The effect of recycling over a mining oligopoly

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Abstract

In this paper we apply a leader(s)-followers model to show the effect of a competitive fringe of recyclers over a mining oligopoly. For the mining firms, we point out a trade-off between market share and market power. A more competitive virgin sector reduces the share of the secondary supply but at a cost of a lower market power regarding the downstream industry. Besides, we show the existence of an optimal number of a mining firms that would push recyclers out of the market supply. Regarding the recycling activity, a technology threshold is required to enter the market and a higher one to ensure a lower market power compared to a situation without recycling. Finally, we consider that a public policy aiming at fostering the secondary sector would only be efficient by adressing simultaneously both the efficiency of recycling and the availability of scrap.

Keywords: oligopoly, market power, recycling, raw materials

JEL Classification: L72, D43

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Introduction

In view of switching from a linear to a circular economy, recycling plays a fundamental role. Beyond the interesting issue dealing with how recycling interferes with 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. From this perspective, in addition to a market power exerted on the downstream sector, the mining firm(s) have the advantage to determine both what remains to be extracted and what could be recycled in the next period. The economic issue on the influence of recycling over a non competitive primary sector, 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. Gaskins (1974) was the first to work on the pro-competitive effect of the recycling sector over a monopoly mining firm. If the competitive supply of secondary aluminum inexorably drives the price toward the competitive level, the court was wrong in its findings. He concluded 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. His results confirmed the Judge Hand's decision, since ≪long run price will be strictly greater than the marginal cost of virgin production, as long as any depreciation occurs in scrap recovery ≫. 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. Grant (1999) also stated that ≪the market power of the dominant firm will continually erode as the amount of resources available for recycling

[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%.

increases over time ≫.

Since a monopolistic market structure does not fit with the mining industry anymore, and that the empirical evidences result from a situation before the World War II, the above literature appears to be dated. Most of all, we consider that recycling as one of the most needed economic activity in the following years and decades, for few reasons. First, the energy transition and the digital economy increase the demand in mineral resources and strengthen the need to adress the scarcity issue. Second, the environmental impacts occuring in the mining sector are tremendous in terms of both emissions of pollutants and biodiversity losses for instance. Last but not least, countries with fewer resources can be highly dependant of others sufficiently endowed, so that implementing a secondary secor at home can be positive in terms of balance trade [3], and for local employment. For these three reasons, recycling plays and will play a fundamental role as a part of the so-called circular economy. However, as far as we know, little attention has been paid to this topic in the economic literature. We assume in this paper that recycling is welfare improving though we do not deal with the environmental aspects and the consequences of recycling in terms of resource conservation. Our goal here is to focus on the magnitude of competition between mining and recycling activities. To do so, we look at how recyclers can enter the market and analyse in which extent they can affect the dominant position of a mining oligopoly.

As far as we know for most virgin resources, the rise in demand and in the international trade of commodities throughout the second half of the twentieth century, as well as antitrust regulations and privatisation of state owned mining firms helped the mining sector to gain attractivity and made it moving from a monopoly to a worldwide oligopoly. Nevertheless, the need to cover important fixed costs and the large scale of destination markets make the mining sector controlled by only few companies (Kesler and Simon (2015)). Unlike in the Alcoa case where the monopoly is vertically integrated (i.e. merger of extraction and melting activities within a same firm), here we modelize an upstream competition holding between the mining oligopoly and the competitive recycling sector. As the Figure 1 shows, both the mining firms and recyclers are willing to provide the metallurgy industry with inputs. The latter is horizontally integrated so that the firms

[3] Dussaux and Glachant (2014) showed that a 10% rise in recycling leads to a 2% decrease of raw materials imports

can produce either with virgin input or with secondary ones.

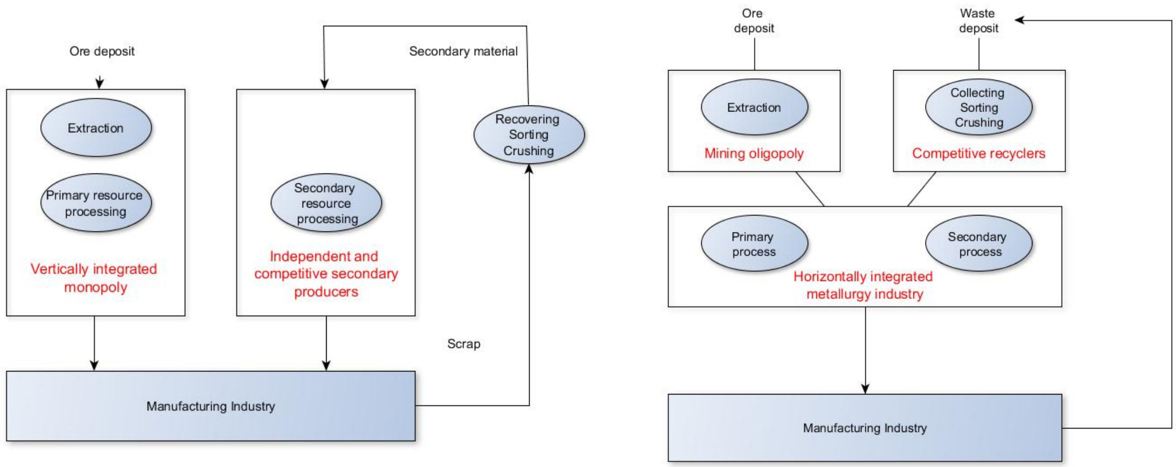

Figure 1: Comparison of the Alcoa case (left) and the current market structure in most of metallic resources sectors (right)

This context also highlights the market power hold by the mining firms towards the downstream industry and the potential effect over the recyclers. Besides, 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, by restraining output they can limit the secondary sector to supply the metallurgy industry. So that the downstream foreclosure here is not caused by a potential contractual arrangement which would aim at raising the cost of recycling, but directly related to the potential reduced primary production. Our paper is divided into the following sections. We first focus on how recyclers can enter the market. In a second secion, we modelize at steady state the competition holding with the mining firm(s) and the effect on the market power. Then, by using different parameter values we apply our model to analyse in which extent recyclers can affect the dominant position of a mining oligopoly (section 3). We finally conclude and discuss with some strategies that can help the mining firms to face this new competition.

1 The recycling sector

We assume in our whole analysis that both primary and secondary resources are perfectly substitutables. 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 [4]. 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 [5]. So we have $0 < \theta < 1$ and $(1 - \theta)$ shows that a proportion of iron and steel is definitely 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 Q^Y (*i.e.* mining output) in t and a secondary production $S_t = r(z_t)\theta Q_{t-1}$. Besides, as $Q_t^Y = \sum_{i=1}^n q_t^i$, we have $Q_t = q_t^i + Q_t^{Y-i} + r(z_t)\theta Q_{t-1}$. Before going through the modelization of the mining profit, we first have to focus on the recycling activity.

(i) How can recyclers enter the market with the presence of a mining oligopoly?

The profit function of the secondary sector is :

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

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

[5] The one time period corresponds theoretically to one life cycle of steel, so that by definition, virgin sales equal total sales minus the secondary supply generated by the previous period's production.

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 $r(0) = 0$, $r'(z) > 0$ and $r''(z) < 0$. The diminishing returns reflect the increasing difficulty to recycle despite of higher expenses per ton of scrap.

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 functional form of $r(z)$ allows us to find the optimal solution which we consider as the marginal cost of recycling $\hat{z}_t = \frac{lnk+lnp_t}{k}$. It verifies that $\Pi_t^{S'} = 0$.

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 very little proportion of scrap is available for recyclers (*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 traditional output equilibrium without recycling at steady state is $Q^{O*} = \frac{n-c}{n+1}$ (*see Appendix A*). 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 to ensure recyclers competing with the virgin producers since θ is closed to 0.

(ii)A room of entry for recyclers: a new competition for the mining firms

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. Through a new mining output equilibrium we first confirm that, like expected, the output is lower when recycling is taken into consideration (*see Appendix B*). Either a monopolistic firm or an oligopoly, the non competitive mining sector has interest to decrease its output in order to prevent the entry of recycling. Therefore, with $Q^{Y*} = (n - nc)(1 + \frac{n}{1-\theta} + \frac{\delta\theta}{1-\delta\theta})^{-1}$, the threshold $\tilde{k}$ becomes:

$$\tilde{k} = \frac{1 + \frac{n-c}{1-\theta} + \frac{\delta\theta}{1-\delta\theta}}{1 + \frac{n\theta}{1-\theta} + \frac{\delta\theta}{1-\delta\theta} + \frac{c}{1-\theta}} \tag{4}$$

It confirms our intuitive previous results that $\frac{\partial\tilde{k}}{\partial n} > 0$ and $\frac{\partial\tilde{k}}{\partial c} < 0$. The negative relationship between scrap availability and the threshold lies in the fact that the expected better supply of recycled materials is anticipated by the mining firms. Hence, they decrease the mining output which gives a rise of the price, and then, a better room of entry for recyclers with low technology. This results stands as long as the mining market structure is non competitive and when the firm(s) can set up a strategy to decrease the virgin output.

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.*

Remark: A situation where $k < \tilde{k}$ means recycling either does not exist, or may exist only at a very marginal level compared to the virgin production. This is the case for resources used in electronic devices such as lithium, silicium or most of the Rare Earth Elements (REE).

Besides, the form of $r(z)$ shows the cyclicity of the recycling activity since it is an increasing function of the price. The optimal level of recycling (i.e. equation (2)) also implies that for any t, we have $\frac{\partial r(z_t)}{\partial Q_t} < 0$. Since the recycling sector is competitive, recyclers are price takers and respond to a decreasing price by restraining their expenses to recycle z. Then, with a constant stock of scrap, we have a lower recycling rate $r(z)$ and lower secondary materials on the market, as it has already been shown in the Alcoa case.

2 Recycling *vs* mining oligopoly

We assume now that a sufficient level of recycling efficiency is reached. It allows the recyclers to enter the market with $0 < r(z) < 1$, and we can focus on the effect on the oligopoly's output [6]. Instead of using the Alcoa case model based on the aluminium market, we take the iron and steel framework. The goal here is threefold. Through our *à la Cournot* model, we first want to observe the effect of recycling over a non cooperative oligopoly instead of a monopoly. This also allows us to shed light on the parameters θ and k related to the magnitude of recycling and that might affect the virgin production. Second, we draw attention on the effect of recycling over the market power of the oligopoly. In a third point, we dwell on strategies that might arise between the oligopolistic firms facing a new competition.

2.1 The model

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

$$\Pi^i = [(1 - Q_t)q_t^i - cq_t^i] + \sum_{\tau=1}^{\infty} \delta^\tau (1 - Q_{t+\tau})q_{t+\tau}^i - cq_{t+\tau}^i \tag{5}$$

with $Q_t = Q_t^Y + S_t$ and where $Q_t^Y = Q_t^{Y-i} + q_t^i$ and c is the marginal cost that we assume, for convenience, constant in the long run. This implies the following FOC (*see Appendix C*):

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

[6] Note that in this paper we do not deal with the dynamic of resource scarcity and we assume an infinite ore deposit. We consider that recycling plays a role in the resource conservation as it indirectly increases the resource stock, but the question of in which extent recycling can stop or slow resource scarcity is out of the frame of this paper.

From which we can aggregate with n firms:

$$1 + \frac{\partial S_t}{\partial Q_t} Q_t^Y = n(p_t - c) - \sum_{\tau=1}^{\infty} \delta^\tau Q_{t+\tau}^Y \frac{\partial Q_{t+\tau}}{\partial Q_t} \tag{6}$$

Here we observe two effects. With $\frac{\partial S_t}{\partial Q_t}$ expected to be negative, we highlight the link between mining output and the recycling supply in period t through the price effect. In addition, the component $\frac{\partial Q_{t+\tau}}{\partial Q_t}$ expected to be positive, captures the fact that recycling creates a loop and rises the resource productivity over time such as a rise of production in t is back on the market in $t + \tau$.

Since $S_t = r(z_t)\theta Q_{t-1}$, we have:

$$1 + \theta Q_{t-1} \frac{\partial r(z_t)}{\partial Q_t} Q_t^Y = n - nQ_t^Y - n\theta Q_{t-1} r(z_t) - nc - \sum_{\tau=1}^{\infty} \delta^\tau Q_{t+\tau}^Y \frac{\partial Q_{t+\tau}}{\partial Q_t} \tag{7}$$

At steady state, we have:

$$Q_t^Y = Q^{*Y} \tag{8}$$

$$z_t = z^* \Leftrightarrow S_t = S^*$$

$$Q_t = Q^*$$

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

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

Hence, the production of the recycling sector becomes $r(z^*) = 1 - \frac{1}{k(1-Q^*)}$, and this implies (*see Appendix D for (9) and (10)*):

$$(n + 1 + d^*\theta Q^* + \sum_{\tau=1}^{\infty} \delta^\tau e_\tau) Q^{*Y} = n(1 - \frac{\theta Q^*(k(1-Q^*)-1)}{k(1-Q^*)} - c) \tag{9}$$

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:

$$0 < (\frac{\theta r(z^*)}{1 - d^* \times \theta Q^*})^\tau < 1 \Longleftrightarrow 0 < e_\tau < 1 \tag{10}$$

From (10), 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 marginal rise of the total output will become constant and equal to 1, higher is τ (i.e. a given period), lower will be e_τ. This captures the marginal resource productivity over time since the output in a period t becomes the input for recyclers allowing them to produce for more than one period (i.e. $Q_{t+\tau}$). With the cumulated depreciation, this marginal rise in production decreases over time until going to 0. Better is recycling, closer to 1 the resource productivity will be, before reaching 0.

Although the explicit form of Q^{Y*} cannot be found here, by using (9) 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 $Q^{Y*} < Q^{O*}$. As it has already been shown in a monopoly case, recycling leads to a lower virgin output. The magnitude of this decrease relies on the level of available stock of scrap and the efficiency of recycling. Any rise of these factors reduces losses of materials and pushes the supply from the secondary production up to the detriment of the mining firm(s). As long as the demand is linear, it seems that these results stands as much as for a monopoly than an oligopoly's. Alike, with (9), we also hilight the negative effect of resource depletion and/or the decreasing level of ore grade that arises in the long run, on the dominance of the oligopoly.

Our assumption to deal with an oligopoly leads us to see what is the effect of a higher number of mining firms on the market. If we expect a positive relation between n and Q^{Y*}, we might wonder how the secondary supply interferes in this relation according to a given level of k and θ.

While the positive relation between Q^{Y*} and n is confirmed (see *Appendix E*), we infer that a higher number of mining firms helps the virgin sector to keep and even increase its dominant position against the secondary sector.

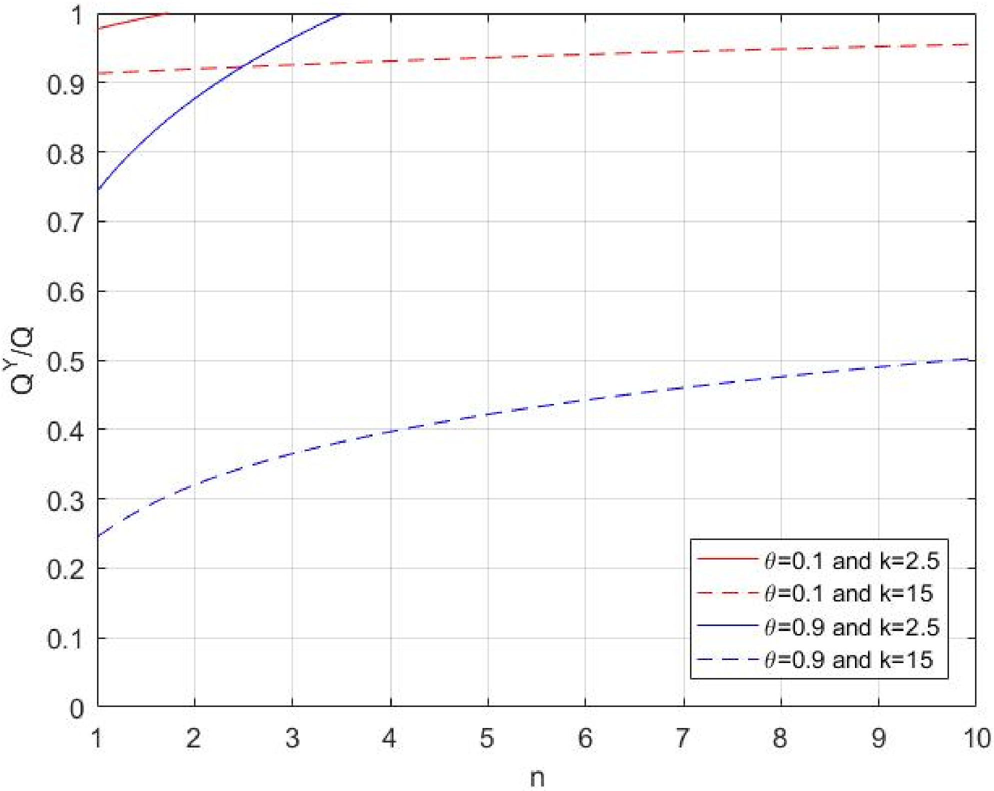

Figure 2: Market share of the oligopoly with respect to n and according to different recycling levels

As we can expect, the need to be more competitive is less important when recycling is low and the market is almost only controlled by the miners (i.e. $Q^Y/Q = 1$). This is illustrated with the red and blue solid lines that capture a low level of recycling efficiency. Also, we assume with the blue dashed line how competitive must be the mining sector to fully control the market, since both availability of scrap and recycling efficiency are at a high level.

Like it exists a threshold $\tilde{k}$ for recyclers to enter the market, our Figure 2 also shows that with a four firms oligopoly, recyclers are out of the market. Hence we assume the existence of an optimal n that pushes recycling away, meaning that $Q^{Y*} = Q^*$. The table below gives the estimated optimal number of mining firms regarding several values of θ and k:

Table 1: Number of mining firms for a full control by the virgin production

Recycling supply	very low	medium	very high
Value of parameters	$\theta = 0.1$ $k = 2$	$\theta = 0.5$ $k = 5$	$\theta = 0.9$ $k = 10$
Optimal n	1	12	80

In addition, we now focus on the effect of a more competitive mining sector on the secondary supply and assume that a higher number of firms implies a ≪price effect ≫and a ≪quantity effect ≫. The former discourages recyclers to rise their expenses for a better recycling rate. The latter is related to the rising available stock of scrap that would help the secondary sector to increase their supply with a constant recycling rate. The Figure 3 below shows various secondary supplies (i.e. according to the related parameters) with respect to the number of mining firms.

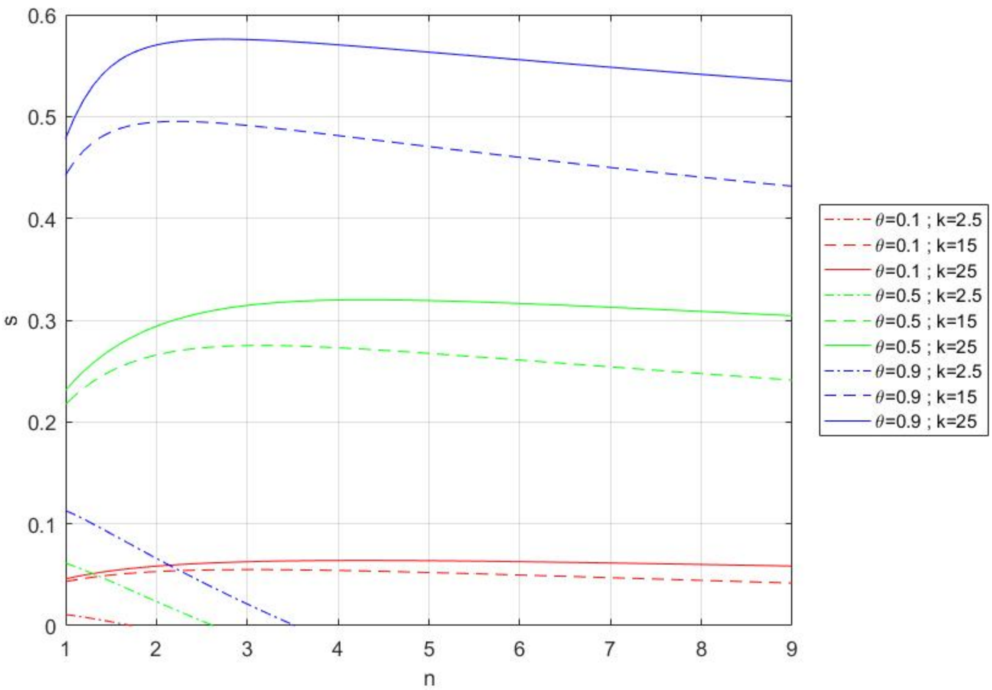

Figure 3: Evolution of the secondary supply regarding the number of mining firms

The influence of the level of technology is confirmed here with the slope of the decreasing trend of s. The lower is k, the higher the slope is. Hence, the need for a high competitive mining industry can be low for the existing firms since s tends more quickly to 0.

With the hump shaped solid and dashed curves, we assume that a high level of recycling efficiency can offset a lower price (i.e. the price effect) induced by a more competitive virgin sector. Meanwhile, the stock of available scrap rises with the number of mining firms. This temporarly implies a greater secondary supply despite of a decreasing recycling rate.

Proposition 2: *A more competitive mining activity implies a lower share of the secondary sector. Except for a very high level of recycling efficiency, the secondary supply is more sensitive to the decreasing price than the rising stock of scrap, that comes from a higher number of mining firms.*

Remark 1: In addition, the rise of n prevents from the entrance of new recyclers as it pushes the threshold $\tilde{k}$ up (c.f. *Proposition 1*).

Remark 2: However, if this rise in the number of firms seems to benefit to the virgin producers by limiting the influence of recyclers, it might also reduces the market power through a decreasing price.

2.2 The effect of recycling over the market power

(i): The price equilibrium

We define the secondary supply in t as $S_t = \theta(1 - \frac{1}{kp_t})Q_{t-1}$, and by comparing with the secondary demand we have :

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

At steady state, we find the following equilibrium price :

$$p^* = \frac{1 - Q^{Y*}(1-\theta)}{1 + k\theta Q^{Y*}} \tag{11}$$

Using (11) and the results from (Gaudet and Van Long, 2003), where they showed for a monopoly that $Q^{Y*} < Q^{O*} \leq Q^*$, it appears that the equilibrium price is lower or equal in a situation with recycling than without. Since we showed $\frac{\partial Q^*}{\partial n}$ the price is even lower in a case of an oligopoly. The magnitude of the decreasing price relies on the recycling related parameters θ and k that push the secondary supply, and the number of mining firms.

Proposition 3: *At steady state, a more efficient recycling technology, a better availability of scrap and a higher number of firms in the virgin sector, tend to push the price of the output down, to the benefit of the downstream industry.*

Assuming a constant marginal cost for the miners, the existence of recycling implies a lower market power. However, a non competitive market structure holding in the virgin production can lead to the implementation of strategies and modify the market conditions. For instance, like stated by Tirole (1988) in his textbook or Gaskins (1974) and Martin (1982) in their respective paper, the monopolist strategically decreases its output in order to limit the stock of scrap and prevent from the future competition of recyclers. This logically tends to push the market power up to the detriment of the downstream industry.

(ii) The Lerner index

Using the Lerner index that measures the mining market power and assuming a situation where $k \to \tilde{k}$ (c.f. equation (2)), we have $r(z^*) \to 0^+$ and since $\frac{Q^{Y*}}{Q^*} \to 1^-$, we infer :

$$\frac{Q^{Y*}}{Q^*}\frac{1}{\eta(Q^*)} \geq \frac{1}{\eta(Q^{O*})} \equiv L^{Q^{Y*}} \geq L^{Q^{O*}} \tag{12}$$

where $L^{Q^{Y*}}$ and $L^{Q^{O*}}$ are the Lerner indexes respectively for a situation with recycling and without recycling, and $\eta(Q) = \frac{-p(Q)}{Qp'(Q)}$ is the price elasticity of demand. As the previous literature contends, this situation where the market power is equal or greater in a situation with recycling than without, occurs when the virgin producer(s) can restrain its output. However, all of this is shaded by the given level of recycling and the share of the secondary production in the market.

Assuming the opposite case where $k \to +\infty$ and we have $r(z^*) \to 1^-$, the ratio $\frac{Q^{Y*}}{Q^*}$ tends to 0 and the Lerner index would become lower, such as:

$$\frac{Q^{Y*}}{Q^*}\frac{1}{\eta(Q^*)} \leq \frac{1}{\eta(Q^{O*})} \equiv L^{Q^{Y*}} \leq L^{Q^{O*}} \tag{13}$$

Hence, this leads us to draw attention on the role of k and to infer the existence of a threshold $\bar{k}$ meaning the recycling rate is high enough to create a lower mining market power than a situation without recycling.

With (9), we have:

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

$$\bar{k} = \frac{n\eta(Q^{O*})\theta Q^*}{[Q^*\eta(Q^*)(n+1+d^*\theta Q^* + \sum_{\tau=1}^{\infty}\delta^\tau e_\tau) + n\eta(Q^O)(c+\theta Q^* - 1)](1-Q^*)} \tag{14}$$

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 both market power with and without recycling, moves with the following exogeneous parameters.

First, as we might expect we have $\frac{\partial \bar{k}}{\partial c} < 0$ and $\frac{\partial \bar{k}}{\partial \theta} < 0$. If we expect a rise in the marginal cost of the primary production due to scarcity for instance or a higher proportion of scrap available for recyclers through a greater θ, a rise of k will not be necessary to lower the market power.

We also have $\frac{\partial \bar{k}}{\partial n} > 0$ which means that a rise in the number of firms logically pushes the market power down. Hence, the minimum level of recycling efficiency also must rise because the initial market power of the oligopoly will be lower with the higher number of firms. In other words, the more competitive is the primary sector, more efficiency is required in recycling to push the market power to the competitive level.

Proposition 4: *The threshold $\bar{k}$ above which the recycling sector makes the market power lower than a situation without recycling decreases with the marginal cost of the primary sector and with the proportion of available scrap, and rises with the number of firms of the oligopoly, .*

Remark 1: Since recyclers rise their expenses with the price, we notice that a lower market powwer would also have a negative effect on the secondary industry. Meanwhile, a better efficiency of recycling would help them to less rely on the market conditions and the decreasing price.

3 The role of θ and k to boost the recycling supply

As the previous sections highlights, the amplitude of the effect of recycling over the oligopoly relies on the number of mining firms (c.f. *Proposition 2*), the technology of recycling and the proportion of available scrap. Here we estimate how a change in the secondary supply affects the oligopoly's output. Using our model setup at steady state in the previous section, we apply different values of parameters θ and k to see how it affects the virgin production.

(i) With a fixed θ and a moving k

By plotting our variables with different level of θ and with respect of k we have:

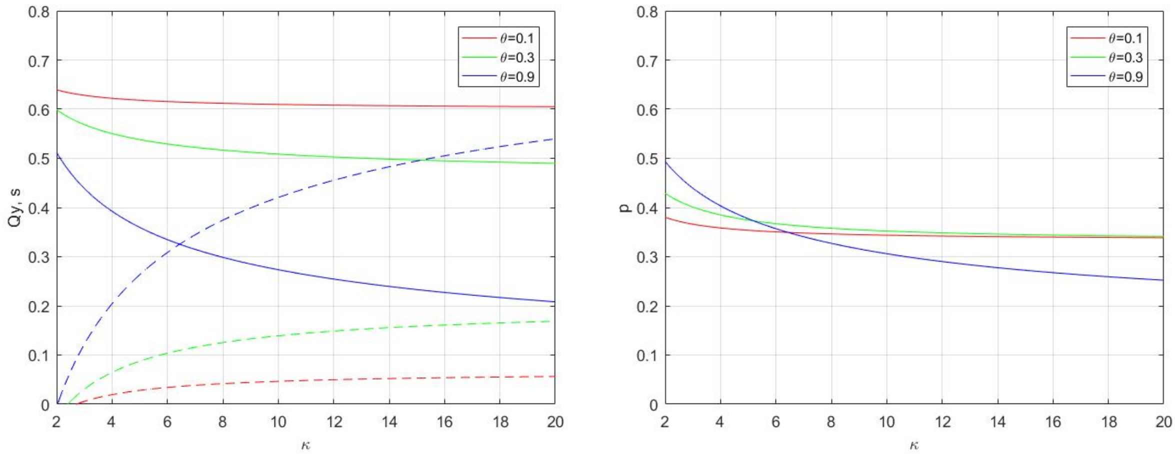

Figure 4: Evolution of the mining and virgin ouputs, and the price, with respect to k

By looking at the graphs above, first we highlight the importance of a high θ to observe a real change in the share of secondary and virgin supplies. For a given level of recycling efficiency and assuming that 90% of production is going to the scrap stock, the secondary supply is even greater than the virgin production [7]. With $\theta = 0.1$ or $\theta = 0.3$, no matter the level of recycling efficiency, the stock constraint appears too high for a significant rise of the secondary supply and a significant change in the market supply structure. This is also seen on the graph (2), where a low level of θ does not push the price down despite of the rise of k, compared to the blue curve with $\theta = 0.9$.

[7]Note: Here we plotted for a number of firms $n = 2$. A higher number of firms pushes the k allowing the secondary supply to be greater than the virgin one, at a higher level.

(ii) With a fixed k and a moving θ

Conversely, by plotting our variables with different levels of k and with respect of θ we have:

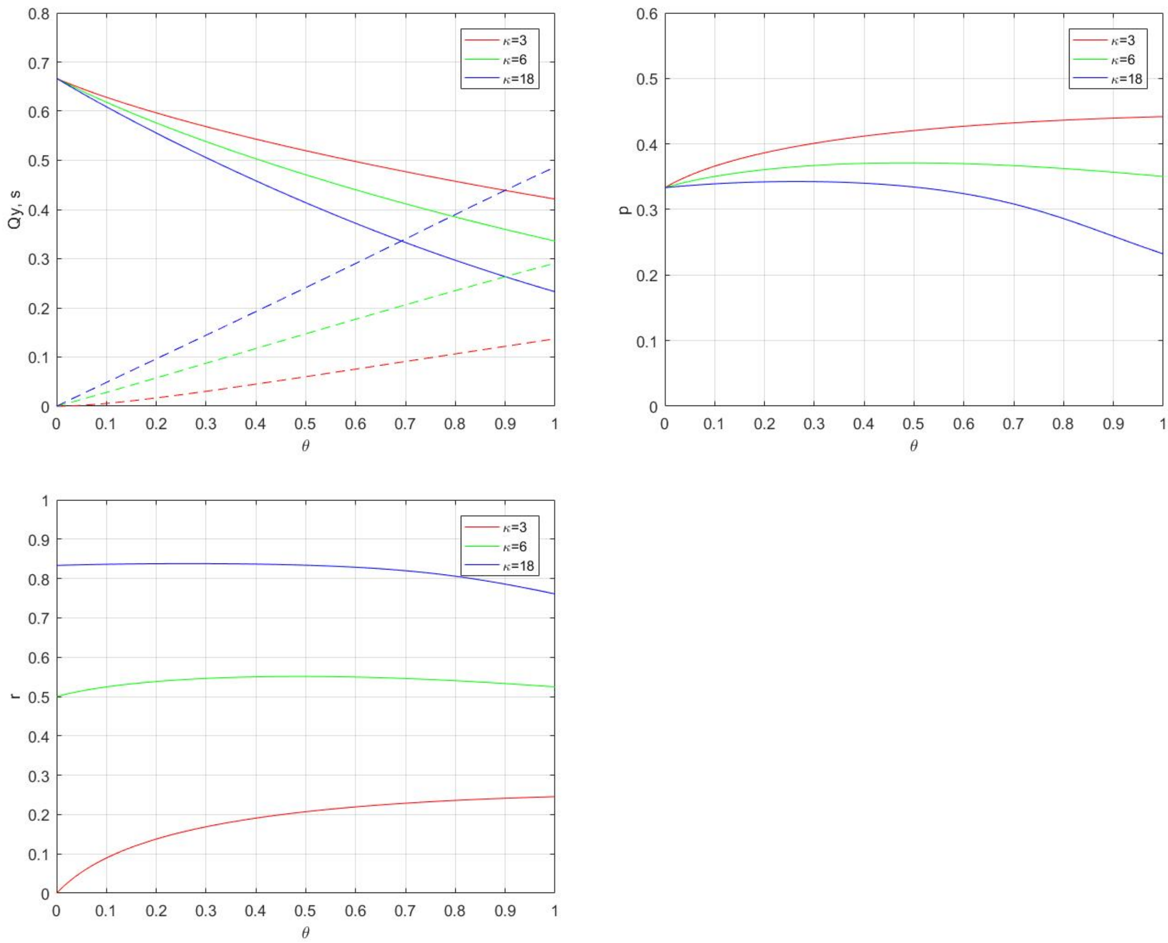

Figure 5: Plots of the mining and virgin ouputs, the recycling rate, and the price with respect to θ

The two graphs above confirm our previous statement about the possibility of having a greater secondary supply compared to the virgin production. However, regarding the level of recycling already reached with our k values (graph (3)), this seems to be a tough challenge. For instance, a 50% recycling rate combined with a very high value of θ helps the secondary supply to rise but not enough to dominate the market supply. In addition, we can observe on the graph (2), the possibility of a higher price with the existence of recycling. By assuming a constant marginal cost of the mining oligopoly, this leads to a greater market power despite of recycling, like we show in the previous section.

The analysis of the determinants of recycling supply sheds light on the need for high levels in both the availability of scrap and recycling efficiency. In terms of public policy, any incentives to encourage recycling appears to be usefull for entering into the market and lowering the market power, but as long as a sufficient stock of scrap is not reached, the share of recycling supply in the market will be maintained low.

4 Concluding remarks

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 oligopolistic. The effect of a higher number of mining firms is threefold. First, this plays a role in the entry of recyclers since more competitive is the virgin sector, more efficient the technology to allow a recycling activity must be. Second, as we showed in the second section, a more competitive mining market structure leads to a higher market share for the virgin producers. The decreasing price discourages recyclers to rise expenses and this also pushes the threshold $\tilde{k}$ up. However, this appears to be done at a cost of a lower market power. Third, this trade-off between market share and market power implies indeed the existence of potential strategies in the mining sector, and more competitive the latter is, more difficult is the possibility of setting up strategies. If such non competitive behavior arises, the firms have to take into consideration the efficiency of recycling and the level of availability of scrap [8], since the sensitivity of the secondary supply regarding these parameters differs. For instance, the secondary supply can rise with a more competitive sector in a case of a high recycling efficiency, thanks to a greater stock of scrap despite of a decreasing recycling rate. From the recyclers side, we point out the challenge of gathering high values in both a recycling efficiency technology and a high stock of available scrap. This is also challenging in terms of public policies that could adress the environmental and scarcity issues of resource extraction.

[8]For instance, this can be estimated through the end use products structure that differs regarding the economic development of countries.

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Appendix A: The mining equilibrium output without recycling

The profit function of the mining firm i is:

$$\Pi^i = [(1 - Q_t^O)q_t^i - cq_t^i] + (1 + \delta + \delta^2)$$

where Q_t^O is the mining output in t.

From the FOC and by aggregating with n firms we have:

$$Q^O = \frac{n - nQ^O + n[1 - Q^O + \delta(1 - Q^O)] - c}{(1 + \delta + \delta^2)}$$

$$Q^{O*} = \frac{n - c}{n + 1} \tag{15}$$

Appendix B: The new mining equilibrium output with recycling

To facilitate the computation and analysis of $\tilde{k}$, we assume that the firms consider $r(z) = 1$ so that the level of recycling only depends on θ. 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 simplest profit function of firm i is:

$$\Pi^i = \sum_{\tau=0}^{\infty} \delta^{t+\tau}(1 - Q_{t+\tau} - c)q_{t+\tau}^i \tag{16}$$

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

$$Q_t^Y = n - nQ_t^Y - n\theta Q_{t-1} - nc - \sum_{\tau=1}^{T}(\delta\theta)^\tau Q_{t+\tau}^Y \tag{17}$$

At steady state, the equilibrium becomes:

$$Q^{Y*} = (n - nc)(1 + \frac{n}{1-\theta} + \frac{\delta\theta}{1-\delta\theta})^{-1} \tag{18}$$

And with $\theta = 0$, we have $Q^{Y*}(\delta;\theta) < Q^{Y*}(\delta;0)$

Appendix C: 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 $r(\hat{z}_t)\theta Q_{t-1}$, is:

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

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:

$$(1 - Q_t^{Y-i} - 2q_t^i - \theta Q_{t-1}q_t^i\frac{\partial r(\hat{z}_t)}{\partial Q_t} - \theta Q_{t-1}r(\hat{z}_t)) - c - \sum_{\tau=1}^{\infty}\delta^\tau q_{t+\tau}^i\frac{\partial Q_{t+\tau}}{\partial Q_t} = 0 \tag{19}$$

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:

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

Since we know that $Q_{t+\tau} = Q^Y_{t+\tau} + \theta r(z_{t+\tau}) Q_{t+\tau-1}$, 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

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

This implies

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

Hence

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

And we finally have:

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

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

Appendix D: At Steady State

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

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

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

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

Define

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

With

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

This implies

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

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 $\tau > 0$,

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

Appendix E: Plots of variables with respect to the number of mining firms

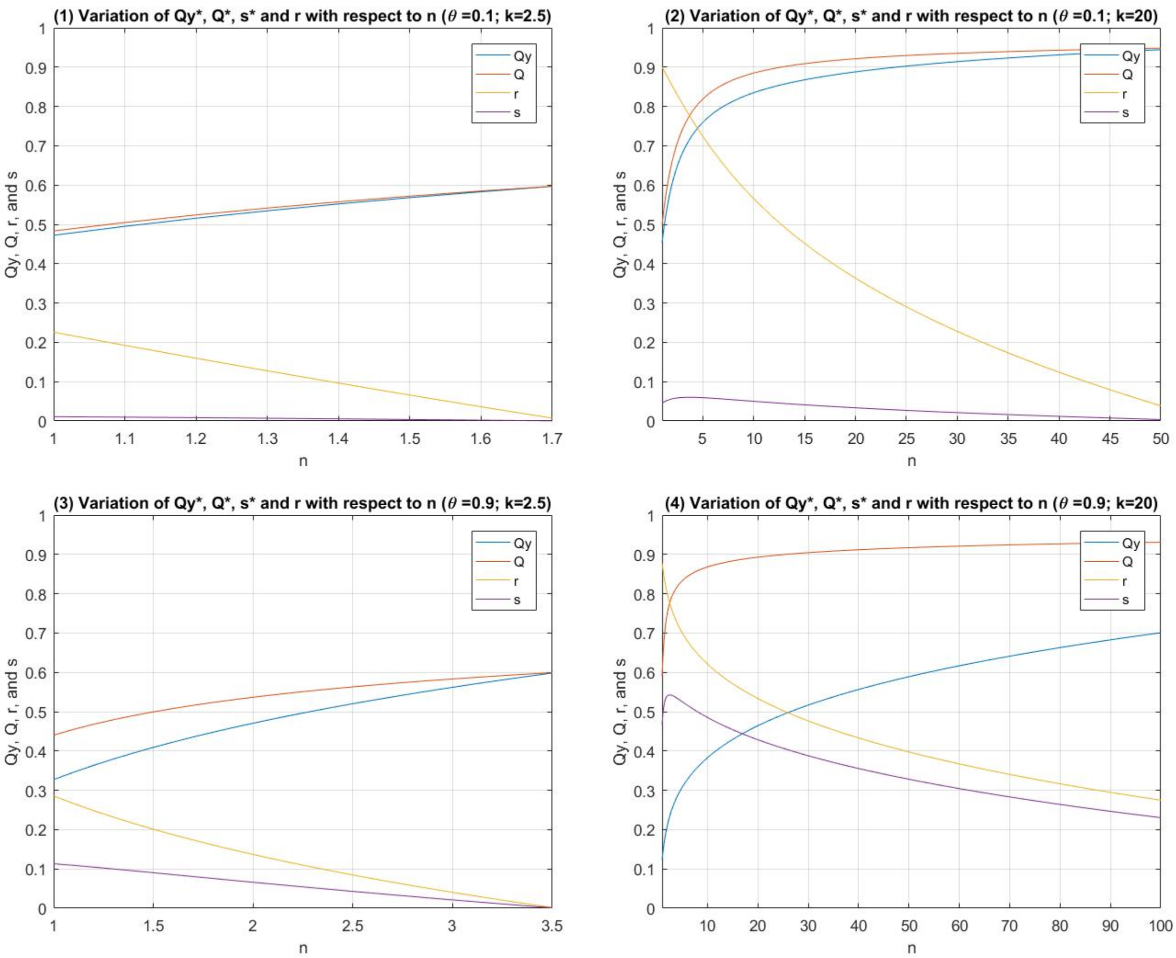

Figure 6: Supply of virgin and secondary materials with respect to the number of mining firms and the initial share of recycling