t+\tau-1}}{\partial Q_t}.\end{aligned}$$

Remark: The above equation is true for the general case.

Appendix B: At Steady State

At steady state we have for $\tau \geq 1$:

$$\begin{aligned}e_\tau &= \frac{\partial Q_{t+\tau}}{\partial Q_t} \\ &= \frac{\theta r(z_{t+\tau})}{1 - \frac{\partial r(z_{t+\tau})}{\partial Q_{t+\tau}} \times \theta Q_{t+\tau-1}} \frac{\partial Q_{t+\tau-1}}{\partial Q_t} \\ &= \frac{\theta r(z^*)}{1 - d^* \times \theta Q^*} \frac{\partial Q_{t+\tau-1}}{\partial Q_t} \\ &= \frac{\theta r(z^*)}{1 - d^* \times \theta Q^*} e_{\tau-1}.\end{aligned}$$

Observe that when $\tau = 0$, $e_\tau = e_0 = 1$. This implies for any $\tau \geq 1$ we have

$$\begin{aligned} e_\tau &= \frac{\theta r(z^*)}{1 - d^* \times \theta Q^*} e_{\tau-1} \\ &= \left(\frac{\theta r(z^*)}{1 - d^* \times \theta Q^*} \right)^2 e_{\tau-2} \\ &= \cdots \\ &= \left(\frac{\theta r(z^*)}{1 - d^* \times \theta Q^*} \right)^\tau. \end{aligned}$$

Define

$$A(Q^*) = \frac{\theta r(z^*)}{1 - d^* \times \theta Q^*}.$$

We will calculate the formula of A in the case $r(z) = 1 - e^{-kz}$. Since z^* is solution to $r'(z^*) = \frac{1}{1-Q^*}$, we have

$$z^* = \frac{\ln k + \ln Q^*}{k},$$

and

$$r(z^*) = 1 - \frac{1}{k(1 - Q^*)}.$$

This implies

$$d^* = \frac{\partial r(z^*)}{\partial Q} = -\frac{1}{k(1 - Q^*)^2}.$$

We have the formula of $A(Q^*)$

$$A(Q^*) = \frac{\theta \left(1 - \frac{1}{k(1-Q^*)} \right)}{1 + \frac{\theta Q^*}{k(1-Q^*)^2}}.$$

Obviously, we have $0 < A(Q^*) < 1$. We have also for any $\tau > 0$,

$$e_\tau = \left(A(Q^*) \right)^\tau.$$