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The Economics of Recycling Rate: new insights from a Waste Electrical and Electronic Equipment

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Abstract

In this paper, we address the issue relative to the determinants of metal recycling rate. The literature on recycling flows is scarce and does not directly address the issue of achieving high recycling rate. In addition, the existing literature has not quantified the recycling rate response to metal price. This is why we explore factors of the recycling rate of different metals embodied in computer. We examine the effect of metal price, metal concentration in product, relative concentration ratio (competition between primary and secondary supply) and embodied value on recycling rate. Although we find a significant effect of metal price on recycling rate, the marginal response is very low across different type of models (OLS, GLM, FRMER, left censored Tobit). This effect is not surprising and in line with the existing literature relative to recycling flows. Conversely, it seems that recycling rate is more elastic to other technical factors like the metal concentration in products or the relative concentration ratio. We discuss public policies deriving from our results. We need more data and interdisciplinary studies to support these preliminary results.

JEL classification: C25; C26; Q53;Q57

Keywords: Recycling rate; Metal; Price; Circular economy; GLM, WEEE

1. Introduction

For a decade now, numerous reports and studies indicate that the dynamic of metal consumption and overall natural resource consumption are unsustainable (Ali et al. , 2017; UNEP, 2019; 2016). Sources of concerns relate on the ability of economic system to quickly discovers, open and operate new mines to address the demand surge. Quite differently, others analyses underline the vulnerability of strategic sectors (digital, green energy and military sectors) to the unavailability of specific key metals (Department Of Energy, 2011; European Commission, 2010; JRC et al., 2011; Blagoeva et al., 2016; World Bank, 2017). This motivates the search of delinking primary resource consumption through material efficiency and recycling.

At the other end of the pipe, solid, air, water and soil pollutions generated by economic activities also produce important sources of concerns. Among them, global warming is one the most prominent issue (IPCC, 2014). But again, it seems that the garbage problem is strongly link to natural resource over consumption (Behrens et al., 2007; Brooks and Andrews, 1974; Schandl and West, 2010; Smil, 2013; UNEP, 2013a). For instance, Fizaine and Court (2015) show that metal production absorbs 10% of primary energy production while at a more important scale, Smil (2013) demonstrates that the production of metals, plastics, construction materials, paper and fertilizers need 20% of total energy supply. Naturally, this important energy consumption translates into green house gases emissions. For instance a recent report from the UNEP (2019) argues that global material extraction and processing are responsible for 50% of global greenhouse gases emissions. Solid wastes also involve important environmental and health issues (UNEP, 2013b). Again, the flow of global solid wastes (2.01 Gt in 2016[1]) is increasing and is most often at best landfilled or worst, dispersed in the environment. In this context, the "seventieth continent" of plastic in pacific is an astonishing illustration of the big challenge raises by the management of increasing solid wastes (Lebreton et al., 2018). Moreover, even the flow of solid wastes from sectors often seen as dematerialized like the digital sector poses huge challenges. Indeed, the flow of waste electric and electronic equipments are also increasing (44.7 Mt in 2016) and generate important health and environmental issues for countries where metal wastes leak (Baldé et al., 2017; Cui and Roven, 2011).

Due to the previous facts mentioned above, recycling and circular economy are now seen as promising tools for reducing both primary resource needs on one hand and wastes at the other hand. To start with, increasing recycling rate involves several cobenefits like:

- The decrease of the environmental impact associated with wastes (air, water and soils pollutant emissions)
- The saving of landfill space.
- The substitution of the more important energy and environmental cost of primary production (greenhouse gases, water consumption, floor space consumption).
- The improvement of resources conservation.
- The increase of the geopolitical independence to raw material producing countries.
- The creation of a local alternative substitute to imported financing armed conflict raw materials.
- The reduction of the potential disequilibrium between demand and supply brings by supply diversification.
- The creation of jobs and local infrastructures link to the activity.

[1] This figure is provided by the World Bank and could grow by 70% by 2050.

- The partial decoupling of metals subject to primary byproduction thanks to the raise of secondary supplies (Blomberg and Söderholm, 2011; Hagelüken, 2014; UNEP, 2013a).

Moreover, in contrast to reduce and reuse activities, recycling activity characteristics are closer to the business of old throughput economy, sharing scale economy and cost minimization through international trade specialization (Ghisellini et al., 2016; Stahel, 2013).

Unfortunately, despite these important advantages, recycling activities and more especially metal recycling suffer from important lack of knowledge on several topics.

Firstly, we observe that despite voluntary goals of international organizations and national government, metal recycling rates are low and are expected to remain stable in the coming decades (Ali et al., 2017; UNEP, 2013a). To break this curse, we need to identify the best triggers of high recycling rate and avoid potential useless and expensive public policies. More precisely, with end of life recycling rate below one percent, many minor metals do not profit from the opportunities provided by recycling (UNEP, 2011). However, the consumption of minor metals increases quickly due to their important use in Electric and Electronic Equipment. Indeed the sector of ITC meets an important growth and implies many issues associated with resource and energy conservation. For instance, a French report from the Shift Project (2018) demonstrates that energy consumption for digital technologies is growing at 9% per year. Conversely to energy intensity of other sectors (-1.8% per year), the energy intensity of digital sector rises at 4% per year. This work also underlined that 45% of this energy is devoted to the production of electronic and electric equipment using a large variety of energy intensive metals. In addition, if several metals find in Waste Electric and Electronic Equipments (WEEE) are well recycled, unfortunately this hierarchy between what is recycled and what is not do not include the environmental cost of metals (external costs). Therefore, we meet some paradoxes in recycling where major metals are better recycled than minor metals although the unitary environmental costs of the former are well below that of the latter (Nuss et al., 2014). For instance, if we focus on famous different environmental indicators like the global warming potential (kg CO2eq./kg), the terrestrial acidification, the freshwater eutrophication, we observe that the unitary environmental impact of metals like iron, aluminum or copper is one, two or three order of magnitude lower than those of germanium, gallium and tantalum (minor metals). Therefore, we need to understand how recycling activities work for these metals and what is the best way to achieve high recycling rate targets.

Secondly, recycle metals is far away from other recycling operations. There are at least three major differences between metal recycling and other major material recycling (paper, paperboard, glass and plastics). Conversely to materials like paper, paperboard or plastic, pure metal allows theoretically infinite recycling[2] (UNEP, 2013a). In addition, wastes containing metals is less homogenous than paper and plastic wastes. The number of elements, the high spread of quality and the concentration of metals in products involve high challenges absent from other major recycled wastes. Consequently, WEEE recycling facilities are really different from for instance paper recycling facilities. More precisely metal recycling claims high capital investments and even high technologies for separating most of specialty/rare/precious/base metals. For instance, one billion dollars has been invested in the Umicore recycling and refining plant operating WEEE in Belgium (Hagelüken and Corti, 2010). This plant extracts 30 tons of gold, 37 tons of platinum group metals, 1000 tons of silver, and 68,500 tons of other metals per year from wastes. That makes it the third gold mine in the world. For comparison, a standard paper recycling facility requires 30-50 millions dollars. This is why some scholars advocate

[2] This does not means that we can operate a 100% recycling rate efficiency but only that metal quality does not down-cycling when recycled.

embracing the issue of metal recycling separately from other materials (Andersson and von Borgstede, 2010; Lakhan, 2014; Hagelüken, 2014).

Thirdly, the previous literature is focusing on the household and municipal collecting steps but the industrial recycling step has not been deeply analyzed. To be more precise, a quick overview of the literature relative to recycling shows that three main corpus are available: (i) studies relatives to households and municipal wastes, (ii) studies that model the economics of specific resource industry, (iii) studies analyzing the technical characteristics of wastes. To begin with, there is a huge volume of studies analyzing the different factors of recycling rate of municipal wastes (Berglund and Söderholm, 2003; Dijkgraaf and Gradus, 2017; Sterner and Bartelings, 1999; Yang and Innes, 2007). A complete survey of these studies is beyond the scope of this paper (see Fizaine, 2018). Although this literature includes the overview of the impact of many factors (income, education, age, household size, population density, pay-as-you-throw princing system), there are numerous gaps to be filled. First, they do not quantify the effect of raw material price on recycling rate. Second most of these studies do not desegregate the different flows of raw materials. This could be problematic because the recovery and recycling rate could differ greatly across different raw materials (Andersson and von Borgstede, 2010; Lakhan, 2014). In addition, metals hold very specific characteristics and thus must be examined separately (Hagelüken, 2014). To go on, other more related studies are embracing the economics of recycling rate in a more conventional way. They explicitly model the supply and demand of secondary metal flows (Blomberg and Söderholm, 2009; Edwards and Pearce, 1978). In contrast to the first literature, metal prices are taken into account. They reach the same conclusions: secondary recycled flows are price inelastic (Edgren and Moreland, 1989; Edwards and Pearce, 1978). Although scarce, the estimates do not really change across metals. For instance for aluminum price elasticity vary within a range of 0.18 to 0.32 (Blomberg and Hellmer, 2000; Blomberg and Söderholm, 2009, 2011; Carlsen, 1980; Slade, 1980a) while similar estimate are quantified for copper: 0.2-0.29 (Fisher et al., 1972; Gomez et al., 2007; Slade, 1980a, 1980b).The outcomes highlighted by these studies are very interesting but cannot be directing applied to recycling rate. In addition, they only document the price impact for copper and aluminum, two metals which are currently quite well recycled. No conclusion can be established for minor metals which nevertheless inundate WEEE. Lastly, other scholars - mostly engineers and geologists - have shown that dilution of metal in products could impact the incentive to recycle products (Johnson et al., 2007; Rombach, 2006; Vidal, 2017; Vidal et al., 2017). Unfortunately, these studies do not explicitly integrate the effect of metal price and generally adopt a descriptive approach (scatter graph, no modelization).

Fourthly, we need to understand how the global warming fighting policies interact with recycling and circular economic policies. For yet, most of studies analyze these issues separately while there are (at least theoretically) the possibility of complementary or substitute effects between them (crowding out).

This is why we need to investigate this topic and the stakes associated with the global understanding of metal recycling rate in WEEE. In this paper, we wonder to explain the main determinants of metal recycling rate. Is the price (through taxes) a promising tools for achieve high recycling rate target? Are there other determinants of metal recycling rate? Do the fighting climate policies would promote recycling through taxing CO2?

We show that the effect of metal price on recycling rate is rather weak. Conversely, recycling rate seem more elastic to other variables like metal concentration in products, embodied metal value and above all, to relative concentration ratio. Due to previous results, the internalization of greenhouse gases costs would not lead to a great increase of metal recycling rate. Therefore, we stress that no overlap is apparent between climate policies and recycling polices. The paper also reveals that material/technical design policies can be promising and that focusing on economical tools like taxes could be disappointing as also advocated by Söderholm (2011). Finally, we highlight the existence of a potential tradeoff between high material efficiency target and high recycling rate target (for metals).

Overall, this paper brings a quadruple contribution to the existing literature. First, we assess the economic incentives (price) relative to raw material recycling rate. Second, we examine the question of "fringe materials" through the example of minor metals. Third, to our knowledge this is the first paper that explores the determinant of recycling rate in a material perspective (element in cross section) and focus on the industrial step rather than a static or dynamic monography. Fourth, we build a bridge between economic and technical approach by using economic and technical determinants of recycling rate (first use and estimation of relative concentration ratio and embodied metal value). Surprisingly enough, most of the prospective studies presented in the introduction do not model/include the impact of metal recycling. Some of the papers deliberately ignore the issue (Moss et al., 2013; Northey et al., 2014; World Bank, 2017) while others introduce exogenous and arbitrary recycling rate (Blagoeva et al., 2016; Sprecher et al., 2017; Ali et al., 2017; Vidal, 2017). Therefore, the results from this study could also help scholars who want to design future prospective studies related to metal availability.

In order to answer to the issue raises in this introduction we proceed as follow. In the next section *Methodology and data*, we present the data and different modelizations used in this paper. In a third section *Results*, we provide different estimates of different modelizations. In a fourth section *Discussion*, we introduce robustness and sensitivity analyses. This part also includes a discussion about potential caveats of this study. The last part of discussion is dedicated to public policies recommendations and future studies. We conclude in a last section.

2. Methodology and data

2.1 About recycling rate

According to the UNEP report (2011), there are at least four different recycling rates: end of life recycling rate, old scrap collection rate, recycling efficiency rate, recycling content. Here, we use the recycling efficiency rate and designate it by the general term of recycling rate. Recycling efficiency rate is computed as the ratio of recycled metal on the collected metal. Therefore, this measure is focused on the industrial recycling step rather than on the step of waste collection occurring at the household scale (old scrap collection rate). The product of the old scrap collection rate by the recycling efficiency rate provides the end of life recycling rate.

2.2 Data

We retrieve data from different sources: recycling rate of different metals in computer[3]and the average metal concentrations in computer (% of total weight) come from UNEP report (UNEP, 2013a). The price of metals ($/kg) is provided by USGS. Average mining concentration and crustal grade (%) are found in three references (Craig et al., 2001; Fizaine and Court, 2015; Valero and Botero, 2002) while unitary energy consumption of metals (GJ/t) is provided by Nuss and Eckelman (2014). The main descriptive statistics can be found in table 1.

Moreover the figure 1 shows that value of metals embodied in printed wired boards of computers is mainly derived from the value of gold (18$), copper (14$), aluminum (9$), tin (6$), nickel, lead and

[3] i.e printed wire boards in Europe.

silver (between 3 and 5$), beryllium palladium and zinc (between 1 and 3$) rather than other metals (less than one dollar).

	Unity	Mean	Standard deviation	Median	Q1	Q3	Min	Max
ConcentrationM	%	5.64%	10.54%	0.55%	0.04%	5.60%	0.00%	50.00%
Price	($/kg)	2138.99	7844.91	23.30	2.46	342.50	0.14	40000.00
ConcentrationP	%	1.74%	4.56%	0.01%	0.00%	0.03%	0.00%	20.47%
Recycling rate	%	32.40%	40.20%	0.00%	0.00%	77.50%	0.00%	99.00%
RCR	-	1.04	2.69	0.06	0.00	0.78	0.00	13.86
Threshold	-	0.20	0.40	0.00	0.00	0.00	0.00	1.00
Embod. Value	$	2.22	4.32	0.17	0.01	2.01	0.00	17.50
Unit. Energy Cons.	GJ/t	10286.53	38939.82	156.50	53.18	1720.00	4.00	208000.00
Av. grade crust	%	0.49%	1.76%	0.00%	0.00%	0.01%	0.00%	8.23%

Table 1 Main descriptive statistics

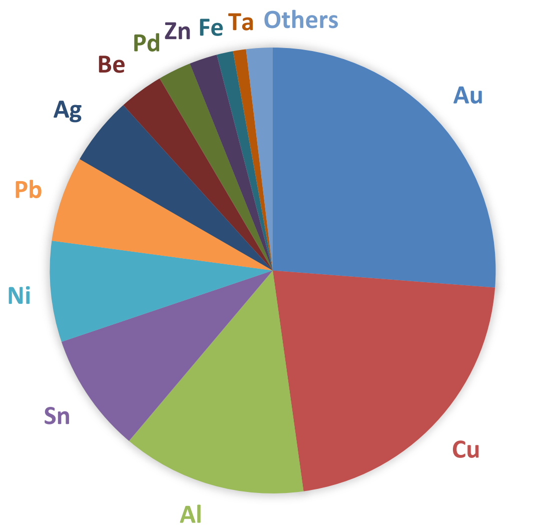

Figure 1 Main metal values available in printed wire boards from computer. Source UNEP (2013a) and computations.

2.3 Specification

According to different studies (Johnson et al., 2007; Vidal, 2017), we explore the impact of different determinants of metal recycling rate in computer. In a first model, we suppose that recycling rate is depending on three factors: the price of metal, the concentration of metal in computer, and the ratio between metal concentration in computer and in metal concentration in deposits (thereafter RCR):

$$Recycling\ rate_i = c + \beta_1 price_i + \beta_2 concentration\ p_i + \beta_3 \frac{concentration\ p_i}{concentration\ m_i} + \varepsilon_i \qquad (1)$$

Metal *Price* increases the revenue of recyclers, *concentration p* decreases the cost of recycling while relative concentration ratio (thereafter *RCR)* resumes the effect of competition between primary mining and secondary supply (recycling). In a second model, we substitute the RCR variable by a dummy variable indicating whether the average metal concentration is higher in products than in primary metal deposits:

$$Recycling\ rate_i = c + \beta_1 price_i + \beta_2 concentration\ p_i + \beta_3 threshold_i + \varepsilon_i \qquad (2)$$

Where threshold takes the value 1 if the element concentration of products is higher than the element mining concentration and 0 otherwise. Lastly, we simply check the impact of price and logarithm of RCR:

$$Recycling\ rate_i = c + \beta_1 price_i + \beta_2 \ln\left(\frac{concentration\ p_i}{concentration\ m_i}\right) + \varepsilon_i \qquad (3)$$

Moreover, other scholars asked us to check the possibility that recycling rate can be impacted by the metal value include in the computer rather than the metal price itself. The variable *Value* has been computed as follow:

$$Metal\ value\ available\ (\$) = \ Price \times Concentrationp \times Total\ Weight \qquad (4)$$

Then we estimate the following effect of the embodied value on the recycling rate:

$$Recycling\ rate_i = c + \beta_1 Embodied\ Value + \beta_2 \ln\left(\frac{concentration\ p_i}{concentration\ m_i}\right) + \varepsilon_i \qquad (5)$$

2.4 Models and issues with estimations

To assess the potential impact of each determinant, we provide a series of graphical (scatter plots) and non conditional tests of means for the different variables. We proceed as follow, we sorted the sample by increasing value for each variable (4) and separate the sample into two part. We then perform a t-test of equality of means (average recycling rate in each sub-sample). We also represent the average recycling rate for each sub-sample when the total sample is sorted by increasing value and separate into three parts (tercile).

In a second part, we use econometric methods. More especially, before providing the estimate of equation 1-5, we need to fixe some usual econometric issues raise by our data.

Small sample size

Our data are few and the sample is small (observations: 30). Small sample size can be problematic because it generate low statistical power and inflated effect size. Although we are aware of these issues, there is no easy way to deal with small sample size. Moreover, the lack of studies in this topic is likely to be due to the lack of data. Nonetheless, inflated effect size is not problematic here because our data are exactly showing the reverse (ie. we are not showing a more important effect of some variables on recycling rate). In addition, the discussion and originality of our paper is not based on the absence of detected effect of the variable which could be due to low statistical power.

To avoid the loss of freedom degrees, we introduce a low number of independent variables (a maximum of three variables).

Heteroscedasticity

The heteroscedasticity could be problematic due to its effect on the statistical inference. We check that issue thanks to the White test. If the test rejects the assumption that the variance of residuals is homoscedastic, we estimate heteroscedasticity-consistent standard errors (White/Hubbert covariance).

Collinearity

Collinearity could inflate standard errors and lead to non-significant result. Again, we report the variance inflation factor (VIF) and delete variable with VIF superior to 10. This does not happen in our model estimations (VIF statistic is always behind 2).

Non linearity

The use of Ordinary Least Square (OLS) on fractional dependent variable is highly debated. The use of this kind of model on this form of data can lead to the ignorance of non linear effects, the generation of impossible outcome (negative percentage or higher than 100% predicted percentage). Here, we report OLS results for illustration and estimate Generalized Linear Model (GLM). GLM models avoid the generation of impossible outcomes and are recommended to modelize proportions (Baum, 2008; Papke and Wooldridge, 1996). More specifically, we use the binomial family with a logit link:

$$y^* = \ln\left(\frac{y}{1-y}\right) = X\beta + \varepsilon \tag{6}$$

We also use a robust variance estimator in the GLM as recommended by different scholars (Baum, 2008; Papke and Wooldridge, 1996; Wooldridge, 2011). The use of probit link does not lead to different results although the prediction power is less important (see appendix 1.2).

Endogeneity

We could suspect endogeneity between prices and metal recycling rate. This is why we employ Fractional Response Model with Endogenous Regressor (FRMER). FRMER use a similar framework than GLM but allow the treatment of endogenous variables (Wooldridge, 2011). Following Jordan and Eggert (2018) we take primary unit energy consumption of each metal (GJ/t) and average grade of metal in the crustal crust as instrument for price. The primary metal unit energy consumption as well as the crustal grade of metal are fixed by physic laws and are not depending on economic parameters so we cannot suspect that there are endogenous to recycling rate or price. For illustration only, we report standard post-estimations from traditional two stage endogenous regression for price in natural logarithm and price in level (Appendix 1 - Instrumental variables). The R^2 of the first stage is high (0.92 and 0.98) with an important F statistic (120 and 789) avoiding the issue associated with weak instruments. In addition, the Sargan and Basmann tests cannot reject that our instruments are uncorrelated with the error term (p value associated with Sargan: 0.74/0.28 and Basmann: 0.76/0.32) and Anderson LM statistic test leads to the rejection of the assumption that our model is underidentified. According to other scholar's comments, we have replicated the process with the average grade in crustal crust and five years lead metal price as alternative instruments for metal price. The results are quite similar and provided in the appendix 1.2 (see FRMER 1.1 and 1.2).We provide the results associated with FRMER framework in the result section.

3. Results

3.1 Relationship between variables and recycling rate

The different scatter plots in figure 2 show that all variables seem to be positively correlated to the recycling rate. However, the relationship between price of metals and recycling rate is rather weak as indicated by the scatted plot and the test of equality of means (table 2). Conversely, the correlation of the recycling rate with other variables seems more explicit. Figure 3 also supports this first statement.

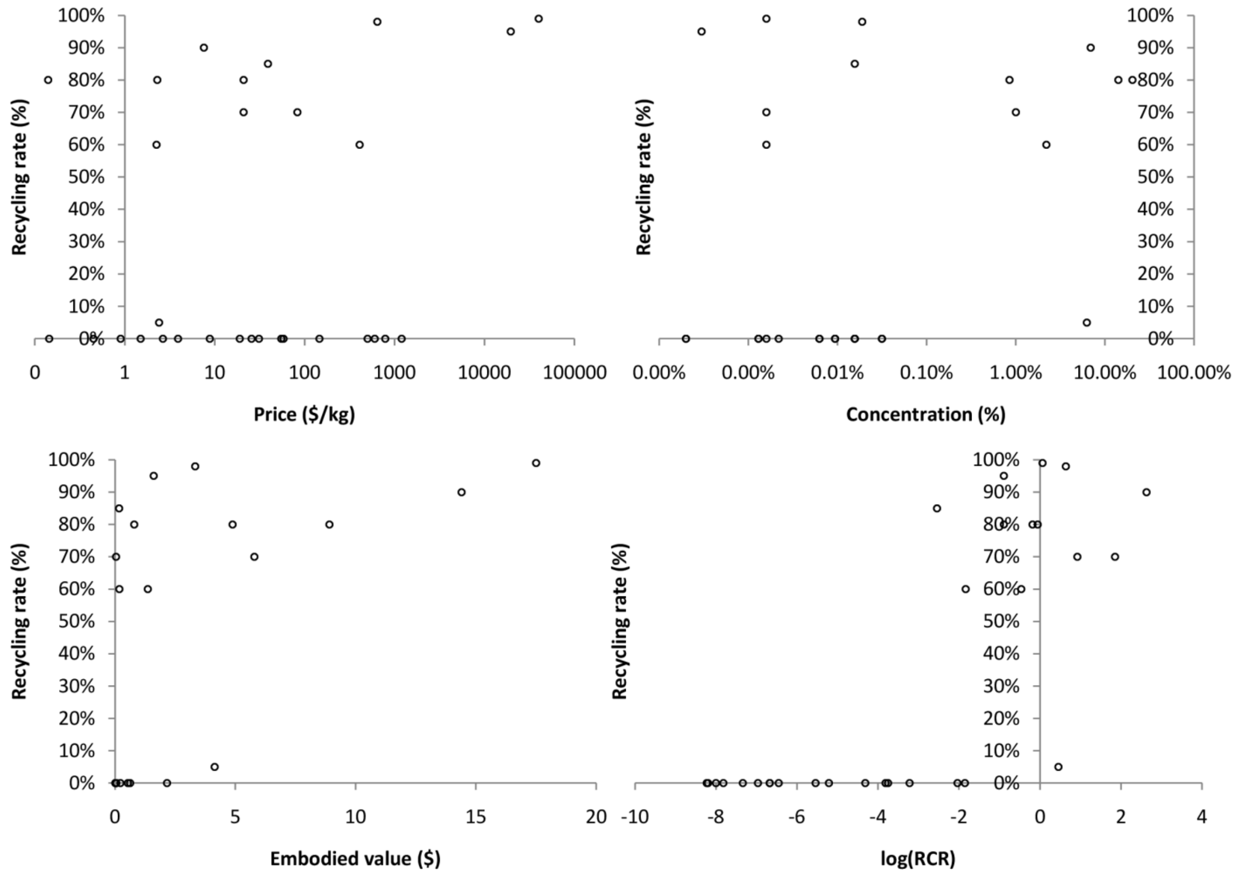

Figure 2 Scatter plots between different variables and recycling rate (%).

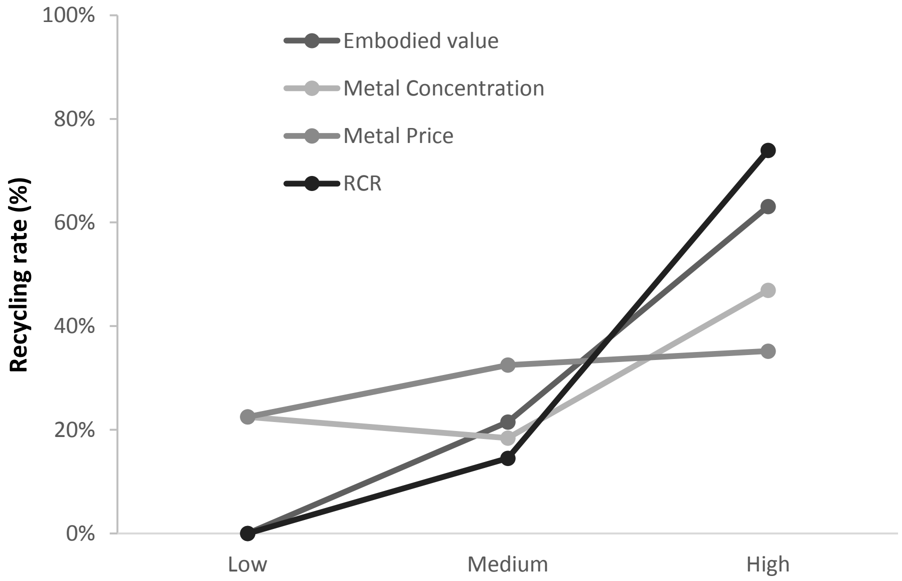

Figure 3 Average recycling rate when data are sorted by tercile of values.

	Price		Concentration		RCR		Embodied Value	
	Low	High	Low	High	Low	High	Low	High
Average Recycling Rate	31.0%	33.8%	21.6%	43.2%	0.0%	64.8%	10.3%	54.5%
Standard deviation	0.39	0.44	0.38	0.42	0.00	0.35	0.27	0.41
Equality of means*	-0.18 (p=0.85)		-1.48 (p=0.15)		-7.20 (p=0.00)		-3.47 (p=0.0017)	
Conclusion	Equal means		Equal means		Non-Equal means		Non-Equal means	

Table 2 Tests of mean equality when the sample is sorted by increasing value and breaking down in two part. *When variances are equals we perform the t-test of egality of means and the Satterthwaite–Welch t-test otherwise (for unequal variances).

Tables 3, 4 and 5 provide estimate of specification 1-5 with OLS, GLM and FRMER models. Most of the time, all of the variables are significant at 5% and sometime 1% of risk. The signs of different variable coefficients are identical across the models and are in line with theoretical expectations. In this way, the price is positively correlated with recycling rate. The higher is the metal concentration in the product, the less is the cost of metal recovery so the higher is recycling rate. The effect of supply competition is also perceptible through the results. Indeed, the effect of *RCR*, *threshold* and *logarithm of RCR* are all positive. In this regard, the more important is the metal production concentration relatively to metal mining concentration, the more the recycling rate of the metal will be important. This means that the presence of high concentration (low cost) mining alternatives disfavors the recycling of metal from low metal grade products. The effect of embodied value is also observable with a significant coefficient of 0.02. This means that an increase of one dollar of the metal value embodied in the computer is correlated to a rise of two percent point of the recycling rate.

In addition, as expected the prediction of OLS models generates impossible forecasts. The OLS methods also provide significant estimates of the intercept. The interpretation of these results is problematic because it allows a positive (non zero) recycling rate with a zero level for price/concentration and RCR variables. This is why we need to go further by using GLM and FRMER models.

All variables are also significant in the GLM and FRMER models. The different coefficient associated with the variables cannot be directly compared with OLS estimations due to the nonlinear transformation. The predictions provided by these models are more adequate. The models reproduce an important share of the variance, nearly 47% to 70% of the variance observed. The instrumentation of price with unit energy consumption and average crustal grade does not modify greatly the results although the Wald test of exogeneity reject the assumption there is no endogeneity at 5% risk threshold.

OLS - Recycling rate (%)	(1)	(2)	(3)	(4)
Intercept	0.164627 (0.06642)**	0.1560699 (0.06899)**	0.577273 (0.0670)***	0.525836 (0.1056)***
Price	0.000023 (0.00001)***	0.000017 (0.00001)**	0.000013 (0.00001)**	-
ConcentrationP	2.93432 (1.29229)**	3.306493 (1.29228)**	-	-
RCR	0.05703 (0.02182)**	-	-	-
Threshold	-	0.36863 (0.15341)**	-	-
Ln(RCR)	-	-	0.087194 (0.0140)***	0.077951 (0.01469)***
Value	-	-	-	0.021899 (0.00929)**
F	7.73***	7.20***	25.84***	23.54***
R^2	0.4714	0.4537	0.6568	0.6355
VIF	[1.01-1.06]	[1.02-1.12]	[1.05]	[2.16]
JB	6.43**	2.07	0.81	0.15
Heteroscedasticity test	1.78	0.65	1.77	3.89**

Table 3 Estimate of specifications 1-3 with OLS

GLM & FRMER - Recycling rate (%)	GLM(1)	GLM(2)	GLM(3)	FRMER(1)	FRMER(2)	FRMER(3)
Intercept	-1.826929 (.4606745)***	-1.845957 (.5039149)***	0.5137347 (0.4513746)	-1.005963 (0.252363)***	-0.99643 (.2662858)***	0.3150084 (0.2411082)
Price	0.0002185 (0.0000343)***	0.0002248 (0.0000397)***	0.0001433 (0.0000299)***	0.0000814 (0.0000119)***	0.000063 (0.000017)***	0.0000491 (0.00001)***
ConcentrationP	14.69676 (3.639253)***	16.31619 (4.46999)***	-	8.437343 (2.00898)***	9.215483 (2.259796)***	-
RCR	0.5288516 (0.2664065)**	-	-	0.2318354 (0.1014585)**	-	-
Threshold	-	2.068012 (0.924391)**	-	-	1.03647 (0.5026551)**	-
Ln(RCR)	-	-	0.7603299 (0.1641071)***	-	-	0.4303107 (0.0821208)***
Wald chi2	45.18***	36.63***	46.79***	53.37***	42.93***	67.58***
R^2	0.5388	0.5042	0.7054	0.4714	0.4537	0.6568
Wald test of exogeneity	-	-	-	5.53**	6.94***	8.65***

Table 4 Main results associated with specifications 1 to 3. Note: Generalized Linear Models (GLM), Fractional Response model with endogenous regressors (FRMER). Energy consumption per unit of metal (GJ/t) and average grade of metal in crustal crust is used as instruments.

OLS/GLM - Recycling rate (%)	OLS(4)	OLS(5)	GLM(4)	GLM(5)
Intercept	0.525836 (0.1056)***	0.61849 (0.065842)***	0.492242 (0.628568)	0.688861 (0.442526)
Ln(RCR)	0.077951 (0.01469)***	0.070753 (0.021253)***	0.713117 (0.173157)***	0.596868 (0.120218)***
Value	0.021899 (0.00929)**	-	0.077208 (0.067875)	-
Ln(Value)	-	0.032299 (0.022157)	-	0.260828 (0.110927)**
F	23.54***	22.83***		
Wald chi2			24.21***	26.54***
R^2	0.6355	0.6284	0.6604	0.6711

Table 5 Main results associated with specification 5 including embodied metal value.

3.2 Marginal effects

To make an appropriate interpretation of variable coefficients in the different models, we compute the average marginal effects on recycling rate for the different variables (see figure 4 and table 6). Four interesting statements can be drawn from these computations. First, the average marginal effect of metal price while significant is low. A metal price increase of 1000$ per kg leads to an average of **+1.94 percentage points** of recycling rate. Second, increasing the metal concentration in product greatly enhances the recycling rate. An addition of 1 point of percentage of metal concentration is correlated to a rise of metal recycling rate by +**2.52 percentage points**. Third, increasing the RCR by one corresponds to a rise of recycling rate by +**6 points of percentage**. Fourth, metal which have a concentration in product higher than their mining concentration also have a higher recycling rate of approximately 31 percentage points. The effect of the embodied value is significant and close to 0.02 indicating that one dollar of metal value corresponds to an increase of the recycling rate by 2 points of percentage. However, the average marginal effect is no longer significant when using GLM models. Conversely, the same specification with the embodied value in logarithm reaches opposite conclusions. In any events, the value is at best indicating that a one unity increase[4] of the metal value logarithm is correlated to a rise of 3 points of percentage of recycling rate.

[4] This represents an average increase of each embodied metal value by 3.92$ for the sample (mean = 2.22, median = 0.17).

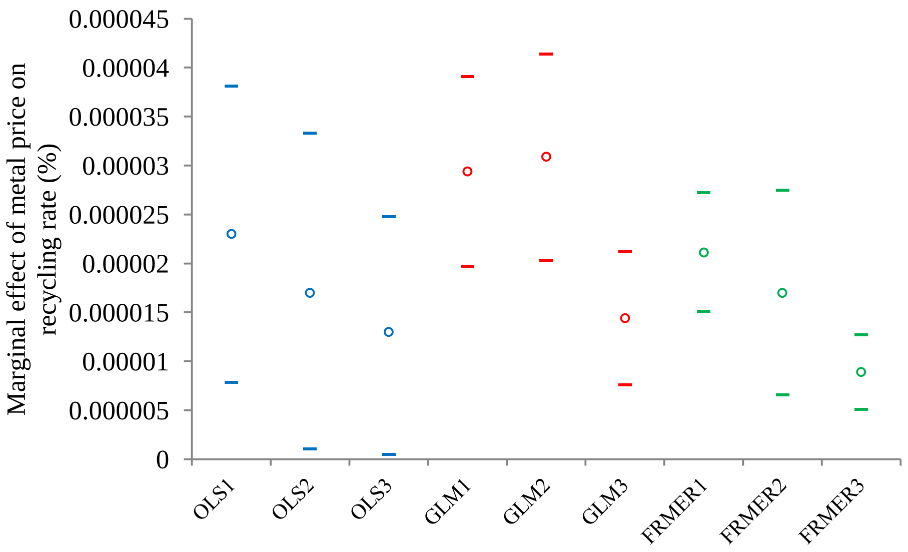

Figure 4 Marginal effects of price on metal recycling rate according to different modelizations. Note: Average marginal effect across models: 0.0000194.

Variable		OLS1	OLS2	GLM1	GLM2	FRMER1	FRMER2
ConcentrationP	Mean	2.9343	3.3065	1.9777	2.2392	2.1911	2.4942
	Upper bound (95%)	5.5907	5.9628	2.6842	3.0398	2.9103	3.3367
	Lower bound (95%)	0.2780	0.6502	1.2712	1.4386	1.4719	1.6517
		OLS2	GLM2	FRMER2			
Threshold	Mean	0.3686	0.2838	0.2805			
	Upper bound (95%)	0.6840	0.4520	0.5008			
	Lower bound (95%)	0.0533	0.1156	0.0602			
		OLS3	OLS4	GLM3	GLM4	GLM5	FRMER3
ln(RCR)	Mean	0.0872	0.078	0.0765	0.0768	0.0631	0.0781
	Upper bound (95%)	0.1159	0.1081	0.0878	0.0983	0.0758	0.0896
	Lower bound (95%)	0.0585	0.0478	0.0651	0.0554	0.0504	0.0665
		OLS1	GLM1	FRMER1			
RCR	Mean	0.0570	0.0712	0.0602			
	Upper bound (95%)	0.1019	0.0070	0.1077			
	Lower bound (95%)	0.0122	0.1353	0.0128			
		OLS4	GLM4				
Value	Mean	0.0219	0.0083				
	Upper bound (95%)	0.04095	0.021				
	Lower bound (95%)	0.00284	-0.005				
		OSL5	GLM5				
ln(Value)	Mean	0.0323	0.0276				
	Upper bound (95%)	0.0778	0.0433				
	Lower bound (95%)	-0.0132	0.0119				

Table 6 Average marginal effect of different variable on recycling rate for different models.

3.3 Predictions

We report in figure 3 the predicted and actual recycling rate for specification 3 across different models. As we can see, the GLM and FRMER models perform better than OLS models. The OLS forecast is more erratic and get a higher dispersion than the forecast of GLM/FRMER models. Nonetheless, despite a good overall forecast, all models fail to predict correctly the recycling rate of different metals like lead (overestimation) or cobalt (underestimation). This could come from other variables not taken into account in our different specifications like the effect of REACH regulations which are difficult to model.

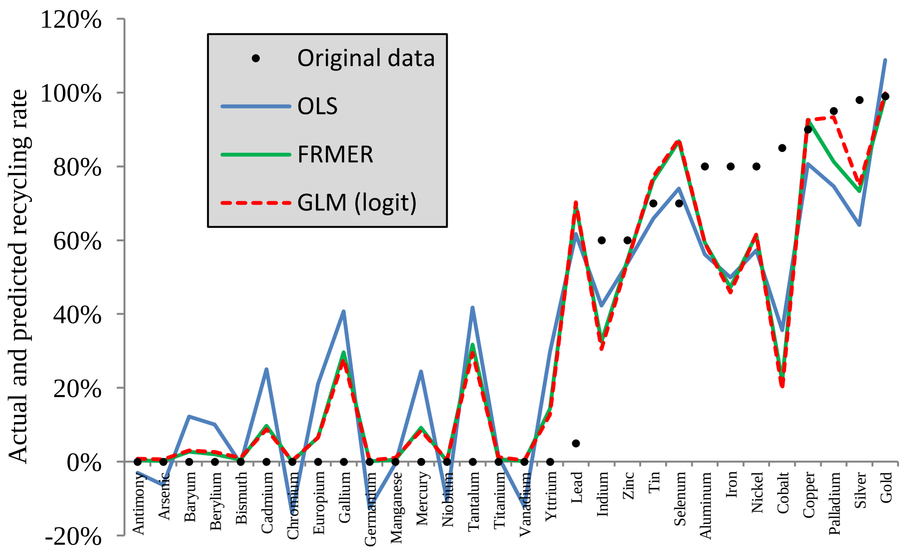

Figure 5 Predictions of specification (3) according to different models.

4. Discussion

In the discussion part, we deal with different robustness and sensitivity analysis associated with the outcomes get in the results section. Then we discuss the impact of the different statements described in results section for public polices and future studies.

4.1 Does metal price really matters? A robustness analysis

The results get in this study are important because it seems that the effect of metal price on metal recycling rate is very low. These results are in line with low price elasticity of metal recycling flows find in the economic literature (see introduction). Moreover, another study related to the end of life metal recycling rate and performed on another cross sectional database reaches the same conclusion (Fizaine, 2019). Our result is thus not specific to the metal recycling efficiency rate.

One can ask whether this effect could come from our choice to introduce metal price in level rather than in logarithm. This choice does not affect the low level of marginal effect of metal price (see alternative robustness analysis presented in table 5). For instance, the highest estimate found in robustness analysis is +7.9 percentage points of recycling rate per unit of price logarithm (1.2). Remember that at the average observation of the sample (28\$/kg[5]), an increase of one unit of logarithm represents nearly 50\$/kg which is approximately equivalent to a tripling of price. Although these large and temporary price variations can occur naturally, it is quite unlikely that governments can reach this target by the tax lever. In addition, the price effect is not different when considered alone (1.4).

We have also conducted a sensitiveness analysis (see appendix 2 - sensitiveness analysis). We delete one metal each time and reiterate the estimation of OLS and GLM model for specification (1) which integrates all variables. The conclusion for price effect does not change and is still significant. Nonetheless, we observe that gold and palladium impact the price effect (in level) although the variable remains significant. We find a similar sensitivity for iron with the *concentrationp* variable and for copper, selenum and lead with the RCR variable.

[5] Here we compute the exponential of the mean of price in logarithm. This mean differs from the average price (see descriptive statistics.

Lastly, we have also performed different robustness analyses using left censured Tobit model because different metals are not recycled in our sample (see appendix 3). The marginal effects for price remain significant, low and close to the range of other estimates (1.4-3.5x10^{-5}). Conversely, the marginal effect of others variables increase.

Recycling rate (%) - OLS	(1)	(1.2)	(1.3)	(1.4)
Intercept	0.1646268 (0.06642)**	0.686629 (0.170334)***	0.684212 (0.135858)***	0.279579 (0.071993)***
Price	0.000023 (0.00001)***	-	-	0.000021 (0.000001)**
Ln(Price)	-	0.078853 (0.021525)***	0.035633 (0.023799)	-
ConcentrationP	2.934317 (1.29229)**	-	-	-
Ln(ConcentrationP)	-	0.075673 (0.020497)***	0.028281 (0.024365)	-
RCR	0.0570336 (0.021819)**	0.032890 (0.022386)	-	-
Ln(RCR)	-		0.072373 (0.021908)***	-
F	7.73***	9.25***	14.82***	5.50**
R^2	0.4714	0.5163	0.6310	0.1642
JB	6.43**	0.73	2.02	4.55
White test	1.78	1.86	0.67	0.80

Table 7 Robustness analysis. Note: GLM estimations give similar results.

4.2 Internalization of externalities in metal prices

As described before, the response of recycling rate to price seems to be very low. In those conditions, one can ask whether the internalization of externalities in metal price could lead to higher metal recycling rate.

At 100$ per ton of $C0_2$ equivalent, price metal increase remains greatly moderate for most of metals. Except for aluminum (a 35% price increase) and steel (+100%), the impact is low for base metal: copper (+3.68%), nickel (+3.10%), zinc (+13.78%). Precious and minor metals get similar results: gold (+3.13%), Silver (3.05%), palladium (1.99%), Indium (+2.5%). Therefore, due to a low elasticity of metal price to carbon tax and a low elasticity of recycling rate to metal price, increasing metal price thanks to the internalization of externalities should not help to achieve high recycling rate target.

Obviously, greenhouse gases emissions are not the only externalities associated with primary metal production (e.g. environmental burden of waste disposal). Moreover, we do not discuss here the usefulness of public policies of internalizing the cost of greenhouse gases emissions; we simply show that there is no overlap between climate public policies and resource conservation policy.

4.3 Modification of metal concentration in products (eco-conception)

Increasing metal concentration in products could be more promising as public policies than using the price channel. This option has already been advocated by the partisan of eco-conception (Braungart and McDonough, 2011). Make more easily recoverable metals in products by increasing their concentration could reduce the cost of recycling thus promote it. Increasing metal concentrations in products could also foster recycling rate through the channel of competition between primary and secondary production. If urban mining (recycling) is less costly than primary mining, activities will gradually switch to the former.

Unfortunately, by aiming cost reduction, component miniaturization and nanotechnologies are preventing this effect. Indeed, there is here a paradox carried by the 3R strategy (reduce, reuse and recycle): public policies implementing them self-neutralize. A paradox that lead the first principle (Reduce) to drive the third out (Recycle).For instance technical progress and cost optimization have led to a downward trend of precious metals content in electronic products although that is not systematic for all metals (Adie et al., 2016; Cui and Roven, 2011). Another phenomenon is the substitution of pure metal by a lower quantity of metal mixture. This can only lead to downward incentives to extract and recycle metals due to lower metal value content and to increasing technical difficulties to recovery each element.

4.4 Metal depletion and decreasing deposit concentrations

An increasing number of studies show that average metal grade deposits are continuously decreasing. This can be observed at different scale (deposits, country, global) and different metals (Crowson, 2012; Mudd, 2010; Schodde, 2010). It leads to an increasing energy(Fizaine and Court, 2015), water and acid input consumptions(Mudd, 2010; Mudd and Diesendorf, 2008) but could also make recycling more viable and profitable (increase of RCR). Obviously, this can only happen if (i) metal grade deposits continue to decline, (ii) metal concentration in products raise or remain stable, (iii) the effect of technical progress reduction cost is not unbalanced in favor of primary mining. Regarding the overall view of the scholar J. Tilton suggest that this last assumption does not happen in the "benevolent past" (Tilton, 2003) and that the rise of the recycling due to mineral depletion is not expected to be true in the mid-term (Tilton, 1999). Obviously this optimist forecast about future primary metal depletion is not shared by some other scholars (Kerr, 2014; Northey et al., 2014; Ali et al., 2017) but is beyond the scope of this paper.

4.5 What is lacking? - Improving our knowledge about price effect on recycling rate

Our models are not perfect and need to be improved in numerous ways. First, due to the lack of data and more generally of information, we use cross sectional data. This implies that we do not catch the dynamic of recycling rate. Although, the dynamic of recycling rate for many metals are flat, the use of panel data may greatly changes the results. Second, the economics of recycling rate involve many complexities not captured by our model. For instance, the presence of organic component, the number of product parts and elements (Dahmus and Gutowski, 2007; Greenfield and Graedel, 2013; Gutowski et al., 2013), the dispersion between the average metal concentrations, the interaction effect with the concentration of other metals (coproduct recycling) or the diversity of products could greatly modify the profitability of recycling. Unfortunately, these variables are rarely quantified and even less rarely linked to recycling rate. Therefore, improving our knowledge about recycling is equivalent to raise the question about the availability of comprehensive and interdisciplinary data associated with recycling.

5. Conclusion

In this paper, we explore the different factors relative to the recycling rate of metals in computer. We can explain the recycling rate of metals by their price, their concentration in the product and the relative metal concentration between products and primary deposits. The marginal response of recycling rate to price seems to be very low whatever the specification and the model used. This finding is in line with the sparse literature on metal recycling flow. Others technical factors (relative to metal concentration) could have a deeper impact on recycling rate although their modifications with public policies could be challenging. Lastly, there may be some crowding out effect between circular economy levers, especially between dematerialization and recycling activities.

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Appendix

Appendix 1.1 - Instrumental variables for metal price

IV - Recycling rate (%)	(IV1.1)	(IV1bis)	(IV1.2)
Intercept	0.1673336 (0.0618967)***	-0.0043171 (0.0985931)	0.1644332 (0.0618433)***
Price	0.0000219 (0.0000069)***	-	0.000023 (0.0000069)***
Ln(Price)	-	0.0594803 (0.020499)***	-
ConcentrationP	2.914621 (1.203681)**	4.262002 (1.361367)***	2.935725 (1.203088)**
RCR	0.0570325 (0.0203215)***	0.0522964 (0.020814)**	0.0570337 (0.0203127)***
Wald-chideu	25.51	23.25	26.78
R^2	0.4709	0.4483	0.4714
First stage			
F	120	789	1548
R^2	0.92	0.98	0.99
Instruments for price	Average grade in crust	Average grade in crust	Average grade in crust
	UnitaryEnergyconsumption	UnitaryEnergyconsumption	Five year lead metal price
Exogeneity of IV			
Sargan (score)	1.1291 (p = 0.2880)	0.105358 (p = 0.7455)	1.11921 (p=0.2901)
Basmann chi2	0.977713 (p = 0.3228)	0.088107 (p = 0.7666)	0.96882 (p = 0.3250)

Appendix 1.2 FRMER results with different instrumental variables and models

GLM & FRMER - Recycling rate (%)	GLM(1) link = logit	GLM(2) link = probit	FRMER (1.1)	FRMER (1.2)
Intercept	-1.826929 (.4606745)***	-1.059855 (0.2573156)	-1.005963 (0.252363)***	-1.073982 (0.260287)***
Price	0.0002185 (0.0000343)***	0.0001179 (.000022)***	0.0000814 (0.0000119)***	0.0001298 (0.0000274)***
ConcentrationP	14.69676 (3.639253)***	8.816868 (2.048088)***	8.437343 (2.00898)***	8.887523 (2.049361)***
RCR	0.5288516 (0.2664065)**	0.239629 (0.1041614)**	0.2318354 (0.1014585)**	0.24192 (0.1059287)**
Av. Marginal effect Price	0.0000294***	0.000029***	0.0000211***	0.0000314***
Av. Marginal effect Concent.	1.977687***	2.166764***	2.191102***	2.15305***
Av. Marginal effect RCR	0.0711656**	0.0588893**	0.0602055**	.0586064**
Wald chi2	40.51***	37.55***	53.37***	33.23***
R^2	0.5388	0.5251	0.4714	0.4714
Wald test of exogeneity	-	-	5.53**	0.53

Appendix 2 - Sensitivity analysis for specification 1

Price effect	CoeffOLS	t-value	CoeffGLM	z-value
1	0.000023	3.0890218	0.00021853	6.34251718
2	0.000023	3.04609264	0.00021487	6.21682606
3	0.000024	3.52111105	0.00021546	5.8043915
4	0.000023	3.04591681	0.00021483	6.21410215
5	0.000023	3.04602982	0.00021482	6.21418988
6	0.000023	3.0550414	0.00021786	6.39327767
7	0.000023	3.04625958	0.00021493	6.22009535
8	0.000023	3.04603778	0.00021482	6.21537523
9	0.000023	3.04597305	0.00021484	6.21483168
10	0.000024	3.53530878	0.00023777	7.31427405
11	0.000022	3.15633569	0.00022099	6.29704914
12	0.000023	3.21022126	0.00022401	6.34335629
13	0.000023	3.06039178	0.00021996	6.51612613
14	0.000023	3.05918761	0.00021855	6.3690771
15	0.000023	3.05744953	0.00021861	6.43846659
16	0.000023	3.0685561	0.00022365	6.74313576
17	0.000023	3.24319429	0.00022278	6.12414062
18	0.000023	3.04604784	0.00021483	6.21460277
19	0.000023	3.04648488	0.00021497	6.22409096
20	0.000024	3.37505485	0.00023158	6.65118172
21	0.000023	3.04691991	0.00021514	6.23276923
22	0.000040	2.41094253	0.00023749	7.12129741
23	0.000019	2.41244395	0.0001527	4.34677267
24	0.000023	3.12381735	0.0002133	6.35020543
25	0.000023	3.11652941	0.00021701	6.2747484

26	0.000023	3.04892375	0.00021549	6.26432933
27	0.000023	3.04597899	0.00021483	6.21432742
28	0.000023	3.04635068	0.00021496	6.2221865
29	0.000023	3.04692754	0.00021508	6.23199923
30	0.000023	3.18664969	0.00022647	6.35286121

Concentration P	Coeff	t-value	Coeffglm	z-value
1	2.42216864042598	1.58387502922824	12.5320922527957	3.23934130931676
2	2.89078208070413	2.20151028714727	14.3956778274842	3.94909488772636
3	3.19264251238441	2.69092281957862	16.288835116852	4.47444596636755
4	2.8906489856624	2.20129345701122	14.3951546019954	3.94863244528755
5	2.89119056857711	2.20204155254838	14.3975733426777	3.95018818137783
6	2.88881769561848	2.20201068792602	14.3797556369337	3.95020666083091
7	2.89066320995544	2.2014287214392	14.3949760356367	3.9489156812036
8	2.89023845820261	2.20122429502931	14.3923714146623	3.94824242061719
9	2.89075742890998	2.20143265611757	14.3956576702454	3.9489354327424
10	3.11561541098519	2.61899640675414	16.4018838753441	4.45451849187002
11	3.05579855621419	2.47730795299052	14.8024067882978	3.79182804150268
12	3.02260459756971	2.35369098476442	15.1620269409246	4.04450912379946
13	2.88707098960997	2.20173711281508	14.3668475391282	3.94967881809882
14	2.8343522377023	1.31835732727486	14.7741125252087	2.14495589315144
15	2.88480841952818	2.20012516237624	14.3538692884679	3.94490919777537
16	2.88584325969194	2.20246985934498	14.3548861461914	3.95182144163231
17	3.04694540161827	2.39352550859336	15.6996894613945	4.11686693779484
18	2.891288256893	2.20209383040845	14.3981634748268	3.95034472435824
19	2.89000224747619	2.20106369991295	14.3909601345683	3.94791300001362
20	3.02982595228113	2.45613083490217	15.5813270110787	4.07794302578205
21	2.89038487325529	2.20129661180835	14.3931968745433	3.94863897703307
22	2.99435570162534	2.32777582587576	14.7440792886467	4.04701891569393
23	2.96858532019015	2.30799609501731	14.6198993771628	4.01914597046539
24	3.23497907957478	2.49579257821217	16.9038248722045	5.09563106347375
25	3.06605112400088	2.30908628927694	13.5916361977673	3.63888535413876
26	2.88635778435386	2.19979309052411	14.3668843090673	3.94369174709842
27	2.89093714844656	2.20166661074634	14.3964909300904	3.94942454893813
28	2.89052539551567	2.20128058827878	14.3942693546325	3.94860656205623
29	2.88940153090088	2.20079440386587	14.3871563231464	3.9471431609017
30	2.90560258448703	2.256077303476	14.7433211800502	3.9106594728264

RCR	Coeff	t-value	Coeffglm	z-value
1	0.0590799938858098	2.64988714969997	0.529073636002518	1.99642339886082
2	0.0563440541431601	2.54200271617773	0.514472396768426	1.9880819977069
3	0.0533147806035845	2.66429045943686	0.437148374946569	2.57612546940083
4	0.0563464564538031	2.54204201747022	0.514503613401108	1.98802461074776
5	0.0563426810168062	2.54208082683608	0.514508157376046	1.98800419867647
6	0.0562982647255993	2.54204299383644	0.513327675510568	1.99022721580045

7	0.0563439771034554	2.5420345405866	0.514459477365966	1.98810239988094
8	0.0563582361854432	2.54308058762084	0.514786299190712	1.98739432001878
9	0.0563449173537282	2.54199222297193	0.514483747023239	1.98806373002008
10	0.0596050355825796	2.96927698750786	0.603764749022162	1.97187711435645
11	0.130700614375147	2.97173894427902	0.779334685368163	1.57164759084673
12	0.0541514386361695	2.48613396856749	0.457127360708328	2.22816437187564
13	0.0562818468519962	2.54265799085185	0.512788549311952	1.99127903653447
14	0.0574777464052564	2.44637327090344	0.528543306564444	1.98685071767611
15	0.056381451434405	2.54875021944838	0.51515929561859	1.98540710869711
16	0.0562333510550594	2.54206248642116	0.511440200562084	1.99426950402574
17	0.0584335558698592	2.7212324581615	0.567239403091228	1.97128826837846
18	0.0563400286197299	2.54188136515534	0.514449561943511	1.98812965864552
19	0.056356416836162	2.5430488587842	0.514719629083671	1.9875187665212
20	0.0569933007795829	2.73868416182045	0.516062009353362	2.16958216867136
21	0.0563411398881096	2.54202133031237	0.514370387315121	1.98826426109378
22	0.0579972388551178	2.67055410269053	0.530434269790068	1.9836038320276
23	0.0578151864181302	2.66162890465552	0.528873185406358	1.97682614912906
24	0.0569811551493359	2.64607297898309	0.589437350381421	1.66827658804989
25	0.0514283413189071	2.13737402609764	0.858165764727905	1.12827247013069
26	0.0564331809664394	2.5497015657529	0.516478373352298	1.9827171503345
27	0.0563437790379702	2.54199542486446	0.514486313538111	1.98805647743785
28	0.0563441505699101	2.54202679997769	0.514444153462792	1.98813195903912
29	0.0563659066260565	2.54392716336787	0.514919698285861	1.98702985180144
30	0.0578175986655311	2.65798198203425	0.536155438124745	2.04322200044329

Appendix 3 – Alternative models – Left Censured Tobit

Recycling rate (%)	Tobit(1)	Tobit (2)	Tobit (3)	Tobit(4)	Tobit(5)	Tobit(6)
Intercept	-.2513849 (0.1814775)	-0.3051003 (0.1928403)	0.5635287 (0.0996537)***	-0.2233031 (0.1971879)	0.3537006 (0.1297589)**	0.5912701 (0.095384)***
Price	0.000035 (0.000009)***	0.000024 (0.0000128)*	0.000014 (0.000005)**	-	-	-
ConcentrationP	5.291654 (1.193004)***	5.955068 (1.278419)***	-	-	-	-
Threshold	-	0.7215953 (.2437557)***	-	-	-	-
RCR	0.0934093 (0.0368382)**	-	-	0.0437285 (0.0463913)	-	-
Ln(RCR)	-	-	0.2111639 (0.0352678)***	-	-	0.1697008 (0.0319274)***
Value	-	-	-	0.0778412 (0.0216533)***	-	-
Log(Value)	-	-	-	-	0.2077594 (0.0339973)***	0.0694806 (0.0218846)***
F	8.62***	8.56***	20.17***	8.28***	37.34***	19.83***
R²	0.4038	0.3997	0.6580	0.3043	0.4920	0.6333
JB	4.62*	1.43	3.37	3.10	0.41	6.84**