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From trash to treasure: Trade insights on raw material substitution

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From Trash to Treasure: Trade Insights on Raw Material Substitution

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May 8, 2026

Abstract

Recycling and waste trade are increasingly important for mitigating supply risks and environmental concerns associated with raw material imports, yet little is known about the economic and technical potential for substitution between recycled and virgin materials. This paper estimates material-specific cross-price elasticities of substitution using novel global trade data for major recyclable materials from 2013 to 2023, instrumenting virgin-material prices with export restrictions. Results show substantial heterogeneity across materials: those with established recycling technologies respond strongly to price incentives, while others display limited substitutability, highlighting the role of technological feasibility beyond economic viability. Using the estimated elasticities, I evaluate the policy mix required to meet the EU's 25 percent recycled-content target and document a central misalignment between circular-economy goals and climate-optimal policy.

Keywords: Trade, Scrap, Raw Materials, Circular Economy

JEL Classification: F18, Q53, Q37, Q27

1 Introduction

Global demand for industrial raw materials has grown rapidly and is expected to accelerate further as economies digitalise and electrify (IEA, 2025), yet access to these inputs has become increasingly uncertain. Production is geographically concentrated and major suppliers have expanded their use of export restrictions (Svatikova et al., 2025), exposing import-dependent economies to geopolitical risk. These supply-side concerns coincide with mounting environmental pressures: metal production alone accounts for roughly 40% of industrial greenhouse gas emissions and 10% of global energy use (Raabe, 2023), while secondary material production requires substantially less energy than primary extraction and reduces emissions by 56–98% (BAFA, 2024). Despite these geopolitical and environmental incentives, the adoption of recycled inputs remains surprisingly limited across most materials (IEA, 2024), raising a central question: why is substitution toward secondary materials so low, even when the potential benefits for environmental outcomes and supply chain resilience are large? Since the decision to use scrap inputs in production is ultimately an economic one (Hagelüken and Goldmann, 2022), understanding the economic incentives behind secondary-material demand is essential for the design and evaluation of recycling and circular-economy policies.

This paper examines whether the adoption of recycled inputs is constrained by *economic viability*, specifically whether higher prices for virgin materials induce demand to shift toward recycled alternatives. Using global trade data for 21 recyclable materials from 2013–2023, I estimate the material-specific cross-price elasticity of demand between virgin and recycled imports. To isolate virgin-material price variation unrelated to scrap demand, I instrument prices with an index of virgin material export restrictions imposed by major producing countries. These policies generate upstream supply shocks that shift virgin prices independently of secondary material demand. I then use the estimated elasticities to quantify the taxes and subsidies required to meet the European Union’s 25% recycled-content target, drawing on a reduced-form calculation. Lastly, I analyze how the input share changes when the environmental externalities of primary extraction, relative to secondary material use, are internalized in relative prices using the social cost of carbon (SCC).

The results reveal substantial heterogeneity in substitution patterns, with cross-price elasticities ranging from 0.9 to 3.4. Elasticities are higher for materials with established and commercial recycling technologies (notably bulk metals such as iron and aluminium) and lower for materials where recycling processes remain less established (such as nickel or cobalt). This implies that *economic viability* becomes central once *technological feasibility* is given. Finally, I show, that SCC-consistent pricing would raise recycled-input shares beyond 25% EU target for many materials.

The idea that secondary materials can reduce the environmental footprint of industrial production and enhance supply security is long-standing (Risch, 1978; Ayres, 1997). Many

scrap streams contain higher material concentrations than primary ores making recycling an efficient alternative to virgin extraction ([Johnson et al., 2007](#)). As a result, much of the existing research on recycling emerges from engineering and industrial ecology ([Brunner and Rechberger, 2016](#); [Brooks et al., 2019](#); [Raabe, 2023](#)).¹

In economics the theoretical literature has begun to investigate the interaction of global virgin and recycled material markets: [Egger and Keuschnigg \(2024\)](#) develop a model linking global recycling to final-goods production, and [Söderholm and Ekvall \(2020\)](#) discuss optimal recycling policy in globally integrated material markets. Empirical economic research, by contrast, has primarily examined scrap flows through a “waste-haven” lens. [Kellenberg \(2015\)](#) show that high-income countries with strict environmental regulations tend to export scrap to lower-income countries with laxer standards, a pattern echoed by [Bernard \(2015\)](#). China’s abrupt ban on scrap imports, after years of absorbing more than half of global scrap trade, further exposed this system: [Atalar et al. \(2024\)](#) and [Sommer \(2024\)](#) document the emergence of new scrap-importing countries, particularly Turkey, and the associated environmental harms. While this literature provides valuable insights into the consequences of international scrap trade, it pays comparatively little attention to scrap as a production input rather than a disposal challenge.

Only a small number of studies explore the economic determinants of secondary-material consumption. However, existing work faces two main limitations. First, studies focusing on specific countries or individual materials offer limited comparability across materials. Second, analyses that aggregate across many materials, such as [Dussaux and Glachant \(2019\)](#), mask material-specific dynamics, despite evidence that recycling technologies and substitutability differ widely across materials. [Zhou et al. \(2022\)](#) argue explicitly for material-level analyses of global scrap flows. Along these lines, [Fizaine \(2020\)](#) examine the economic determinants of recycling rates across materials and find limited price responsiveness, but their cross-sectional design restricts inference about causal price effects. Overall, the literature on the economic determinants of secondary-material demand is small and still lacks global, material-specific, causally identified evidence on substitution between virgin and recycled inputs. This paper contributes by providing such evidence for 21 recyclable materials using a consistent global dataset.

The paper also speaks to the academic and policy analysis of achieving the goals set in EU Critical Raw Materials Act (CRMA) ([EC, 2024](#)). One of the ambitions is to achieve a 25% recycled-content share for critical raw materials. Most of the discussion is based on the supply side - which is essential: [Baldassarre and Carrara \(2025\)](#) discuss the relevance of R&I to reaching the necessary scrap supply need to achieve the 25% goal. [Crîstiu et al. \(2025\)](#) discuss optimal design of sustainable supply chains for critical raw materials

¹A second strand of work comes from scrap-management and urban-planning perspectives ([Yang and Innes, 2007](#); [Reno, 2015](#)). These studies analyze domestic collection, sorting, and recycling systems and highlight important institutional and infrastructural constraints. However, they offer only a partial view of recycled-input use in an increasingly globalized economy, where scrap flows routinely cross borders and international markets shape secondary-material demand.

recycling.

My paper contributes to the literature by studying the demand side. By setting the 25% target the EU implicitly assumes that substitution is technologically feasible and is or can be made economically viable through price-based instruments. My results suggest that this assumption holds for materials with established and commercial recycling technologies, such as aluminum, lead and iron. For these materials, substitution elasticities are high and moderate taxes and subsidies can meaningfully shift input use. For materials with low elasticities, however, even large interventions may generate limited substitution, indicating that complementary investments in technology, scrap collection, and sorting are required.

Lastly, this paper contributes to the literature on optimal policy-mix design for achieving environmental objectives. This literature is extensive (Fullerton and Wu, 1998; Bennear and Stavins, 2007; Acemoglu et al., 2012; Milios, 2021; Svatikova et al., 2025). Söderholm and Ekvall (2020) emphasize that although taxes on virgin inputs and subsidies for recycled inputs are economically equivalent in that both operate through the relative price of inputs, they act on distinct policy margins. Taxes directly penalize the use of virgin materials, whereas subsidies are framed as support for recycling activities. Because these instruments differ in their political salience and distributional implications, they are often viewed as politically complementary rather than interchangeable in policy design. Although the European Commission has long acknowledged the importance of resource taxation for advancing a circular economy (EC, 2011), governments have remained hesitant to impose virgin-material taxes due to competitiveness concerns (Domenech and Bahn-Walkowiak, 2019).

By providing first-order approximations of the tax and subsidy levels required to achieve given recycled-content targets, this paper provides insights on feasible policy combinations. I show pronounced heterogeneity in the policy effort required to achieve recycled-content targets. This heterogeneity can be traced to three fundamental factors: differences in baseline recycled-input shares, variation in the virgin–recycled price wedge, and material-specific substitution elasticities.

The remainder of the paper proceeds as follows. Section 2 describes the mechanism which forms the foundation for the empirical analysis. Section 3 presents the construction of the global virgin and scrap trade dataset. Section 4 outlines the empirical strategy that exploits supply-driven price shocks from export restrictions. Section 5 reports the aggregate and material-specific elasticities. Section 6 uses these elasticities to quantify material-specific policy mixes to achieve higher scrap input rates and compares them to the social-cost-of-carbon benchmark. Section 7 concludes.

2 Conceptual Framework

This section describes a conceptual framework of material flows. The objective is to formalize the substitution decision between virgin and recycled inputs, which forms the theoretical foundation for the empirical specification in Section 4.

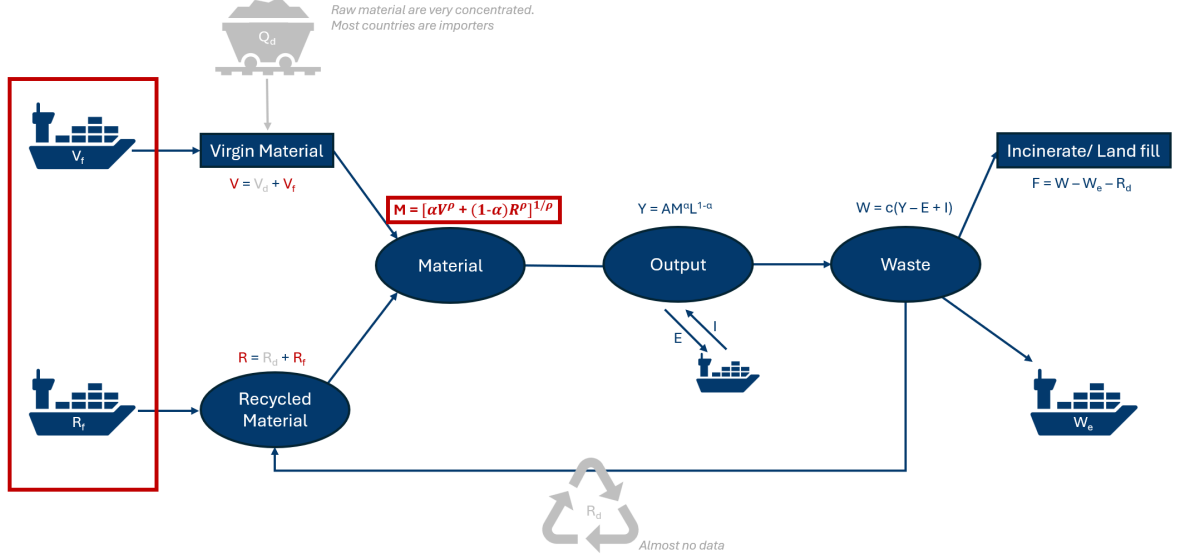


Figure 1: Closed-loop supply chain framework

Notes: This figure illustrates a closed-loop flow of materials. See text for variable definitions.

Building on Egger and Keuschnigg (2024), Figure 1 illustrates a closed-loop flow of materials. Total material input is $M = V + R$, where virgin material combines domestic extraction and imports ($V = V_d + V_f$) and recycled material combines domestically recycled and imported scrap ($R = R_d + R_f$). These feed into production $Y = AM^\alpha L^{1-\alpha}$, generating waste $W = c(Y - E + I)$, which is then either exported (W_e), recycled domestically (R_d), or disposed of via incineration and landfill ($F = W - W_e - R_d$).

Two distinct decisions shape scrap flows. The first is the upstream scrap *treatment decision* between landfiling, incineration, recycling, or export, which determines the supply of recyclable material available to the circular economy. The second is the *input-choice decision*, in which production sectors choose the mix of virgin and recycled materials used in production. In this paper, I focus on the input-choice decision, treating the availability of recycled inputs as given.²

To formalize the substitution between virgin and recycled materials, I assume that production sectors combine virgin inputs V and recycled inputs R into a material aggregate M . Virgin and recycled materials are imperfect substitutes, reflecting well-documented

²This focus is motivated by two considerations. First, abstracting from recycled-supply conditions allows the analysis to isolate demand responses. Second, data on recycling activity is available only at an aggregated material level, whereas the analysis in this paper requires studying individual materials due to their heterogeneous characteristics. Consequently, I abstract from modeling the supply side in detail.

differences in purity, composition, processing requirements, and technical compatibility across metals and plastics (McMillan et al., 2012; Huysveld et al., 2022). I capture this using a constant-elasticity-of-substitution (CES) aggregator:

$$M = [\alpha V^\rho + (1 - \alpha)R^\rho]^{1/\rho}, \quad \rho = \frac{\sigma - 1}{\sigma}, \quad (1)$$

where σ denotes the material-specific elasticity of substitution and α is a material-specific weight that reflects structural or technological dependence on virgin inputs.

Recycled inputs typically require additional processing, such as sorting, removal of impurities, or specialized equipment, before they can be used in production (Tercero Espinoza et al., 2020). These frictions effectively raise the cost of using recycled inputs. I represent them as an *adaptation cost* t_R so that the effective price of the recycled input is:

$$p_R^{eff} = p_R + t_R \quad (2)$$

Reductions in t_R , for example due to technological improvements or higher-quality collected scrap, increase the effective substitutability between virgin and recycled materials even when observed market prices remain unchanged.

Given input prices (p_V, p_R^{eff}) , a representative producer chooses V and R to minimize costs:

$$\min_{V, R} C = p_V \cdot V + p_R^{eff} \cdot R, \quad (3)$$

The first-order conditions yield the following input ratio:

$$\frac{R}{V} = \left(\frac{p_V}{p_R^{eff}} \cdot \frac{1 - \alpha}{\alpha} \right)^\sigma. \quad (4)$$

This expression highlights the mechanism at the core of the analysis: when the price of virgin materials rises relative to recycled inputs, producers substitute towards greater use of recycled inputs. The extent of substitution depends on the elasticity of substitution σ , while α captures structural factors such as technological barriers or quality constraints that make virgin inputs more or less central in production.

This framework delivers two testable predictions that guide the empirical analysis. First, an increase in the price of virgin materials p_V raises the input ratio R/V , that is, producers shift toward greater use of recycled inputs. Second, the magnitude of this response is governed by the elasticity of substitution σ , which varies across materials depending on the maturity of recycling technologies and the quality of available scrap. The empirical strategy for testing these predictions is outlined in Section 4.

This framework highlights that virgin and recycled materials are not perfect substitutes due to the additional costs associated with recycling. However, as the adaptation cost t_R

approaches zero, the substitution decision becomes determined by relative prices.

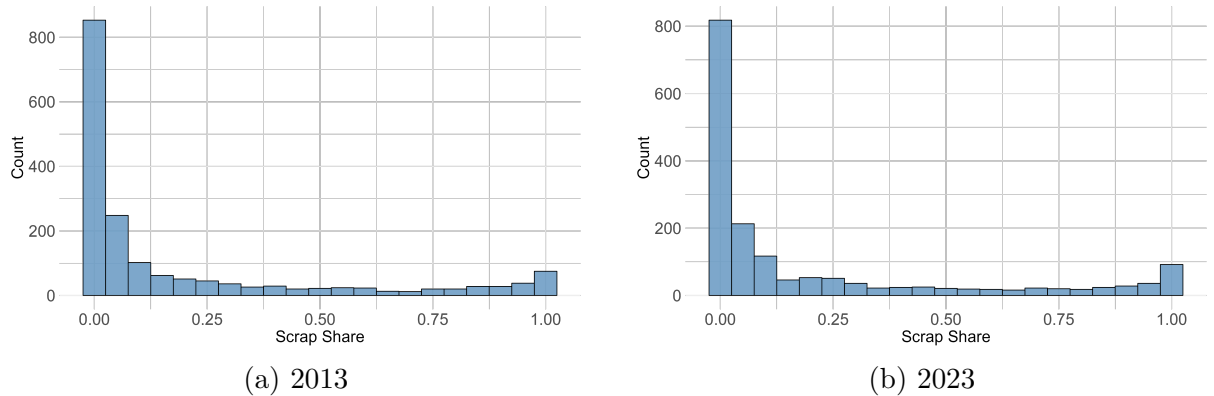
3 Data

I construct a unique dataset which integrates information from international trade statistics of virgin and scrap materials, global commodity markets, and policy-based export restriction. The dataset focuses on 21 industrial materials that meet two criteria: (i) they are identified by the European Union as recyclable materials, and (ii) their corresponding scrap products have distinct HS6 codes. The sample period spans 2013–2023. This section describes the construction of the material–country–year panel and provides descriptive patterns.

Trade Data: The starting point is the selection of the appropriate HS6 codes. Scrap material codes are taken from [Eurostat \(2023\)](#), which provides a list of HS codes for scrap of recyclable materials. Virgin material HS codes are identified using material reports from [SCRREEN Project \(2023\)](#) and supplementary research. Trade data is from BACI ([Gaulier and Zignago, 2010](#)).

For most materials, scrap imports represent only a small share of total material inflows. Figure 2 shows the distribution of scrap share imports across all materials for the first and last year of my sample. The median scrap share is approximately 5%, indicating that global demand for most industrial materials is met primarily through virgin production. A detailed presentation by material is shown in Figure A.1. A few high-volume materials (aluminum, iron and steel, and copper) account for the bulk of scrap trade and exhibit substantially higher scrap shares, which increases the mean and widens the distribution (Table B.1). This pattern is persistent over the sample period and suggests substantial heterogeneity in substitution potential across materials.

Figure 2: Distribution of Scrap Share

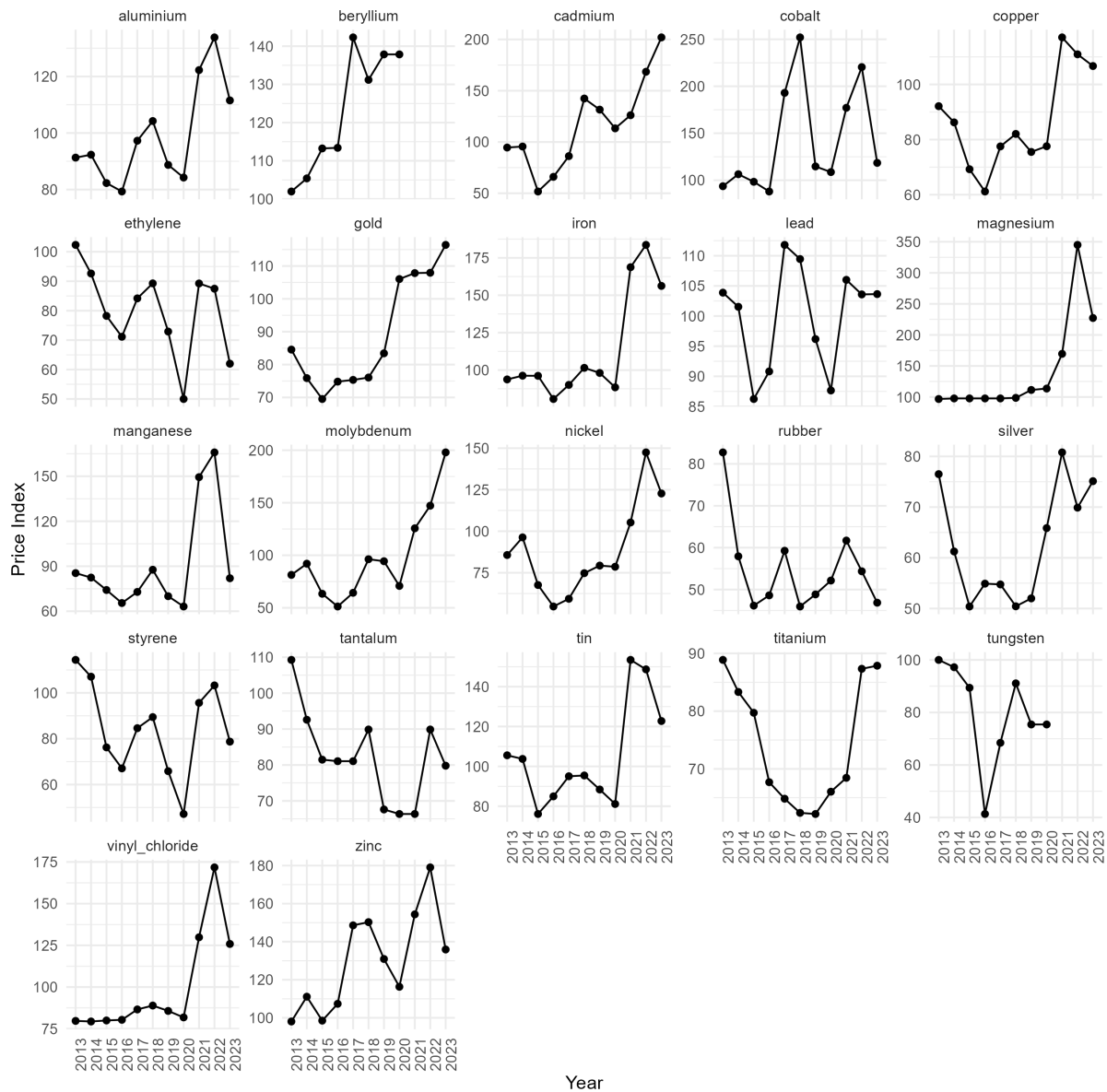


Notes: This figure shows the distribution of $scrap_share_{jmt}$, defined as scrap imports of a material as a share of total material imports, for the first and last year of the sample. Calculations are based on BACI trade data. See text for further details.

Prices: Global virgin material prices, denoted $price_{mt}$, are measured using spot prices

from major commodity exchanges (WRDS, 2024). These spot prices correlate strongly with global average trade unit values for the corresponding virgin materials (measured as total value over total quantity), as shown in Table B.2. For each material, I construct an index normalized to 2018: ($price_{m(t=2018)} = 100$). The prices display substantial time-series variation and considerable heterogeneity across materials (see Figure 3). This variation in material-specific global prices is a key source of identifying variation for the substitution elasticity.

Figure 3: Virgin Material Price Indices



Notes: This figure shows virgin material price indices over time. Price variation across materials and over time is the key source of identification. See text for further details.

Export Restrictions: For an IV strategy described in the next section, I use data from the OECD Inventory of Export Restrictions on Industrial Raw Materials (OECD, 2024). This dataset provides exporter–HS6 product–year information on export restrictions im-

posed by countries that account for more than 3% of global primary production. Because restrictions are reported at the level of exporter i and HS product p , I construct a global, material-level index that aggregates across exporters and HS products within each material category. The goal is to translate exporter-product-level restrictions into a measure of global supply pressure at the material level. The construction follows a weighted scheme designed to reflect both product-level and exporter-level relevance. First, each exporter-product pair is coded as one if any export restriction is in place and zero otherwise. Second, since many materials map to multiple HS codes, each HS product is weighted by its share in global trade of the corresponding material to reflect its relative importance. Third, to account for the fact that restrictions imposed by major exporters affect global supply more strongly than those imposed by minor exporters, each exporter-product pair is additionally weighted by the exporter's share of world exports for that HS code. Combined, these steps yield an index that captures the global intensity of export restrictions for each material in a given year.

Formally, the index for material m in year t is defined as:

$$barrier_index_{mt} = \sum_{p=1}^P \sum_{i=1}^I \frac{q_{p(t-1)}}{q_{m(p)(t-1)}} \times \frac{q_{ip(t-1)}}{q_{p(t-1)}} \times barrier_{ipt} \quad (5)$$

The weight $\frac{q_{ip(t-1)}}{q_{p(t-1)}}$ captures an exporters i share of global trade for product p one year prior to the introduction of an export restriction for this product p by the exporter i . The second weight $\frac{q_{p(t-1)}}{q_{m(p)(t-1)}}$ captures the products share in total material flows m . Using lagged trade weights ensures that the index captures the relevance of each exporter and HS product without introducing mechanical contemporaneous correlations between the instrument and price outcomes.

The resulting index ranges from 0 to 1, with higher values indicating greater intensity of export restrictions on a given material. By construction, this index reflects the global supply-side pressure stemming from policy-induced disruptions in raw material availability.

4 Empirical Strategy

This section outlines the estimation of the elasticity of substitution between virgin and scrap materials, using the cross-price elasticity of scrap-import demand with respect to exogenous variation in virgin-material prices. The empirical strategy is designed to test the two predictions derived in Section 2: that higher virgin material prices shift demand toward recycled inputs, and that the magnitude of this response varies across materials depending on the elasticity of substitution σ .

4.1 Estimating Sigma

The parameter of interest is the elasticity of substitution, σ , from (4). This equation implies the following log-linear relationship between the relative demand for recycled inputs and the relative input prices:

$$\ln\left(\frac{R}{V}\right) = \sigma \cdot \ln\left(\frac{p_V}{p_R}\right) + \sigma \cdot \ln\left(\frac{1-\alpha}{\alpha}\right) \quad (6)$$

A direct estimation of (6) is not feasible for two reasons. First, the dependent variable $\ln(R/V)$ is undefined in a number of cases, because $V = 0$. Second, systematic data on scrap prices are unavailable. Estimating the equation using only p_V would therefore absorb p_R into the error term. The empirical strategy below addresses both issues.

4.1.1 Relative Demand

The dependent variable $\ln(R/V)$ is undefined in a number of observations, since a number of importers exclusively imports scrap ($V = 0$). Dropping these cases would remove economically meaningful variation. To address this, I work with the scrap share in total imports of each material:

$$scrap_share_{jmt} = \frac{q_scrap_{jmt}}{q_scrap_{jmt} + q_raw_{jmt}} \quad (7)$$

This is the share of scrap imports of country j of material m in total imports of the respective material m .³ This share is proportional to the theoretical quantity ratio. Using the identity

$$\ln\left(\frac{R}{V}\right) = \ln\left(\frac{scrap_share}{1 - scrap_share}\right) \equiv \text{logit}(scrap_share),$$

the log of the relative ratio can be written in terms of the log-odds of $scrap_share$. Given that the dependent variable is a fraction $[0, 1]$ (either because an importer exclusively imports virgin material ($R = 0$) or exclusively imports scrap ($V = 0$)), I estimate the conditional mean using the fractional logit method of (Papke and Wooldridge, 1996, 2008):

$$\text{logit}(\mathbb{E}[scrap_share_{jmt}]) = \beta_1 \cdot \ln(price_{mt}) + \gamma_{jt} + \delta_{jm} \quad (8)$$

where $price_{mt}$ captures p_V and β_1 is the slope of the log-odds of the *conditional mean* scrap share with respect to virgin-material prices. To interpret β_1 as the CES elasticity of substitution σ , I show in the following subsection that my instrument for $\ln(price_{mt})$ captures exogenous movements of p_V in the relative price $\ln(p_V/p_R)$. In addition, an

³Total material imports include refined primary materials and scrap material.

assumption is required that deviations of the realized share from the CES-implied share are mean-zero conditional on X_{jmt} .⁴ Under these conditions, β_1 can be mapped to the CES elasticity of substitution σ .

4.1.2 IV Estimation

The second key challenge in estimating substitution between virgin and recycled inputs is the absence of transparent scrap-price data. If virgin and scrap prices co-move in response to common demand shocks and scrap price is omitted, the error term becomes correlated with the observed virgin price. This would generate omitted-variable bias that attenuates the estimated effect. To examine the relationship of virgin and scrap prices, I construct a global trade-unit-value-based scrap price index and correlate it with the virgin material price index. As shown in Table 1, there is a positive and significant correlation, consistent with the assumption that both prices respond to common underlying shocks.

Including a trade unit value price index as a proxy for p_R directly in the demand equation would be endogenous, as unit values respond to demand shocks through quality choice and markups. Hence, the identification of the elasticity of substitution requires isolating variation in virgin prices that is orthogonal to scrap prices. To address this problem, I employ an instrumental-variables strategy that leverages shocks to the global supply of virgin raw materials. Specifically, I instrument the virgin material price with an index of export restrictions imposed by countries that account for more than 3% of global virgin material production. The identifying assumption is that export restrictions, which are driven by domestic political, strategic, or fiscal considerations, are not systematically correlated with the demand-side shocks in importing countries that also influence scrap prices.

Column (2) of Table 1 illustrates this logic: once the virgin price is replaced with its IV-predicted counterpart, the significant and positive correlation between virgin and scrap prices disappears. This is consistent with the instrument removing demand-driven co-movements.

Several concerns may arise regarding the instrument. First, export restrictions could affect scrap prices through equilibrium channels. As restriction lead to higher virgin material prices, demand switches towards scrap materials resulting in a rise of scrap prices. Second, restrictions might not be motivated by domestic considerations but instead be a response to global price cycles. I test both concerns by examining the correlation of the export restriction index with my constructed scrap prices proxy and with lagged virgin prices. Table 2 presents the results and shows no statistically significant correlation; therefore, neither concerns appear to apply.

⁴ Suppose the CES mechanism implies an index η_{jmt} such that the implied share is $\Lambda(\eta_{jmt})$. Assuming $s_{jmt} = \Lambda(\eta_{jmt}) + u_{jmt}$ with $\mathbb{E}[u_{jmt} | X_{jmt}] = 0$ yields $\mathbb{E}[s_{jmt} | X_{jmt}] = \Lambda(\eta_{jmt})$ and thus $\text{logit}(\mathbb{E}[s_{jmt} | X_{jmt}]) = \eta_{jmt}$. If instead unobserved heterogeneity enters inside the index (e.g. $s_{jmt} = \Lambda(\eta_{jmt} + \varepsilon_{jmt})$), the mapping is generally approximate and β_1 should be interpreted as a reduced-form composition response.

Table 1: Correlation of Virgin and Scrap Material Prices

Dependent Variable: Model:	Scrap Price	
	(1)	(2)
Virgin Price	0.5377*** (0.0967)	
$\widehat{\text{Virgin Price}}$		0.0482 (0.2887)
<i>Fixed-effects</i>		
Year	Yes	Yes
Material	Yes	Yes
<i>Fit statistics</i>		
Observations	236	236
R ²	0.63503	0.60391

Notes: This table reports the correlation between the virgin commodity exchange price index and the global scrape trade unit value index which is a proxy for scrap prices. Both indices are measured as the natural logarithm of the indices. The unit of observation is material-year. $\widehat{\text{Virgin Price}}$ Index is the predicted prices based on Equation 9. Standard errors are shown in parentheses, clustered at the year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. See text for further details.

Formally, the first-stage relationship between virgin prices and the export restriction instrument is:

$$\ln(\text{price}_{mt}) = \pi_1 \cdot \text{barrier_index}_{mt} + \gamma_m + \delta_t + \epsilon_{mt}, \quad (9)$$

where $\text{barrier_index}_{mt}$ is a material-level index summarizing the number of export restrictions imposed by countries accounting for more than 3% of global supply (see Section 3 for details). The material and time fixed effects γ_m and δ_t absorb long-run material-specific trends and global shocks, respectively.

Because the main specification is a nonlinear fractional logit model, standard 2SLS cannot be used. Instead, I follow the control function (CF) (two-stage residual inclusion approach) by Terza et al. (2008), which is consistent for nonlinear models with endogenous regressors. The first-stage residual captures unobserved shocks that are correlated with the endogenous regressor. Including this residual in the second-stage equation controls for endogeneity arising from unobservables that jointly affect virgin and scrap prices as well as the relative demand.

The CF estimator proceeds as follows. In the first stage, I estimate equation (9) and

Table 2: Correlation of Export Restrictions with Virgin and Scrap Material Prices

Dependent Variables: Model:	Virgin Price (1)	Virgin Price Lagged (2)	Scrap Price (3)
Restriction Index	0.4081** (0.1646)	0.2084 (0.2025)	0.0197 (0.1178)
<i>Fixed-effects</i>			
Year	Yes	Yes	Yes
Material	Yes	Yes	Yes
<i>Fit statistics</i>			
Observations	236	236	236
R ²	0.70612	0.67923	0.60391

Notes: This table reports the correlation between the export restriction index and virgin material prices, one-year lagged virgin material prices as well as scrap material prices. Virgin prices are measured as the natural logarithm of the commodity exchange price index and scrap prices are measured as the natural logarithm of the global scrape trade unit value index which is a proxy for scrap prices. The unit of observation is material-year. Standard errors are shown in parentheses, clustered at the year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. See text for further details.

obtain the residuals $\hat{\epsilon}_{mt}$. In the second stage, I estimate:

$$\text{logit}(\mathbb{E}[\text{scrap_share}_{jmt}]) = \beta_1 \cdot \ln(\text{price}_{mt}) + \lambda \cdot \hat{\epsilon}_{mt} + \gamma_{jt} + \delta_{jm}, \quad (10)$$

The export-restriction instrument isolates a supply-driven component of virgin-material price variation that is orthogonal to scrap-market conditions. Within the control-function framework, the first-stage residual $\hat{\epsilon}_{mt}$ captures the residual correlation between virgin prices and unobserved determinants of scrap prices that arises from common demand shocks.

The term λ provides a direct test of endogeneity: if $\lambda \neq 0$, virgin prices are indeed endogenous, and the naïve fractional logit estimator is biased. Inference for all control-function estimates relies on nonparametric bootstrap standard errors, accounting for the two-stage nature of the estimator and the presence of generated regressors (Horowitz, 2001; Terza et al., 2008).

Equation (10) includes two sets of fixed effects that absorb unobserved heterogeneity and reduce identification concerns. Importer–time fixed effects (γ_{jt}) control for all time-varying importer characteristics, such as macroeconomic shocks, general environmental or recycling policy changes, or shifts in aggregate demand, that could otherwise influence the substitution response. Importer–material fixed effects (δ_{jm}) account for time-invariant differences across importer–material pairs, including recycling capacities and structural differences in material use. The resulting variation used to identify β_1 comes from within-

importer changes in material composition that are not attributable to broader economic or structural factors.

To further strengthen the identification, I exclude large global exporters of virgin materials from the sample whenever their global export share exceeds 10 percent. Major exporters may exert market power or influence world prices through their own production or policy decisions. By focusing on importers that act as price takers in world markets, I restrict the sample to countries for which movements in global prices are more plausibly exogenous with respect to their substitution choices. This refinement reduces the risk that the observed price variation reflects strategic supply behavior rather than exogenous shocks.

Within the presented framework, β_1 recovers a consistent estimate of the elasticity of substitution σ .

4.2 Robustness

To assess the sensitivity of the results to the choice of functional form and estimation method, I re-estimate the model using two alternative approaches: a linear IV specification and a Poisson Pseudo-Maximum Likelihood (PPML) estimator.

The linear model is useful both as a benchmark and because it allows for a straightforward implementation of standard IV techniques. The specification is:

$$scrap_share_{jmt} = \beta \cdot \ln(\widehat{price}_{mt}) + \gamma_{jt} + \delta_{jm} + u_{jmt}. \quad (11)$$

where $\ln(\widehat{price}_{mt})$ is the fitted value from the first-stage regression of virgin prices on the export restriction instrument. In this setting, β measures a semi-elasticity: a 1% increase in the virgin price changes the scrap share by $\beta/100$ percentage points. Although the specification does not impose the CES structure, it provides a transparent check on whether the core findings are driven by the nonlinear link function used in the fractional logit specification. The two-stage setup ensures that the coefficient captures only the exogenous, supply-driven component of the raw material price variation.

I also estimate a PPML model, which is commonly used for fractional and zero-inflated dependent variables and has desirable robustness properties.⁵ The PPML estimator is consistent under general forms of heteroskedasticity and easily accommodates observations with scrap share equal to zero. While it enforces non-negativity but not the upper bound of one implied by fractional data, it remains appropriate as long as the conditional mean is correctly specified (Silva and Tenreiro, 2006). The PPML specification is:

$$\mathbb{E}[scrap_share_{jmt}] = \exp(\beta_1 \cdot \ln(\widehat{price}_{mt}) + \lambda \cdot \widehat{\epsilon}_{mt} + \gamma_{jt} + \delta_{jm}), \quad (12)$$

where the inclusion of the first-stage residual $\widehat{\epsilon}_{mt}$ parallels the control-function correction

⁵This applies to the distribution of *scrap_share* as shown in Table B.1.

used in the fractional logit model. Although PPML does not yield a direct estimate of the structural elasticity of substitution σ , the coefficient β_1 can be interpreted as an elasticity of the scrap share with respect to the virgin price.

Comparing results across the linear IV, fractional logit, and PPML estimators provides a comprehensive robustness assessment. Each estimator has different strengths: the fractional logit offers structural consistency, the linear IV model provides simplicity and transparency, and PPML ensures robustness to heteroskedasticity and zeros. The consistency in sign, magnitude, and significance across these approaches strengthens confidence in the empirical finding.

4.3 Material Specific Estimates

Materials differ markedly in their technological properties, recycling costs, and market structure. It is therefore unlikely that a single elasticity of substitution adequately describes all materials. In this subsection, I discuss the material-specific estimation of substitution elasticities while retaining the IV strategy developed above.

To obtain material-specific substitution elasticities, I estimate a fractional logit model in which both the endogenous price term and the control-function residual are interacted with a material indicator. Interacting the first-stage residual allows the second stage to flexibly capture differences in the correlation between virgin prices and unobserved shocks across materials, even though the first stage is estimated jointly.⁶

The second-stage specification is:

$$\begin{aligned} \text{logit}(\mathbb{E}[\text{scrap_share}_{jmt}]) = & \sum_m \beta_m \cdot [\ln(\text{price}_{mt}) \cdot \mathbf{1}_{\text{material}=m}] \\ & + \sum_m \lambda_m \cdot [\hat{\epsilon}_{mt} \cdot \mathbf{1}_{\text{material}=m}] + \gamma_{jt} + \delta_{jm}. \end{aligned} \quad (13)$$

The coefficients β_m are the material-specific elasticities of substitution. The coefficients λ_m capture the presence of endogeneity. A statistically significant λ_m indicates that unobserved shocks are correlated with the virgin material price variation for material m and the outcome variable, thereby justifying the use of the instrumental variables control-function correction.

To assess whether the estimated material-specific effects are driven by the fractional logit functional form, I re-estimate the model using two alternative specifications while main-

⁶A material-by-material first stage estimation is infeasible because the panel contains only eleven annual observations per material. Estimating separate first-stage regressions leads to unstable coefficients. Thus, this specification requires the assumption that the export restriction instrument affects virgin prices similarly across materials. To address the concern that the first-stage results may be driven by a particular material, I conduct a robustness check in which I re-estimate the first stage while sequentially excluding one material at a time. As shown in Table B.3, the coefficient estimates remain stable and statistically significant throughout.

taining the same control-function correction for price endogeneity: a linear IV model estimated by OLS and a Poisson pseudo-maximum likelihood (PPML) model. As discussed in the previous subsection, the estimated β_m coefficients are consistent across the fractional logit, linear OLS, and PPML specifications in terms of sign, relative magnitude, and statistical significance, indicating that the inferred material-specific substitution patterns are not sensitive to the choice of functional form.

5 Results

This section presents the estimated cross-price elasticity of demand for scrap imports in response to global raw material price fluctuations. The estimates quantify the extent to which demand can be substituted toward recycled inputs when the price of virgin materials increases, directly testing the two predictions derived in Section 2.

A rise in virgin material prices p_V narrows the price wedge between using virgin and recycled inputs, improving the *economic viability* of incorporating scrap in production. If substitution elasticities are high, relative prices are the key barrier and price-based instruments, such as virgin material taxes or subsidies for secondary inputs, can effectively shift input use. Conversely, very low substitution elasticities indicate that technological constraints dominate, implying limited scope for price-based incentives and a more central role for R&D support, recycling infrastructure investment or industrial policy.

5.1 Aggregate Effects

Table 3 compares the aggregate substitution estimates across the three econometric frameworks, namely Fractional Logit, PPML, and OLS, each presented both in a naïve specification and with the control-function correction. Across all models, the patterns are highly consistent.

In the naïve specifications, the coefficient on virgin prices is positive but small (0.19 in the fractional logit model). This attenuation reflects the omission of scrap prices: virgin and scrap prices co-move in response to common shocks, so unobserved scrap-price variation is absorbed into the error term and correlated with virgin prices. As a result, the naïve estimates do not identify causal substitution elasticities.

Introducing the control-function correction substantially increases the estimated elasticities by roughly a factor of seven across specifications, consistent with the removal of this downward bias. In the fractional logit model, the elasticity rises to 1.37, indicating elastic substitution in response to exogenous, supply-driven variation in virgin material prices. Estimates from PPML (0.96) and OLS (0.11, in semi-elasticity units) exhibit the same pattern.

The first-stage residual is as expected negative and statistically significant in all control-function specifications. The negative and statistically significant coefficient on the first-

Table 3: Aggregate Price Effect on Scrap Share - Model Comparison

Dependent Variable:	Scrap Share					
	Fractional Logit		PPML		OLS	
Model:	Naive	CF	Naive	CF	Naive	CF
Virgin Price	0.1864*	1.391**	0.0954*	0.9661**	0.0178**	0.1164**
	(0.1126)	(0.6722)	(0.0534)	(0.3958)	(0.0076)	(0.0564)
F. Stage Residual		-1.229*		-0.8843**		-0.1002*
		(0.6790)		(0.3979)		(0.0567)
<i>Fixed-effects</i>						
Imp x Material	Yes	Yes	Yes	Yes	Yes	Yes
Imp x Time	Yes	Yes	Yes	Yes	Yes	Yes
<i>Fit statistics</i>						
Observations	19,265	19,265	19,265	19,265	19,265	19,265
R ²					0.72490	0.72494

Notes: This table compares aggregate naive and control function regression results across different models as discussed in Equation 10 and 12. Virgin price is the natural logarithm of the commodity exchange price index. First stage residual is based on Equation 9. The unit of observation is importer-material-year. Standard errors are shown in parentheses, clustered at the importer-year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. See text for further details.

stage residual indicates that unobserved factors raising p_V are positively correlated with p_R , which in turn reduces demand. Incorporating the control function corrects the resulting omitted-variable bias, implying that the naïve specification understates the true effect of P_V on demand. Inference is based on nonparametric bootstrap standard errors to account for the generated-regressor structure.

The fixed effects play a central role in identification. Importer-time fixed effects (γ_{jt}) control for all time-varying importer characteristics, such as macroeconomic shocks, general environmental or recycling policy changes, or shifts in aggregate demand, that could otherwise influence the substitution response. Importer-material fixed effects (δ_{jm}) account for time-invariant differences across importer-material pairs, including recycling capacities and structural differences in material use. As a result, the coefficients are identified exclusively from variation in the relative use of scrap inputs across materials within the same importer-year, responding to material-specific price fluctuations driven by global supply conditions.

Taken together, these results show that the causal effect of virgin material prices on scrap substitution is economically meaningful once endogeneity is addressed. The consistency of the findings across Fractional Logit, PPML, and OLS reinforces the robustness of the empirical pattern.

While the baseline analysis mainly relies on nonlinear models estimated via a control-function approach, a conventional OLS-IV comparison provides a transparent benchmark

for understanding the direction and magnitude of the endogeneity bias. To facilitate interpretation of the instrument, Table 4 reports a conventional OLS–IV comparison. The naïve OLS estimate in column (1) is the same as reported in Table 3.

Table 4: Aggregate Price Effect on Scrap Share - IV

Dependent Variables: Model:	Scrap Share		Virgin Price
	OLS	IV	1. Stage
Virgin Price	0.0178** (0.0076)	0.1164* (0.0657)	
Restriction Index			0.4606*** (0.0181)
<i>Fixed-effects</i>			
Imp x Time	Yes	Yes	Yes
Imp x Material	Yes	Yes	Yes
<i>Fit statistics</i>			
Observations	19,265	19,265	19,265
F-test (1st stage), Log Price		286.47	
Wald (1st stage), Log Price		645.94	
F-test	2.9537	2.9534	3.8769
R ²	0.72490	0.72242	0.77572

Notes: This table presents the aggregate OLS IV regression results as discussed in Equation 9 and 11. Virgin price is the natural logarithm of the commodity exchange price index. The unit of observation is importer-material-year. Standard errors are shown in parentheses, clustered at the importer-year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. See text for further details.

Column (2) presents the corresponding IV estimate, which isolates exogenous, supply-driven price variation arising from export restrictions. Here the coefficient increases markedly to 0.117, indicating that a 10% increase in virgin prices raises the scrap share by approximately 1.2 percentage points. Relative to the median baseline scrap share of roughly 5%, this effect corresponds to an increase of about 24%. The substantial divergence between the OLS and IV coefficients is consistent with the endogeneity patterns identified earlier.

The first stage reported in column (3) confirms that the instrument is highly relevant. The barrier index strongly predicts virgin material prices, and the resulting F-statistic exceeds conventional weak-instrument thresholds (Olea and Pflueger, 2013). This finding mirrors the significance of the first-stage residuals in the control-function specifications reported in Table 3.

Taken together, the OLS–IV comparison provides a complement to the baseline fractional logit and PPML estimates. Across all approaches, once endogeneity is addressed, virgin price increases induce a meaningful rise in the use of recycled inputs. The magnitude, while economically significant, remains modest in absolute terms, consistent with the

technological and quality constraints that limit substitution for many materials.

5.2 Material Specific Effect

The aggregate elasticity discussed above reflects an average response across materials. Given the substantial technological and market heterogeneity among these materials, this average masks potentially large differences in substitution behaviour. This section therefore presents material-specific elasticities estimated using the control-function approach in the Fractional Logit model, complemented by OLS and PPML robustness checks. The detailed estimates for all three models are reported in Tables B.4 and B.5.

The coefficients of the fractional logit estimation are presented in Figure 4.⁷ For the majority of inputs, the cross-price elasticity of substitution is elastic ($\sigma > 1$), indicating that demand meaningfully increases for recycled inputs when virgin material prices rise. The estimated elasticities exhibit pronounced heterogeneity across materials. The pattern is consistent with the mechanism outlined in Section 2. For materials with established and commercial recycling technologies, such as aluminium, lead or tungsten, exhibit high substitution elasticities. These materials have long-established secondary markets, relatively low quality constraints, and minimal adaptation costs (Eloot et al., 2025; Zeiler et al., 2021). For these inputs, a price increase in virgin materials triggers a substantial and economically meaningful rise in demand for recycled inputs, highlighting the central role of *economic viability* once technological barriers are low.

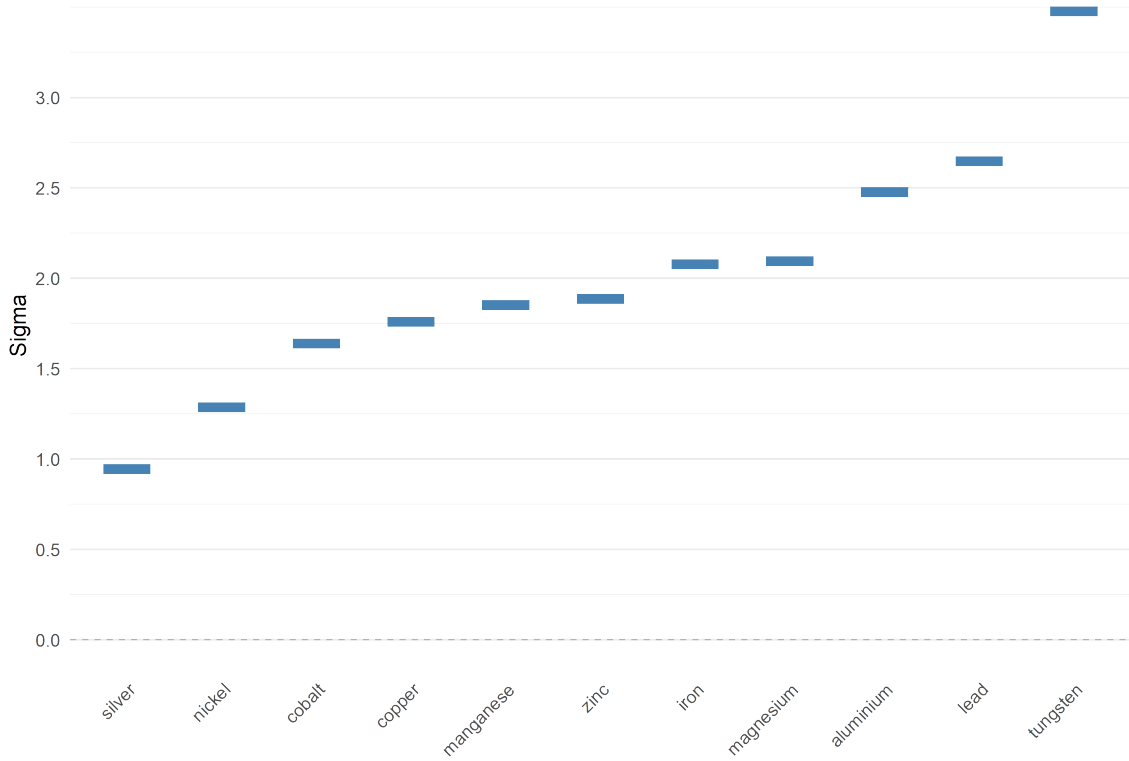
Figure 4 plots the validated elasticities from the Fractional Logit model.

As in the aggregate estimation approach, a natural concern is whether the findings depend on the functional form of the estimating equation. Comparing results across the different model specifications provides a comprehensive robustness assessment. Figure 5 visualizes the rank ordering of material-specific effects across all three specifications and shows that their relative ordering is stable. The consistency of this ranking shows the robustness of the findings. This pattern lends further credibility to the empirical strategy and underscores the importance of adopting a material-by-material approach to examining circularity dynamics.

Taken together, the material-specific results reinforce two key insights. First, substitution is highly heterogeneous, shaped by material characteristics and the state of recycling technology. Second, where technological barriers are low, demand responds strongly to virgin price changes, providing supportive evidence for the *economic viability* channel.

⁷Several materials exhibit extreme estimated elasticities and are excluded from the further discussion. Negative estimates arise for materials such as gold, where virgin and scrap prices are tightly linked, even after instrumenting. This co-movement leaves little independent variation with which to identify substitution responses. Other extreme values, including implausibly large elasticities for materials such as molybdenum, tantalum, and titanium, likely reflect severe data limitations: these materials have few observations, leading to noisy estimates and unstable control-function residuals. These cases do not align with the underlying technology and are therefore excluded from the interpretation of substitution patterns. Plastic materials are dropped from the material specific estimation, since they do not have any variation in export restrictions.

Figure 4: Material Sigmas from Fractional Logit Estimation



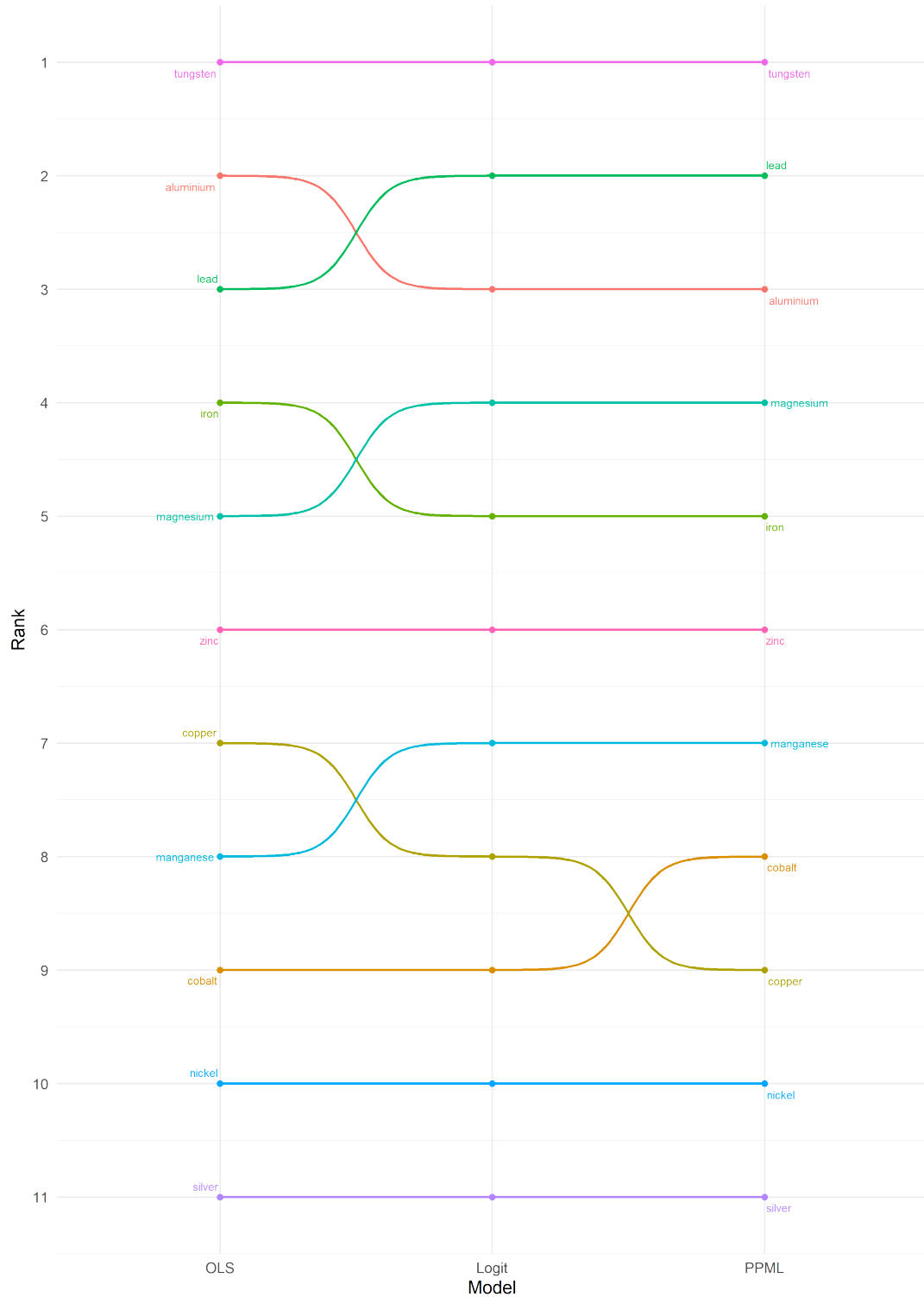
Notes: This figure displays the material specific coefficients of the fractional logit estimation based on equation 13. See text for further details.

5.3 Limitations

A key limitation of this study is its reliance on import data without domestic production data. While this is not a major concern for primary raw materials, since their production is highly concentrated and most countries are net importers, it may shape observed outcomes differently for scrap materials. Since there is almost no data available on domestic recycling activities at a granular material level, using trade data as an approximation is a common approach (DERA, 2023). This has implications for the interpretation of the findings: In countries with established recycling systems, a portion of demand is likely met by domestic scrap before imports become necessary, leading to a downward bias in substitution estimates. However, for countries without established recycling infrastructure, where scrap materials are primarily imported, the estimates should remain robust.

Moreover, this analysis assumes that the supply elasticity of recycled materials is constant across different demand levels. This is, of course, an abstraction necessitated by limited data availability. In practice, supply may become more inelastic as demand increases, for example if limited collection prevent recyclers from scaling production. As Hagelüken (2014) notes, expanding the supply of recycled materials is important to increasing recycled-input rates.

Figure 5: Ranking Material Specific Estimates Across Models



Notes: This figure visualize the rank ordering of material-specific effects across all three specifications: OLS, Fractional Logit and PPML. The consistency of this ranking shows the robustness of the findings. See text for further details.

6 Achieving Targeted Scrap Input Rates

The European Union has announced the objective of reaching a 25 percent recycled-content share in the consumption of key industrial materials by 2030 as part of its broader circular-economy strategy (EC, 2024). Yet, many materials remain below this threshold. The limited adoption of recycled inputs can be attributed to unfavorable relative prices. Virgin materials are priced sufficiently low, whereas recycled inputs involve higher marginal costs due to sorting, cleaning, and quality-adjustment requirements. As a result, firms face limited incentives to substitute towards secondary inputs, despite EU policy ambitions.

This is problematic because the environmental externalities associated with primary extraction remain substantial. Metal production alone accounts for roughly 40 percent of industrial greenhouse gas emissions and 10 percent of global final energy use (Raabe, 2023). Table 5 reports CO₂ emissions per tonne of material from virgin and recycled production. The implied emissions savings from recycling range from 56 to 98 percent, illustrating the scale of externalities not internalized in market prices.

Table 5: Current Scrap Input Shares and Virgin and Recycled CO₂ Emissions

Material	Scrap Share	Virgin	Recycled	Saving in %
aluminum	0.32	9.89	0.53	94.7%
cobalt	0.22	45.27	18.56	56.0%
copper	0.30	6.86	1.73	74.7%
iron	0.31	2.08	0.04	98.2%
lead	0.75	1.35	0.49	63.7%
magnesium	0.13	27.92	1.39	95.0%
manganese	0.09	5.53	3.32	60.0%
nickel	0.16	17.53	1.08	93.9%
silver	0.19	457.59	45.76	90.0%
tungsten	0.35	5.60	3.36	60.0%
zinc	0.14	2.69	0.13	95.0%

Notes: This table presents the end-of-life recycling input rates (EOL-RIR) and the CO₂ emissions in tonnes per tonne of virgin and recycled material production. Savings represent the percentage of emissions reduced by using recycled rather than virgin materials. See text for further details.

To increase recycled-input shares, the literature emphasizes policy instruments that alter the relative prices of virgin and secondary materials, most prominently taxes on virgin inputs and subsidies for recycled inputs. Although taxes on virgin inputs and subsidies for recycled inputs are economically equivalent in that both operate through the relative price of inputs, they act on distinct policy margins. Taxes directly penalize the use of virgin materials, whereas subsidies are framed as support for recycling activities. Because

these instruments differ in their political salience and distributional implications, they are often viewed as politically complementary rather than interchangeable in policy design (Söderholm and Ekvall, 2020). Combining the two instruments can therefore facilitate the implementation of higher recycled-input rates while limiting reliance on any single policy lever. At the same time, governments have been hesitant to impose virgin-material taxes due to competitiveness concerns (Domenech and Bahn-Walkowiak, 2019), despite the European Commission acknowledging the importance of resource taxation for advancing a circular economy (EC, 2011). Achieving ambitious targets through recycling subsidies alone, by contrast, may require substantial fiscal outlays. These considerations motivate a systematic comparison of tax–subsidy policy combinations capable of implementing a given recycled-content target.

This section investigates different policy mixes of tax rate schedules on virgin material and subsidy schedules on recycled materials which would be required to reach the EU’s 25 percent target using a partial-equilibrium framework. I then compare these required policy levels to those implied by internalizing the social cost of carbon. The analysis is based on the material-specific elasticities estimated in Section 5.2.⁸

6.1 A Framework with Taxes and Subsidies

Let p_V and p_R denote the pre-policy prices of virgin and recycled inputs. The government may impose a tax $\tau \geq 0$ on virgin inputs and a subsidy $s \geq 0$ on recycled inputs. Although taxes and subsidies are mathematically perfect substitutes, they are modelled separately, as the instruments differ in their political salience and distributional implications, as discussed above. The cost minimization yields the optimal input ratio:⁹

$$\frac{R}{V} = \left(\frac{p_V(1 + \tau)}{p_R(1 - s)} \cdot \frac{1 - \alpha}{\alpha} \right)^\sigma. \quad (14)$$

Let $\mu = R/V$ denote a recycled-to-virgin input ratio. Solving equation (14) for policies that implement a given target μ_{target} gives the policy constraint:

$$\frac{1 + \tau}{1 - s} = K(\mu_{\text{target}}) \equiv \frac{p_R}{p_V} \cdot \mu_{\text{target}}^{1/\sigma} \cdot \frac{\alpha}{1 - \alpha}. \quad (15)$$

This can be rewritten as:

$$s = 1 - \frac{(1 + \tau)}{K(\mu_{\text{target}})} \quad (16)$$

Equation (16) defines a downward-sloping implementability locus in (τ, s) -space. Through-

⁸The interpretation of the estimates as the elasticity σ holds under the assumptions discussed in Section 4.1.1.

⁹This analysis abstracts from t_R , as these costs do not change in the short term and are assumed to be constant in this scenario. Moreover, no data on t_R are available.

out, the virgin-material tax τ is plotted on the horizontal axis and the recycling subsidy s on the vertical axis, so that the slope of the locus is given by $ds/d\tau = -1/K(\mu_{\text{target}})$. As taxes and subsidies are mathematically perfect substitutes in implementing μ_{target} , additional criteria are required to select a unique policy pair.

6.1.1 Minimum-Distortion Policy

One approach is the minimum-distortion (MD) policy (Baumol and Oates, 1988). This benchmark selects the policy pair (τ, s) that minimizes the quadratic cost $\tau^2 + s^2$ subject to the implementability condition (15). Solving the associated Lagrangian yields

$$\tau^{MD} = \frac{K(\mu_{\text{target}}) - 1}{K(\mu_{\text{target}})^2 + 1}, \quad s^{MD} = K(\mu_{\text{target}}) \tau^{MD},$$

so the ratio of instruments is pinned down by the slope of the policy locus. When the target is close to the baseline μ (current input ratio), the locus is steep: meaning that marginal adjustments in the recycled-to-virgin ratio can be induced primarily through the virgin-material tax. In this region the MD solution relies relatively more on τ in comparison to more ambitious targets.¹⁰ As the target becomes more ambitious, however, K rises and the locus flattens. A flatter locus indicates that additional increases in the recycling share require disproportionately stronger incentives on the recycled-input margin. Because the MD solution equalizes marginal policy costs with marginal leverage, it adjusts by shifting weight toward the subsidy and away from the tax. Hence, the MD allocation becomes increasingly subsidy-intensive as policy ambition grows.

6.1.2 Fiscally Neutral Policy

An alternative, to prevent high expenditures on subsidies, is a fiscally neutral (FN) policy (Fullerton and Kinnaman, 1995). Under this policy, tax revenues must exactly finance the recycling subsidy. Using $R = \mu_{\text{target}} \cdot V$ and pre-policy prices, fiscal balance requires

$$\tau = s \mu_{\text{target}} \frac{p_R}{p_V}.$$

This linear relationship defines the Fiscal Neutrality Line (FNL) with slope

$$\Lambda = \mu_{\text{target}} \frac{p_R}{p_V}.$$

Because Λ is increasing in the policy target, the FNL rotates upward as ambition rises. Intuitively, when recycling remains relatively expensive, fiscal balance at higher targets requires proportionally more reliance on the tax instrument. Combining the FNL with

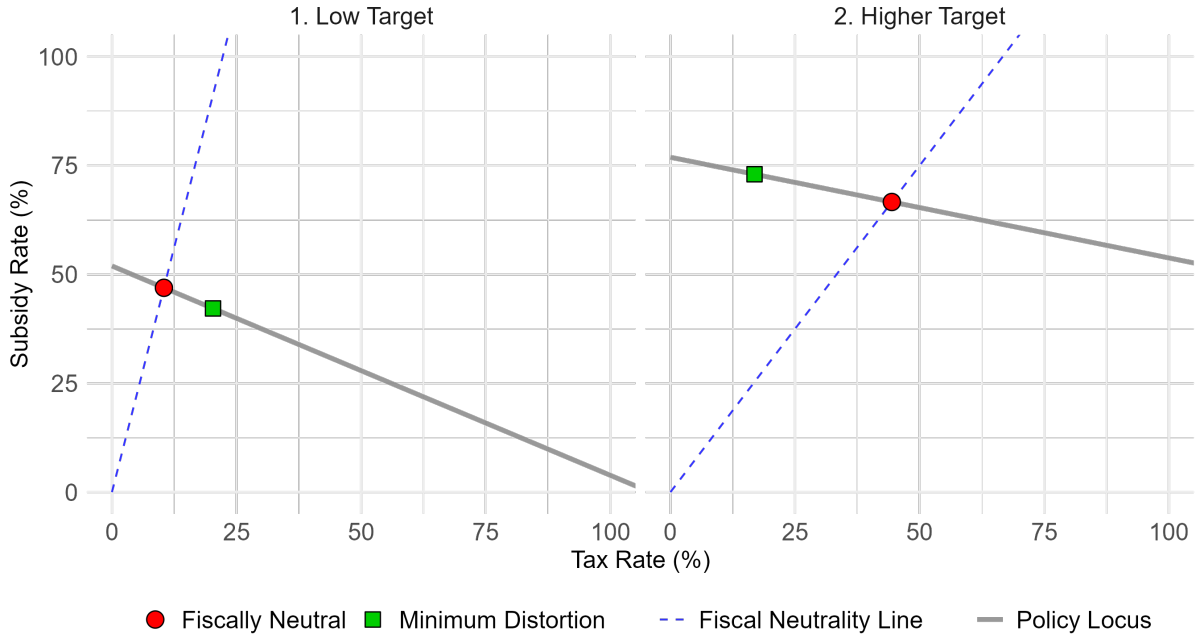
¹⁰Since $s^{MD}/\tau^{MD} = K > 1$ the subsidy remains larger than the tax in absolute terms at any given target.

the implementability constraint yields a unique fiscally neutral policy pair (τ^{FN}, s^{FN}) , both of which increase with $K(\mu_{\text{target}})$.

6.1.3 Policy Comparison

Figure 6 illustrates how the relative roles of virgin-input taxes and recycling subsidies depend on the ambition of the recycling target. The key determinant of instrument choice is the slope of the policy locus, which captures the marginal substitutability between taxes and subsidies in achieving a given recycled-input share.

Figure 6: Policy Mix Comparison: Fiscal Neutrality vs. Minimum Distortion



Notes: This figure illustrates the policy mix under Fiscal Neutrality (FN) and Minimum Distortion (MD) benchmarks for a low and a higher recycling target. The policy locus shows the set of tax and subsidy combinations that achieve a given recycled-input share. The fiscal neutrality line indicates combinations where tax revenue equals subsidy expenditure. Results are based on simulated data using the following parameter values: $\sigma = X$, $\alpha = X$, $t_R = X$. See text for further details.

As policy ambition increases, the flatter policy locus reflects the declining marginal effectiveness of taxation relative to subsidization. The MD benchmark responds by shifting weight toward the subsidy instrument and away from the tax when comparing policies across target levels, even though the subsidy remains larger than the tax in absolute terms at any given target. By contrast, the FN benchmark remains constrained by budget balance: financing higher subsidies requires proportionally higher taxes, even as the tax becomes a weaker instrument. As a result, the divergence between MD and FN policies widens with ambition. While modest increases in recycling can be efficiently achieved through taxes, higher recycled-content targets increasingly require subsidy-based incentives.

6.2 Calculation of policy schedules

To construct the tax rate and subsidy schedules, I draw on several material-specific data points. I proxy the prices of virgin and recycled materials using global trade-unit values for 2019, ensuring internal consistency across input price measures.¹¹ Estimates of recycled-input ratios vary considerably across sources. I therefore rely primarily on Eurostat (2025) and RMIS (2026) and cross-validate their estimates with other available data. Third, the substitution elasticities σ are drawn from the material-specific estimates reported in Section 5.2. Finally, the preference parameter α is recovered by rearranging equation (4) using observed prices and input ratios:

$$\alpha = \left[1 + \mu^{\frac{1}{\sigma}} \cdot \frac{p_R}{p_V} \right]^{-1} \quad (17)$$

Together, these elements yield a material-by-material representation of the technological constraints, market conditions, and price incentives that jointly determine the responsiveness of recycled-input use to policy intervention. Information on emission per ton of produced materials is from BAFA (2024).¹²

6.3 Comparison to the Social Cost of Carbon

Further, I compare the results to the scrap input share that would arise if carbon externalities were fully internalized through prices. Specifically, I consider a case in which both virgin and recycled material prices are adjusted to reflect their respective carbon emissions, priced at the social cost of carbon (SCC). This approach is equivalent to introducing a carbon price wedge into the relative price of virgin and recycled materials. Let CO_2^V and CO_2^R denote production emissions (in tCO_2 per ton of material) associated with virgin and recycled production. Internalizing the carbon externality implies the following price adjustments:

$$\begin{aligned} p_V^{\text{SCC}} &= p_V + \text{SCC} \cdot \text{CO}_2^V, \\ p_R^{\text{SCC}} &= p_R + \text{SCC} \cdot \text{CO}_2^R. \end{aligned}$$

The implied change in relative prices depends on the difference in carbon intensities between virgin and recycled production. Defining avoided emissions as

$$\Delta \text{CO}_2 \equiv \text{CO}_2^V - \text{CO}_2^R,$$

¹¹I use trade-unit values for both virgin and recycled materials, rather than mixing spot prices for virgin inputs with unit values for recycled inputs, to ensure that p_V and p_R are drawn from a consistent underlying price dataset.

¹²For materials with no information in secondary material emissions I assume a conservative reduction of 60% in comparison to the virgin counterpart.

internalizing the SCC effectively lowers the relative price of recycled inputs since $\Delta\text{CO}_2 > 0$ holds for all materials.

Given these SCC-adjusted prices, the relative demand for recycled versus virgin material is determined by the CES structure as

$$\frac{R^{SCC}}{V^{SCC}} = \left(\frac{p_V^{SCC}}{p_R^{SCC}} \cdot \frac{1 - \alpha}{\alpha} \right)^\sigma. \quad (18)$$

Following [Rennert et al. \(2022\)](#) I assume a SCC value of \$185 per tCO₂. This approach does not rely on computing an explicit per-unit subsidy for recycled inputs or tax on virgin materials. Instead, the implied incentive arises endogenously through the SCC-induced change in relative prices.

6.4 Discussion of Results

This subsection discusses three sets of results. First, I characterize the policy mixes required to attain the EU’s 25 percent recycled-input target across materials.¹³ Second, I analyze how the required tax and subsidy schedules evolve as the recycling target becomes more ambitious. Third, I compare the EU target to the recycled-input shares implied by full internalization of carbon externalities via the social cost of carbon (SCC).

Achieving the EU’s 25 Percent Target Figure 7 illustrates, for each material, the combinations of virgin-input taxes and recycling subsidies that achieve a 25 percent recycled-input share under the MD and FN benchmarks.¹⁴

The first pattern that emerges is that, for all materials except manganese, the MD benchmark assigns relatively greater weight to taxation than the FN benchmark at the 25 percent target. This suggests that, at this level of ambition, the marginal leverage of the tax instrument remains substantial: modest taxes on virgin material continue to induce substitution toward recycled inputs, thereby limiting the need for sizeable subsidy outlays.

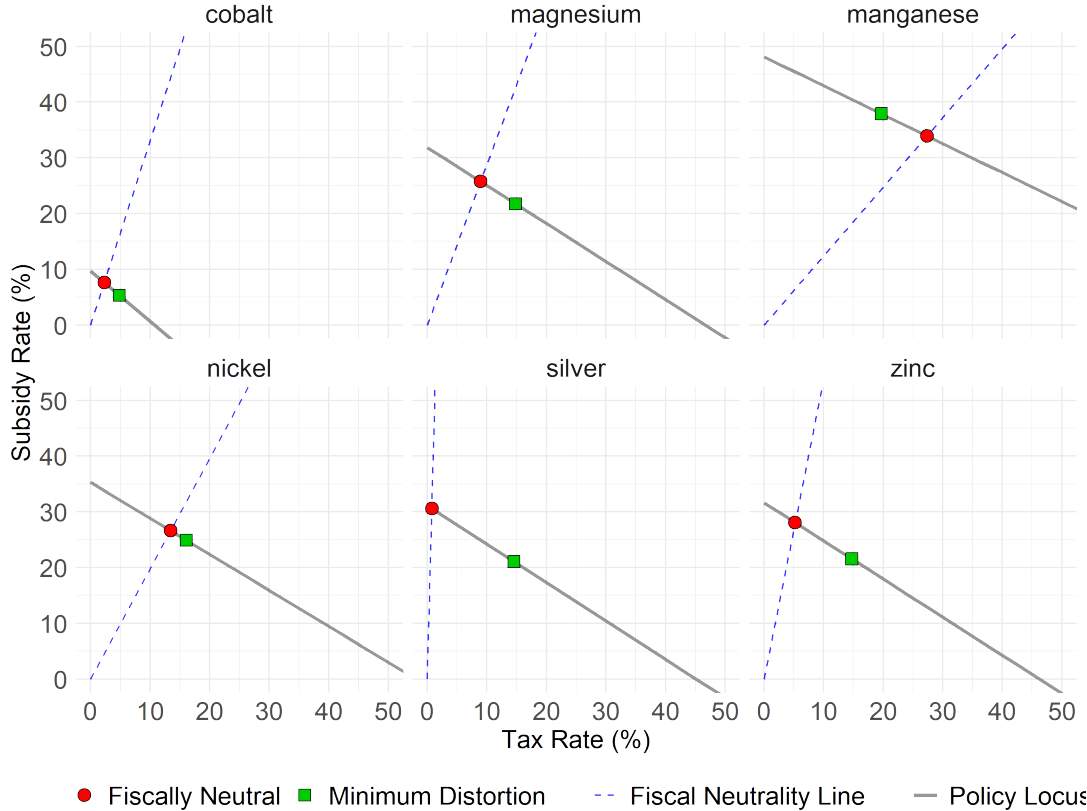
Second, the degree of similarity between the MD and FN policy mixes varies systematically across materials. For materials with a relatively small virgin–recycled price wedge, the two benchmarks yield comparable combinations of taxes and subsidies; in such cases, efficiency considerations and fiscal-balance constraints point in broadly the same direction. By contrast, for materials such as silver, where the relative price differential is large, the divergence between MD and FN policies becomes pronounced.

¹³Since this analysis abstracts from general equilibrium effects and is a first order approximation, it does not take demand induced changes of virgin and scrap materials prices into account. Hence the the FN analysis is an approximation under fixed prices.

¹⁴Materials with recycled-input shares higher then the EU target are excluded from this analysis, since reaching 25 percent for these materials would require negative subsidies or positive taxes on recycled inputs.

Lastly, materials whose current recycled-input shares lie closer to the target exhibit relatively steep policy loci situated nearer the origin, in contrast to materials with low baseline recycling shares. The difference is particularly evident when comparing cobalt (RiR = 22 percent) and manganese (9 percent). This reflects the fact that, when starting from a low baseline, large relative price changes are required to induce meaningful substitution toward recycled inputs.

Figure 7: Policy Mix for 25% Target



Notes: This figure depicts for each material, the combinations of virgin-input taxes and recycling subsidies that achieve a 25 percent recycled-input share under the MD and FN benchmarks. See text for further details.

Policy Schedules and Increasing Ambition Figure 8 generalizes this analysis by tracing the tax and subsidy rate schedules required to achieve a wide range of recycled-input targets. For presentation purposes, I display taxes and subsidies separately, although within each regime (MD and FN) they are jointly estimated. Several robust patterns emerge.

First, policies that rely on a single instrument, either taxes alone ($s = 0$) or subsidies alone ($\tau = 0$), always require the largest intervention rates. This reflects the fact that each instrument on its own must fully compensate for the lack of adjustment along the other margin. The inefficiency of single-instrument policies becomes particularly stark at high target shares.

Second, the tax-only schedules are highly nonlinear and increase sharply as the target rises. For many materials, required tax rates grow rapidly and eventually approach

implausibly high levels. This reflects diminishing marginal tax leverage: as recycled inputs become more widely used, further increases in the recycling share require ever larger increases in the relative price of virgin material. In contrast, subsidy-only schedules tend to grow more smoothly and, at higher targets, converge toward the MD and FN benchmarks.

Third, the MD policy mix exhibits a distinctive inverted-U pattern in the tax rate as a function of the target. At low and moderate recycling shares, taxation plays a central role because marginal tax changes are highly effective. As ambition increases, however, the marginal effectiveness of taxes declines, and the MD solution progressively shifts weight toward subsidies. This pattern directly reflects the flattening of the policy locus derived in Section 6. By contrast, the FN benchmark maintains relatively lower subsidy rates at high targets, in comparison to MD, because fiscal balance requires that expanding subsidies be financed through higher taxes, even when taxes have become a less effective instrument.

Taken together, these results imply that while virgin-material taxes are well suited for achieving modest increases in recycled-input use, ambitious recycling targets increasingly require subsidy-based incentives. Attempting to rely primarily on taxation at high targets leads to rapidly escalating and potentially infeasible tax rates.

Comparison to the Social Cost of Carbon The final exercise compares the EU’s 25 percent recycled-content target to the recycled-input shares implied by full internalization of carbon externalities at the social cost of carbon (see Figure 9). For most materials, SCC-consistent pricing implies recycled-input shares that often exceed the EU target by a substantial margin. This finding highlights that the EU’s circular-economy objective is, for many materials, less ambitious than what would be warranted purely on climate grounds.

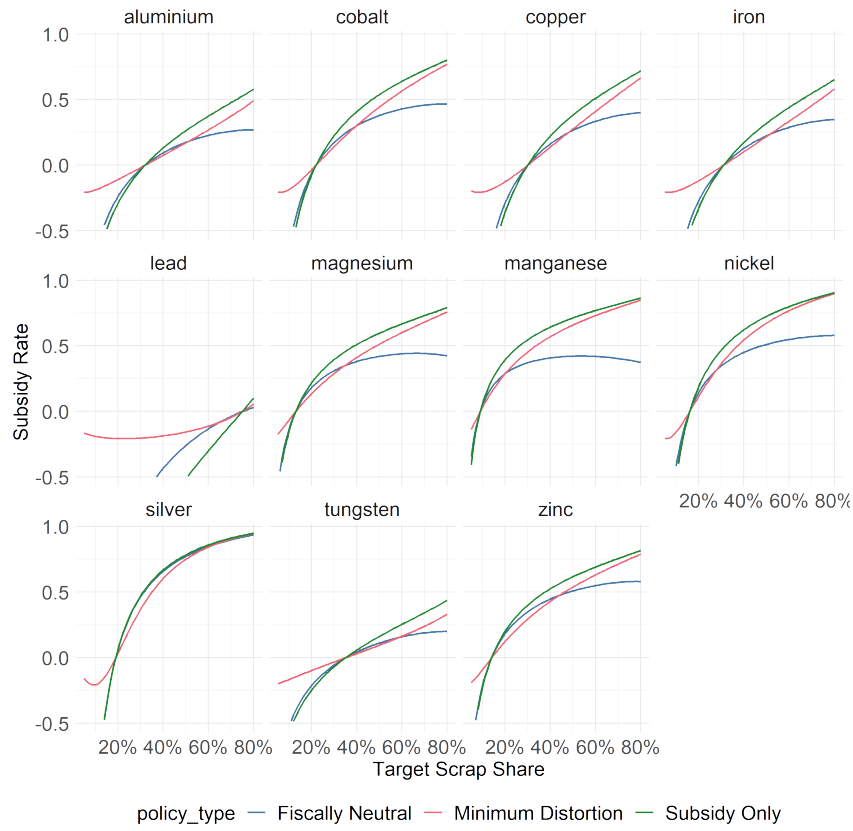
The magnitude of the response varies systematically across materials. Materials with low prices and large emissions differences between virgin and recycled production (such as aluminium, iron and magnesium) exhibit strong increases in recycled-input use under SCC pricing. In these cases, the carbon cost represents a sizeable fraction of the material price, generating a large relative price shift. By contrast, for high-value materials such as silver, carbon costs are small relative to the base price, and SCC pricing induces only modest changes in input composition.

Overall, the comparison reveals substantial heterogeneity in how closely EU recycling targets align with climate-consistent benchmarks. For many materials, achieving the EU target would still leave significant uninternalized climate externalities.

Discussion and Limitations The results underscore pronounced heterogeneity in the policy effort required to achieve a uniform 25 percent recycled-content target. This heterogeneity can be traced to three fundamental factors: differences in baseline recycled-input shares, variation in the virgin–recycled price wedge, and material-specific substitution

Figure 8: Policy Outcomes

(a) Subsidies



(b) Taxes

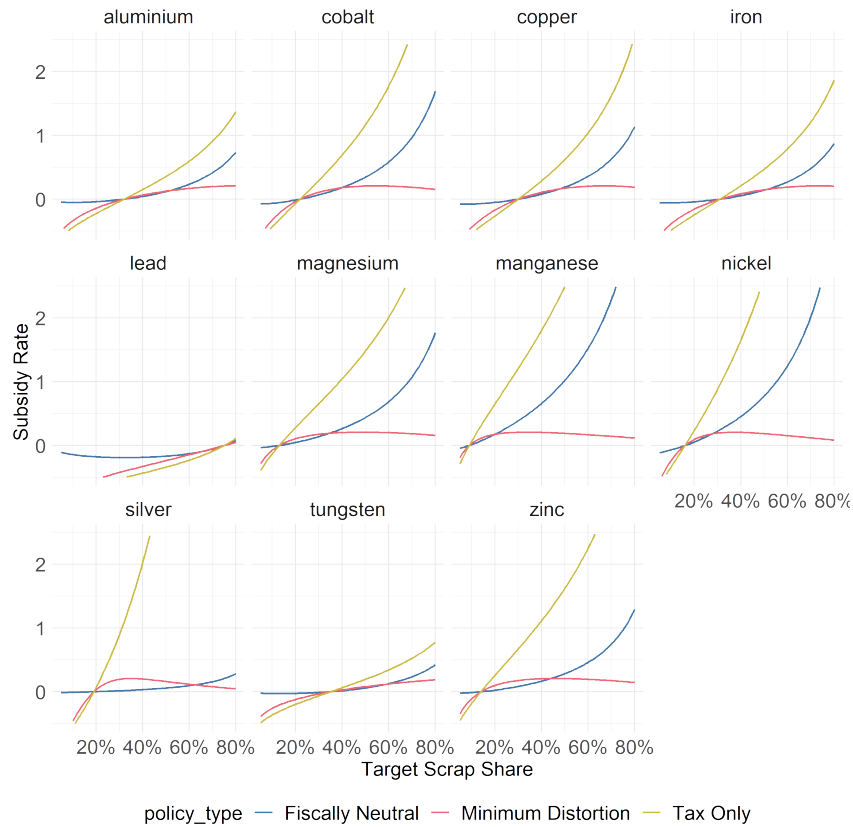
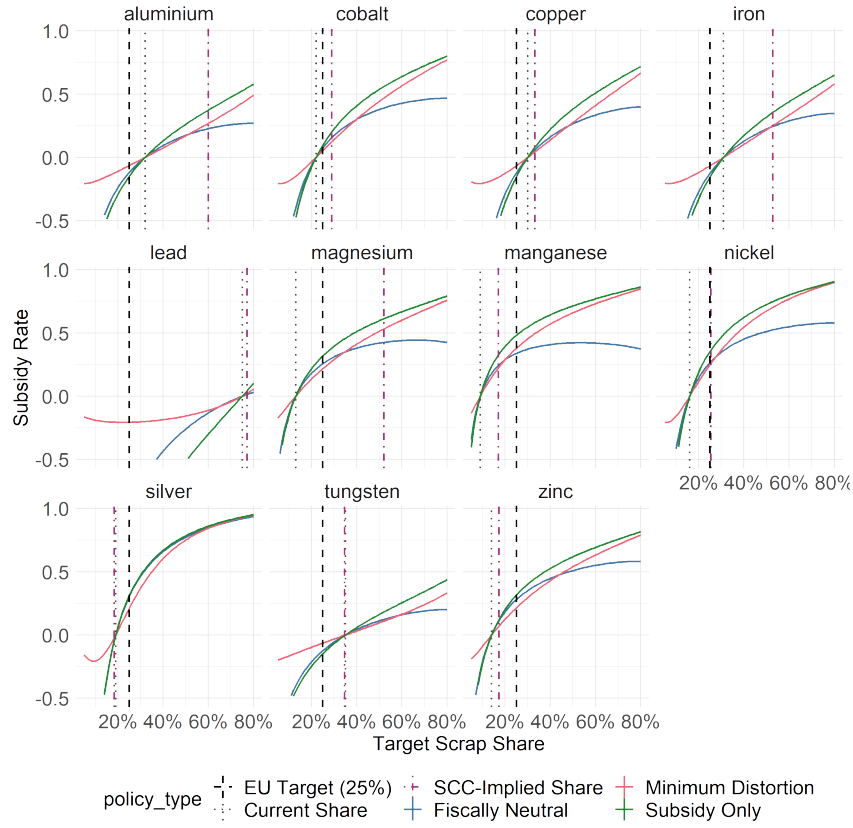
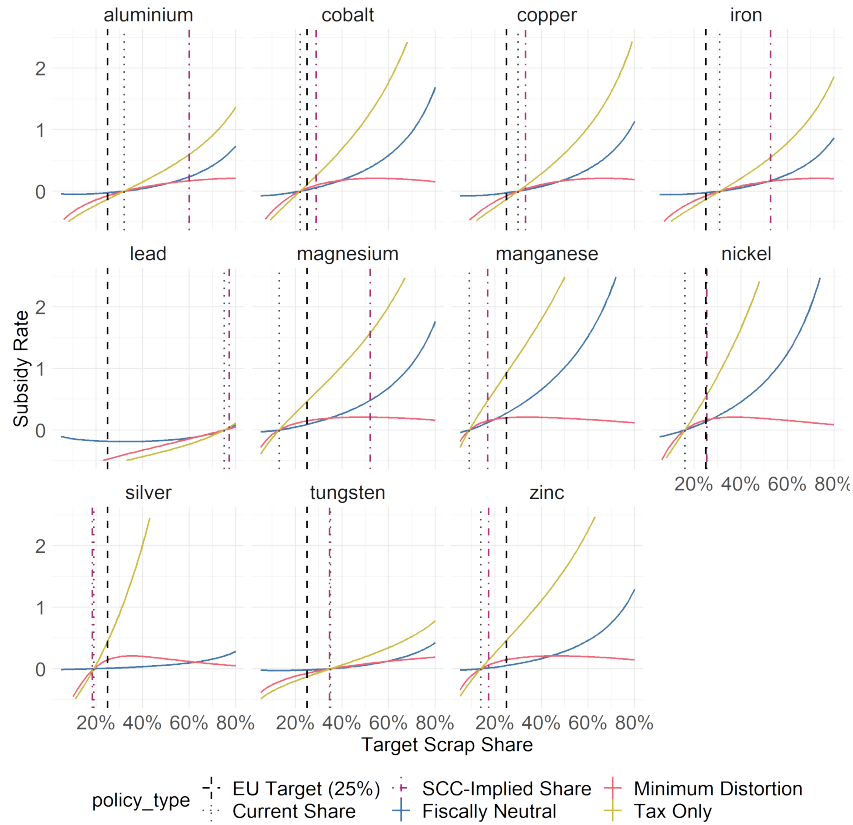


Figure 9: Policy Outcomes

(a) Subsidies



(b) Taxes



elasticities. Hence, a single quantitative target therefore overlays highly diverse technological and economic conditions.

The analysis, however, is subject to two limitations. First, it is conducted within a partial-equilibrium framework, abstracting from general-equilibrium effects. In particular, it omits supply-side responses by assuming a constant supply elasticity for recycled materials across different levels of recycled material demand. In reality, supply may become increasingly inelastic as demand rises (for example, due to capacity constraints that limit the scalability of recycling operations). Second, the analysis estimates the effect along a given demand curve. It does not account for shifts in the curve itself. As such, it abstracts from general-equilibrium effects such as material substitution across sectors, cross-border demand reallocation, or broader income effects.

7 Conclusion

Recycling plays a central role in the transition to a low-carbon and resource-secure economy. For many industrial materials, secondary production requires dramatically less energy than primary extraction, often around of 56–98 percent. These environmental benefits complement the geopolitical value of reducing dependence on concentrated primary suppliers.

This paper investigates the extent to which demand can be substituted from primary to secondary material inputs when virgin prices rise. Using global trade data for 21 recyclable materials from 2013–2023, I estimate the cross-price elasticity between virgin and scrap imports and identify causal effects by instrumenting virgin prices with an index of export restrictions imposed by major producing countries. Building on these elasticities, I quantify the policy interventions required under current technological constraints to reach the European Union’s target of 25 percent recycled content, and compare these requirements to outcomes implied by internalizing the social cost of carbon.

The empirical results show that raw material demand substitutes toward scrap inputs when virgin material prices increase, but the magnitude of this response varies sharply across materials. Technologically mature materials such as aluminium, iron, and lead exhibit relatively high substitution elasticities, meaning that moderate policy interventions can substantially raise recycled-input shares. By contrast, materials with strong quality constraints or limited secondary markets display low elasticities, implying that price-based instruments alone cannot deliver large increases in recycled content. The policy analysis highlights a further tension: for several materials, the subsidy required to reach the EU’s 25 percent target differs substantially from the policies which internalize the social cost of carbon, indicating misalignment between circular-economy goals and climate-optimal policy.

These findings open several avenues for future research. A natural next step is to incorporate supply-side responses into a general-equilibrium framework that captures how

increased recycling demand affects scrap collection, processing costs, and international material flows. Another extension is to link substitution elasticities to micro-level technological characteristics, such as purity requirements or contamination sensitivity, to better understand the determinants of recycling feasibility. Finally, integrating sector-level data would allow for richer analyses of how heterogeneity in production technologies, environmental regulation, or global value chain integration shapes the transition to more circular material use. Together, these extensions would contribute to a more complete understanding of the conditions under which circular material use can support the broader transition to a low-carbon and resource-secure economy.

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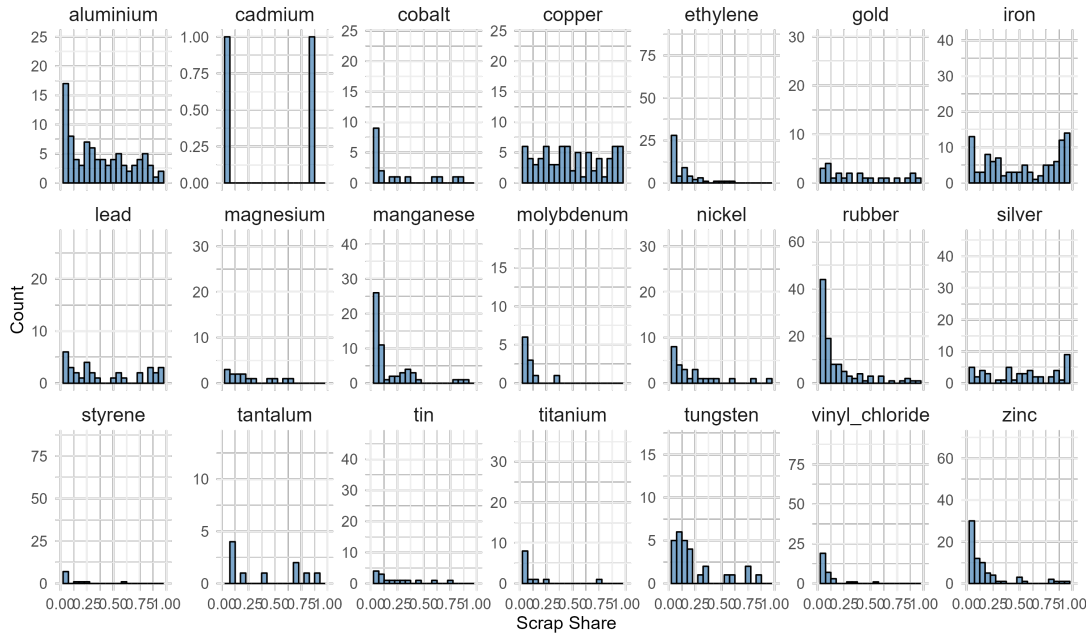
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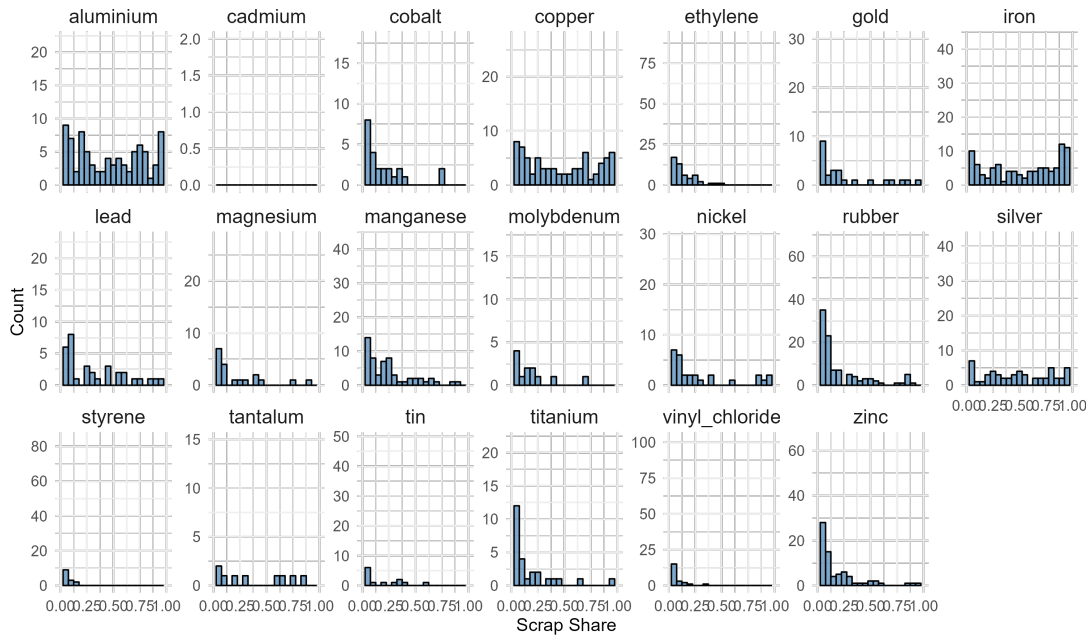
A Appendix: Figures

Figure A.1: Distribution of scrap Share

(a) Year 2013



(b) Year 2023



B Appendix: Tables

Table B.1: Scrap Share Distribution by Material (2013)

Material	Mean	Median	SD	N
Aluminium	0.38	0.29	0.36	129
Cadmium	0.44	0.44	0.59	2
Cobalt	0.10	0.01	0.22	42
Copper	0.48	0.45	0.38	122
Ethylene	0.06	0.01	0.11	141
Gold	0.22	0.02	0.32	57
Iron	0.44	0.32	0.40	163
Lead	0.27	0.06	0.36	64
Magnesium	0.08	0.00	0.16	47
Manganese	0.12	0.03	0.21	100
Molybdenum	0.04	0.01	0.07	30
Nickel	0.11	0.01	0.20	58
Rubber	0.12	0.04	0.19	168
Silver	0.32	0.10	0.38	104
Styrene	0.03	0.00	0.12	98
Tantalum	0.24	0.02	0.36	26
Tin	0.06	0.00	0.14	63
Titanium	0.04	0.00	0.12	48
Tungsten	0.17	0.08	0.25	46
Vinyl_chloride	0.03	0.00	0.07	124
Zinc	0.11	0.03	0.21	144

Notes: This table reports the distribution of scrap share imports by material. In particular the mean, median and standard distribution in the first observation period. See text for further details.

Table B.2: Correlation of Virgin CE and UV Prices

Dependent Variable: Virgin CE Price	Virgin Trade UV Model: (1)
Virgin CE Price	0.5553*** (0.0751)
<i>Fixed-effects</i>	
Year	Yes
Material	Yes
<i>Fit statistics</i>	
Observations	236
R ²	0.61830

Notes: This table reports the correlation between the virgin commodity exchange price index and the global trade unit value index of virgin materials. Both indices are measured as the natural logarithm of the indices. The unit of observation is material-year. Standard errors are shown in parentheses, clustered at the year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. See text for further details.

Table B.3: Leave One Out - First Stage Robustness

Dropped material	Coef. Export Restriction	N
Aluminium	0.469*** (0.018)	17951
Cadmium	0.463*** (0.018)	19342
Cobalt	0.445*** (0.016)	18902
Copper	0.488*** (0.019)	18032
Ethylene	0.399*** (0.019)	17813
Gold	0.461*** (0.018)	18739
Iron	0.504*** (0.018)	17584
Lead	0.439*** (0.018)	18647
Magnesium	0.526*** (0.018)	18847
Manganese	0.434*** (0.019)	18266
Molybdenum	0.485*** (0.018)	19034
Nickel	0.340*** (0.054)	18727
Rubber	0.395*** (0.019)	17517
Silver	0.461*** (0.018)	18221
Styrene	0.419*** (0.019)	18286
Tantalum	0.432*** (0.018)	19078
Tin	0.478*** (0.018)	18682
Titanium	0.485*** (0.018)	18836
Tungsten	0.463*** (0.018)	18996
Vinyl	0.508*** (0.018)	18000
Zinc	0.484*** (0.018)	17780

Notes: Each row reports a separate regression in which the indicated material is excluded from the sample. The dependent variable is the price index. All specifications include importer–time and importer–material fixed effects. Standard errors are shown in parentheses, clustered at the importer–year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. See text for further details.

Table B.4: Material Specific Regressions
- Coefficients

Dependent Variable: Model:	Scrap Share		
	OLS	Logit	Poisson
<i>Virgin Price</i> ×			
Aluminium	0.241** (0.121)	2.475 (1.777)	1.253 (0.941)
Cadmium	-0.184 (0.275)	-0.981 (7.951)	-0.995 (5.116)
Cobalt	0.100 (0.108)	1.639 (1.712)	1.069 (0.943)
Copper	0.110 (0.122)	1.759 (1.756)	1.013 (0.939)
Gold	-0.179 (0.127)	-1.071 (1.754)	-0.229 (0.951)
Iron	0.165 (0.119)	2.077 (1.723)	1.168 (0.927)
Lead	0.196 (0.143)	2.647 (1.893)	1.397 (0.993)
Magnesium	0.123 (0.116)	2.094 (1.737)	1.244 (0.970)
Manganese	0.103 (0.103)	1.852 (1.624)	1.072 (0.877)
Molybdenum	0.201* (0.115)	3.305* (1.864)	2.279** (1.055)
Nickel	0.085 (0.081)	1.285 (1.376)	0.836 (0.743)
Silver	0.023 (0.124)	0.943 (1.744)	0.692 (0.936)
Tantalum	0.283* (0.165)	3.345* (1.859)	1.851* (1.024)
Tin	0.020 (0.115)	-0.814 (1.848)	-0.575 (1.015)
Titanium	0.122 (0.121)	1.653 (1.811)	0.813 (1.003)
Tungsten	0.252 (0.183)	3.476* (1.971)	1.791* (1.071)
Zinc	0.123 (0.117)	1.885 (1.763)	1.123 (0.956)
<i>Fixed-effects</i>			
Imp x Time	Yes	Yes	Yes
Imp x Material	Yes	Yes	Yes
Observations	19,275	19,275	19,275

Notes: This table presents the material specific first stage residual coefficients across different models as discussed in Equation 13. Virgin price is the natural logarithm of the commodity exchange price index. The unit of observation is importer-material-year. Standard errors are bootstrapped and shown in parentheses, clustered at the importer-year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. See text for further details.

Table B.5: Material Specific Regressions
- First Stage Residual Coefficients

Dependent Variable: Model:	OLS	Scrap Share Logit	Poisson
<i>F. Stage Resid ×</i>			
Aluminium	0.166 (0.173)	0.169 (1.849)	-0.208 (0.967)
Cadmium	-0.029 (0.347)	-1.809 (11.667)	-0.582 (8.137)
Cobalt	-0.064 (0.114)	-1.138 (1.771)	-0.677 (0.991)
Copper	-0.103 (0.180)	-2.054 (1.938)	-1.356 (0.975)
Gold	0.169 (0.135)	0.697 (1.841)	0.165 (0.980)
Iron	-0.147 (0.139)	-2.111 (1.933)	-1.261 (0.984)
Lead	-0.028 (0.128)	-0.735 (1.777)	-0.633 (0.938)
Magnesium	-0.147 (0.122)	-2.384 (1.892)	-1.370 (1.095)
Manganese	-0.067 (0.110)	-1.461 (1.667)	-0.794 (0.911)
Molybdenum	-0.180 (0.125)	-2.734 (2.158)	-1.765 (1.263)
Nickel	-0.043 (0.101)	-0.607 (1.678)	-0.311 (0.945)
Silver	-0.228* (0.133)	-2.258 (1.832)	-1.279 (0.956)
Tantalum	-0.192 (0.145)	-2.586 (1.843)	-1.482 (1.012)
Tin	-0.013 (0.135)	0.905 (2.546)	0.870 (1.501)
Titanium	-0.154 (0.113)	-2.869* (1.730)	-2.015** (0.952)
Tungsten	-0.339 (0.219)	-4.309* (2.249)	-2.246* (1.221)
Zinc	-0.103 (0.114)	-1.322 (1.762)	-0.752 (0.968)
<i>Fixed-effects</i>			
Imp x Time	Yes	Yes	Yes
Imp x Material	Yes	Yes	Yes
Observations	19,275	19,275	19,275

Notes: This table presents the material specific coefficients across different models as discussed in Equation 13. Virgin price is the natural logarithm of the commodity exchange price index. The unit of observation is importer-material-year. Standard errors are bootstrapped and shown in parentheses, clustered at the importer-year level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. See text for further details.