Recycling matters –the role of secondary production in metal markets

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ABSTRACT

In an effort to ensure sustainable consumption and production patterns, recycling has been recognized as one key strategy. With technological advancements further enabling more efficient material recovery, recycling is set to emerge as an influential force in global metal markets, reshaping traditional supply-demand dynamics. To better understand the role of secondary production and its interdependencies within these markets, we employ structural vector autoregressive (SVAR) models to simultaneously analyze the relationships between primary and secondary supply, demand, convenience yield, and futures prices from 2010 to 2023. The analysis highlights the critical role of recycling in the aluminum and lead markets, significantly influencing prices, consumption and, convenience yield, helping to mitigate scarcity and lower commodity prices. In contrast, the dynamics of the copper market are dominated by primary producers, reflecting their larger share of total production volume. While primary producers struggle to adapt to market changes quickly, our findings show that secondary production is highly responsive, particularly to fluctuations in futures prices. This responsiveness highlights the ability of recyclers to increase production volumes when market conditions become more profitable. Our findings underscore the contribution of recycling to an efficient market and emphasize its importance in a sustainable and circular metal industry.

1. Introduction

The importance of metals in today's society is underlined by their widespread use, from infrastructure and transportation to electronics and renewable energy technologies. Metals, by virtue of their physical and chemical properties, have become the backbone of industrial development and technological advancement. However, the extraction and processing of metals from their ores are energy-intensive processes that significantly contribute to environmental degradation, including habitat destruction and greenhouse gas emissions. As global demand for metals continues to rise, driven by economic growth but also the transition to a low-carbon economy (World Bank Group, 2017; Schischke et al., 2023), there is an urgent need to address the sustainability concerns associated with metal production and develop strategies to limit the depletion of the world's finite resources.

One promising solution to address these challenges and maximize social welfare (Bongers and Casas, 2022) is the development of a circular economy, which entails the production and use of secondary materials via recycling. According to a report by the Bureau of International Recycling (Grimes et al., 2008), secondary production of certain metals

can reduce CO_2 emissions by up to 99% compared to primary production, underscoring the ecological potential of recycling. Beyond its environmental advantages, recycling also has the potential to reshape the economics of metal markets, making it essential to understand its role and interdependencies within these markets. However, current progress in recycling implementation varies widely across commodities, leading to substantial differences in recycling volumes and their impact on commodity markets. By examining the base metals copper, aluminum, and lead, we can observe markets at different stages of this development, which can be assessed through two key indicators of recycling implementation.

The recycling input rate (RIR) (Fig. 1) measures the share of secondary production in total production and highlights the leading position of lead, with values of 69%, compared to 15% for copper and 19% for aluminum (London Stock Exchange Group, 2024). However, as the RIR is heavily influenced by the lifespan of previously manufactured products, we also present the End-of-Life Recycling Rate (EOL-RR) (Fig. 2). The EOL-RR evaluates the efficiency of the collection, pretreatment, and recycling processes (Eurometaux, Eurofer, 2012), offering a more comprehensive perspective. Despite an insufficient and

inconsistent data basis, the EOL-RRs highlight lead as the most advanced in recycling, while copper exhibits the greatest potential for further development.

Although numerous studies address metal recycling from engineering or environmental science perspectives, the role of recycling within metal markets has been underexplored, with most research focusing primarily on the determinants of secondary supply. Early work by Margaret E. Slade (1980) models the copper and aluminum industries in the U.S. to evaluate the impact of increasing energy prices and declining ore quality on recycling. The study finds that an increase in electricity prices has a positive impact on aluminum recycling, while copper secondary production remains unresponsive to higher electricity costs. Furthermore, the depletion of high-grade copper deposits results in heightened copper recycling efforts and a shift towards substituting aluminum for copper. Blomberg and Hellmer (2000) and later Blomberg and Söderholm (2009) shift the focus of their analysis to Europe. There, they investigate the secondary aluminum supply and demand and find that the supply is inelastic to changes in prices. Gómez et al. (2007) further demonstrate that secondary copper production is highly responsive to changes in old scrap flows. However, old scrap stock, which has not been recycled in prior years, has only a modest impact.

Examining the role of macroeconomic variables, Sourabh et al. (2023) investigate the impact of selected economic variables on the secondary production of copper in India. Their findings indicate that the three contributing indices to the industrial production, mining, manufacturing, and electricity, exert a significant influence on secondary production. Similarly, Fu et al. (2017) investigate the response of secondary copper supply to changes in economic activity and find both industrial activity and world GDP to correlate with scrap supply, while McMillan et al. (2010) identify the annual percentage change in GDP to have a significant positive association with the annual percentage change in net additions to in-use aluminum stock in the United States. In their review of published econometric models and their explanatory variables, Rivera et al. (2021) find only refined copper prices and GDP of all previously studied variables capable of explaining short-term changes in secondary supply.

Adding to the research done by the previous studies, Gleich et al. (2013) investigate the reverse relationship and analyze the explanatory power of secondary production on the market price of chemical elements and find secondary production to significantly influence the price development of 16 out of 18 raw materials. The authors discover the highest explanatory power present in lead and platinum, but also highlight that the recycling volume should only be used as an indicator of long-term supply and price risk. Similarly, Lutzenberger et al. (2017) examine the explanatory power of various fundamental factors and financial market characteristics (e.g., momentum, value) on the expected return of a panel of various metals. They find a weak but significant positive relationship for secondary production but are unable to explain this unintuitive correlation.

Although illuminating, this body of research typically models the interdependent market structure, the autoregressive nature of the processes, and the determinants only to a limited extent. Additionally, a common limitation across the literature is the reliance on annual data, which fails to capture the often short-term dynamics inherent in metal markets. Therefore, we adopt a novel approach within this field of research, using SVAR modeling with monthly data to analyze the interdependencies between primary and secondary production, consumption, convenience yield, and futures prices in the global copper, aluminum, and lead markets. This allows us to disentangle the influence of recycling practices on market dynamics, demonstrating the crucial role of recycling in promoting a sustainable, circular, and efficient metals industry in its pursuit of environmental sustainability and economic viability.

Section 2 of the paper describes the physical links between primary and secondary production. Our data and econometric models are described in Section 3. Section 4 describes the empirical results, while Section 5 concludes.

2. Technological background

In order to analyze the economic interdependencies that exist within metal production and to facilitate the interpretation of the findings of the analysis, it is essential to develop an understanding of the physical relationships that exist between primary and secondary production. Consequently, the subsequent sections will examine some fundamental aspects of the production processes of the analyzed metals.

2.1. Copper

The production of copper (see Fig. 3a), as described by the International Copper Study Group (2023), is a multi-layered process characterized by several features relevant to this study. The pyrometallurgical production of primary copper begins with the extraction of copper-rich ores, predominantly sourced from open-pit mines. The ore is initially concentrated and subsequently smelted. Next, the intermediate is converted and finally refined into copper cathodes of 99.99% purity. In some instances, primary smelters, converters, and refineries are also fed limited amounts of copper scrap in addition to the copper concentrate (Forsén et al., 2017). As an alternative to the described route, approximately 20% of the total mine production is refined by hydrometallurgical processes, resulting in copper of the same purity.

Apart from its use in primary smelters, copper scrap is either fed into secondary copper smelters and refineries or remelted directly (Bertram et al., 2002). The processing of lower-grade copper involves smelting and subsequent refining in an effort to address the presence of contaminants. In contrast, high-grade copper scrap, such as trimmings from initial fabrication, can be remelted directly without undergoing additional refining (Glöser et al., 2013). Consequently, these quantities are not included in the secondary refined production data used.
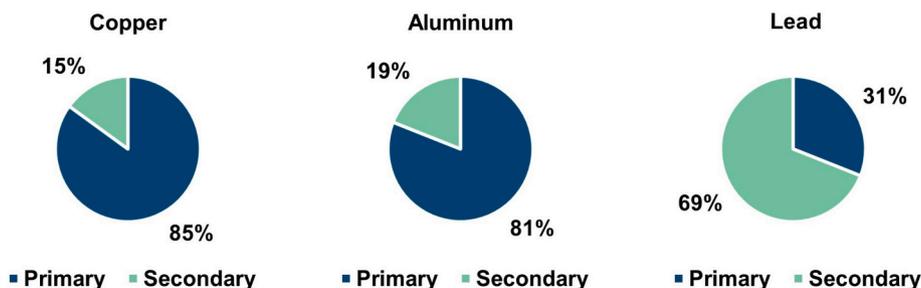

Fig. 1. Share of primary and secondary production in total production volumes in 2023 (London Stock Exchange Group, 2024). It should be noted that, while the data for copper and lead specifically refers to refined metal, no such restriction applies to aluminum.
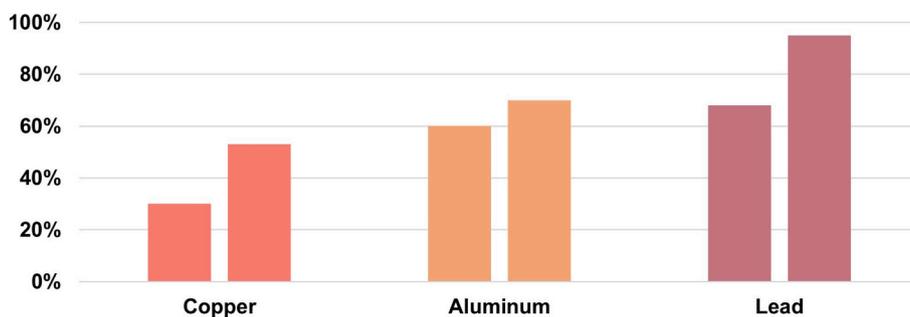
Fig. 2. Global End-of-Life Recycling Rates of copper, aluminum, and lead. The observed differences within a metal arise from variations in reference years, system boundaries, or the underlying data utilized in the cited studies. The recycling rate of 95% for lead is for the United States only. Sources: from left to right (Graedel et al., 2004), (International Copper Association, 2020), (Zheng, 2009; as cited in UNEP, 2011), (International Aluminium Institute, 2009; as cited in UNEP, 2011), (Mao et al., 2008), (Smith, 2002).

2.2. Aluminum

The following subsection presents a description of the global flow of aluminum, as illustrated in Fig. 3b and based on studies of Cullen and Allwood (2013), as well as Chen and Graedel (2012). Primary aluminum is produced in a two-step process, starting with the extraction of alumina (aluminum oxide) from bauxite, an aluminum-rich mineral. Next, alumina is processed into high-purity aluminum by electrolysis, which requires large quantities of electricity. Recycled aluminum, on the other hand, is produced in two different processes, depending on the composition of the scrap alloy. Wrought alloys that have undergone mechanical processing are remelted. Cast alloys containing larger amounts of alloying elements are processed in secondary refineries to remove impurities. However, aluminum recycling shows two weaknesses. Firstly, the addition of high-purity primary aluminum commonly serves to dilute or "sweeten" the scrap, both during remelting and refining. This results in a rapid increase in the embodied energy of secondary aluminum. Based on industry data, Cullen and Allwood (2013) identify the proportion of primary sweetener utilized to be approximately 5% for remelters and 25% for refiners. Secondly, due to the smaller share of alloying metals in wrought alloys, they can be recycled into wrought alloys and downcycled into casting alloys, while the opposite is practically nonexistent. Due to the growth of demand for new aluminum products, new casting alloys are still in need. However, forecasts (Hatayama et al., 2012; Modaresi and Müller, 2012; van den Eynde et al., 2022) show a surplus in unrecyclable casting alloy scrap for the near future. It is therefore of great importance that the different alloys are segregated and sorted in accordance with their respective types.

2.3. Lead

In comparison to copper and aluminum, secondary production represents the primary source of refined products for lead (International Lead and Zinc Study Group, 2023; London Stock Exchange Group, 2024). This is a consequence of the existence of well-established collection and recycling procedures that are supported by the regulatory authorities (Yanamandra et al., 2022). Nevertheless, the processes and relationships between primary and secondary production are comparable to those observed in the case of copper and can be observed in Fig. 3a. The primary production of lead, as described by Laubertová et al. (2017), can be achieved through pyrometallurgical as well as a hydrometallurgical processes. However, as the hydrometallurgical route is not conventionally applied (Pan et al., 2013), we only describe the former. The lead mineral, which frequently contains impurities of silver or copper, is first concentrated and then smelted. The resulting intermediate product is then refined to remove any, often valuable, remaining impurities. Again, several primary production facilities are designed to process small quantities of lead scrap as part of their feed.

Secondary production is primarily concerned with the processing of lead-acid battery scrap, with 86% of refined lead in 2022 being allocated to this purpose (International Lead and Zinc Study Group, 2023). The processes involved are similar to those employed in primary production, entailing a smelting and further refining step at distinct recycling plants. Nevertheless, it is often possible to remelt clean scrap directly (Thornton et al., 2001), thus preventing the need for further refining.

3. Data and methodology

The objective of this study is to analyze the role of recycling within metal markets, focusing on the base metals copper, aluminum, and lead. For this purpose, we apply structural vector autoregressive modeling, originally proposed by Christopher A. Sims (1980), utilizing monthly data on production, consumption, convenience yield, and futures prices spanning from January 2010 to December 2023.

We utilize primary production[1] (*PP*) and secondary production (*SP*) data, serving as proxies for the supply, along with consumption (*C*) data from the World Bureau of Metal Statistics (WBMS) of the London Stock Exchange Group. While the WBMS reports combined consumption data for primary and secondary copper and lead, it only provides primary consumption data for aluminum, which must be considered when interpreting the results. Furthermore, the data on secondary production, which does not distinguish between pre-consumer and post-consumer scrap, includes remelted scrap for aluminum but not for copper or lead. In general, the WBMS data refers to the refined metal in the case of copper and lead, whereas the aluminum figures also encompass alloys. To account for scarcity and as a monthly indirect indicator of the commodity's stock levels (Kaldor, 1939), we calculate the convenience yield[2] (*CY*) at the London Metal Exchange. Finally, we consider the monthly average 3-month futures price (*P*) of the London Metal Exchange, resulting in a set of five endogenous variables $y_t = (PP_t, SP_t, C_t, CY_t, P_t)'$.[3]

As shown in the literature (Binder et al., 2006; McMillan et al., 2010; Fu et al., 2017), the supply and demand of metals are substantially driven by macroeconomic factors such as industrial activity, which,

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[1] The primary production of copper and lead is calculated by subtracting the secondary production data from the total refined production.

[2] The convenience yield is calculated using the cost of carry model, assuming negligible storage costs. The LME cash price and the three-month yield on U.S. Treasury securities are then applied.

[3] As all variables in the model were initially non-stationary (based on an Augmented Dickey-Fuller test at the 5% level), we calculated log returns for all variables except for the convenience yield and the interest rate, for which we calculated the first differences. The resulting variables were seasonally adjusted using the simpledecomp function of the R package "tsapp", and the original variable names were retained.
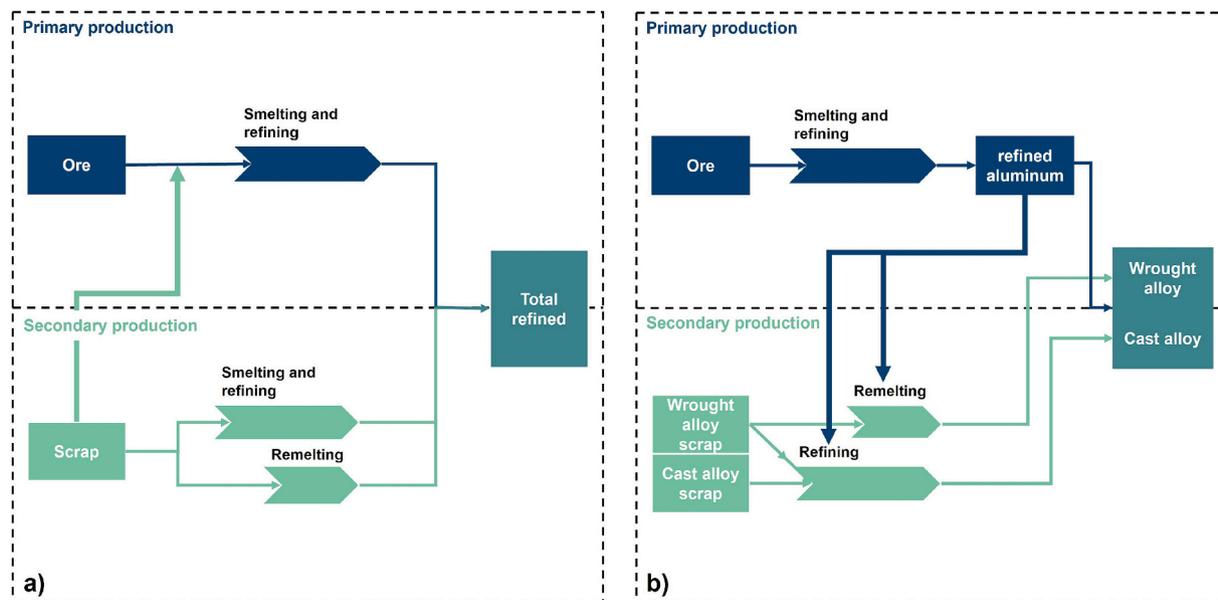
Fig. 3. Simplified illustration of the primary and secondary production processes and the material flows for a) copper and lead and b) aluminum.

following Schischke et al. (2024), are assumed to be exogenous. Therefore, we further control for the four exogenous variables U.S. dollar index (*FX*), industrial production (*IP*), treasury yield (*IR*), and energy cost (*EC*) $x_t = (FX_t, IP_t, IR_t, EC_t)'$. We include the U.S. dollar index to account for the exchange rate, given most commodities are traded in U.S. dollars, but only small quantities are produced in the United States. Furthermore, as a general indicator of economic activity, we include the industrial production of the United States. We consider the market yield on U.S. treasury securities at a 3-month constant maturity, since interest rates affect the cost of borrowing of producers and consumers alike, and the global price of energy index due to the energy intensity of many recycling processes.[4]

Considering those variables, we model the metal markets with the following *SVAR(P)* model (Eq. (1)) with *P* lags[5] by Ordinary Least Squares (OLS):

$$A_0 y_t = A_1 y_{t-1} + A_2 y_{t-2} \dots + A_P y_{t-P} + B_o x_t + \varepsilon_t \qquad (1)$$

where A_p are the matrices of lagged coefficients for lags $p = 1, 2, \dots, P$, while B_o denotes the coefficient matrix corresponding to the exogenous variables. Additionally, the error terms ε_t are assumed to be serially and mutually uncorrelated following a white noise process with $\mathbb{E}[\varepsilon_t] = 0$. Assuming that A_0^{-1} has a recursive structure, the reduced form errors u_t can be expressed by Eq. (2) $u_t = A_0^{-1}\varepsilon_t$:

$$u_t = \begin{pmatrix} u_t^{PP} \\ u_t^{SP} \\ u_t^{C} \\ u_t^{CY} \\ u_t^{P} \end{pmatrix} = \begin{bmatrix} \alpha_{11} & 0 & 0 & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 & 0 & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & 0 & 0 \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} & 0 \\ \alpha_{51} & \alpha_{52} & \alpha_{53} & \alpha_{54} & \alpha_{55} \end{bmatrix} \begin{pmatrix} \varepsilon_t^{PP} \\ \varepsilon_t^{SP} \\ \varepsilon_t^{C} \\ \varepsilon_t^{CY} \\ \varepsilon_t^{P} \end{pmatrix} \qquad (2)$$

Hereby, market-traded futures prices reflect real-time sentiment and are contemporaneously affected by shocks to convenience yield,

consumption, secondary production, and primary production, while influencing these variables with a lag. Conversely, the primary production exhibits a delayed response to shocks in the other variables, given the lengthy process involved in primary production, from mining to the refined metal. Due to the inherent impact of changes in primary supply on secondary production and the shorter production process, we assume that secondary production is contemporaneously affected by shocks in primary production. The availability of metals exerts a direct influence on the quantity of metals that can be consumed within the same period. Therefore, consumption is immediately affected by shocks to both secondary and primary production, but only affected with a lag by the convenience yield and price. Lastly, the convenience yield is contemporaneously influenced by primary production, secondary production, and consumption because it represents the benefit of holding inventories, which depends on the current balance between supply and demand. As the convenience yield is a function of the futures price, it is only affected with a lag.

4. Empirical results

To explore the role of secondary production in the commodity markets, we examine how a shock to one variable affects the other variables in our models. Hereby, we analyze orthogonalized impulse response functions (IRFs) to a one standard deviation shock with 90% confidence bounds. Table 1 provides an overview of the initial significant responses observed in the IRFs, offering a first insight into the dynamics of the examined markets. The table highlights that the occurrence, direction, and timing of effects originating from and impacting secondary production vary considerably across different markets. Consequently, the following subsections provide a more detailed analysis of the results for each commodity, followed by a market comparison and sensitivity analysis.

4.1. Copper

Initially, our analysis focuses on copper (see Fig. 4), the metal with the lowest recycling implementation in our sample. We find that, aside from a response in copper consumption, secondary production does not play a fundamental role in shaping market dynamics for copper. However, as outlined in the data section, directly remelted scrap is not captured in the secondary production data for copper, suggesting that

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[4] Detailed sources and descriptive statistics of the data applied can be found in Appendix A.

[5] To address autocorrelation and heteroscedasticity in the SVAR models, we employ the Breusch-Godfrey test and the ARCH-LM test, adjusting the lag length until neither issue is detected at the 5% significance level. The final models include 4 lags for aluminum and 2 lags for copper and lead.

Table 1
Results of the impulse response function analysis of the commodity-specific SVAR models.

	Cooper	Aluminum	Lead
Impulse from **primary production** to **primary production**	+0	+0	+0
Impulse from **primary production** to **secondary production**	−0		+1
Impulse from **primary production** to **consumption**	+0	+0	+0
Impulse from **primary production** to **convenience yield**			−2
Impulse from **primary production** to **futures price**	−1		+3
Impulse from **secondary production** to **primary production**		+4	+1
Impulse from **secondary production** to **secondary production**	+0	+0	+0
Impulse from **secondary production** to **consumption**	+0		+0
Impulse from **secondary production** to **convenience yield**		+3	
Impulse from **secondary production** to **futures price**		−2	+1
Impulse from **consumption** to **primary production**	+3	−4	
Impulse from **consumption** to **secondary production**			
Impulse from **consumption** to **consumption**	+0	+0	+0
Impulse from **consumption** to **convenience yield**	+1		−0
Impulse from **consumption** to **futures price**			−0
Impulse from **convenience yield** to **primary production**		+5	
Impulse from **convenience yield** to **secondary production**		+1	
Impulse from **convenience yield** to **consumption**	−3		+2
Impulse from **convenience yield** to **convenience yield**	+0	+0	+0
Impulse from **convenience yield** to **futures price**	+0	+0	+0
Impulse from **futures price** to **primary production**			
Impulse from **futures price** to **secondary production**		+2	+1
Impulse from **futures price** to **consumption**			
Impulse from **futures price** to **convenience yield**		+4	+2
Impulse from **futures price** to **futures price**	+0	+0	+0

Note: The table displays the first significant positive (+) or negative (−) effects and the period of occurrence based on the 90% confidence level.

the actual contribution of recycling may be greater. In contrast, futures prices are influenced by shifts in primary production, with a notable decrease in price occurring one month following a positive shock to primary production volumes (Fig. 4c), which we attribute to a surplus in supply. Furthermore, primary production exhibits a significant response to consumption changes three months after a shock (Fig. 4e), suggesting that while primary producers are responsive, they are slow to adjust production volumes. This delay is likely due to the long-term contracts existing between producers and consumers, as well as high utilization rates, which constrain rapid production changes. Lastly, the results illustrate the interconnection described in Section 2.1 between the primary production facilities and their use of copper scrap. Specifically, the incorporation of copper scrap as feed within the various stages of primary production increases the secondary production one month after a shock to the primary production prior to an initial decrease (Fig. 4f).

4.2. Aluminum

In contrast to the copper market, recycling significantly impacts the dynamics of the aluminum market (see Fig. 5). We observe that the futures price of aluminum decreases in response to an increase in recycling volume (Fig. 5a), a response not evident with primary production (Fig. 5c). Additionally, the convenience yield increases three months following a rise in secondary production (Fig. 5e), likely due to a steepening of the futures curve as the futures price decreases relative to the spot price, thereby increasing the convenience yield. The analysis further reveals that secondary production exhibits high responsiveness to fluctuations in convenience yield and futures prices (Fig. 5b). An increase in the convenience yield, associated with declining aluminum stocks, as well as a rise in futures prices, incentivizes recyclers to quickly ramp up production volumes, highlighting their role in enhancing the flexibility of aluminum supply. This observation contrasts with earlier studies by Blomberg and Hellmer (2000) as well as Blomberg and Söderholm (2009), which characterized the aluminum recycling supply of European countries in their earlier sample period of 1983 to 2000 as inelastic. Finally, the results demonstrate that the use of primary aluminum to dilute the impurities of the scrap within the remelting and refining of secondary aluminum plays a crucial role in driving primary

production. Specifically, we find that a positive shock in secondary production increases primary production four months after the event (Fig. 5f). This highlights the time needed for primary production volumes to adapt to the new demand.

4.3. Lead

Finally, we analyze the market dynamics of lead (see Fig. 6), which, despite being the smallest market in our study, has the highest share of recycling in its total production volume. This is reflected in the observed positive response in commodity consumption following a positive shock to secondary production, while a similar effect is also observed for primary production. In contrast to aluminum, we find the futures price of lead to increase one month following a positive shock to the recycling volume (Fig. 6a). Furthermore, the futures price demonstrates an increase three months after the initial shock to primary production (Fig. 6c), while the convenience yield exhibits a decline two months after the same event (Fig. 6e). Given the distinct market environment for lead, characterized by a high proportion of secondary production derived primarily from its use in lead-acid batteries, but constrained by high regulations due to its toxicity (Reck and Graedel, 2012), we assume that market participants respond cautiously to a sudden increase in both primary and secondary production due to potential long-term supply constraints.

Furthermore, we observe that only the secondary production of lead, but not the primary production, responds significantly to changes in market conditions. Specifically, we find that recycling volumes increase one month after a shock to the futures price (Fig. 6b), further demonstrating the recyclers' ability to adapt production quickly. Refined primary lead production, on the other hand, does not respond to changes in either consumption, convenience yield, or futures price (Fig. 6d), likely owing to the market's high reliance on secondary production. As observed with copper, lead recycling volumes tend to increase one month after a rise in primary production, due to similar production processes that incorporate scrap as feedstock within primary production (Fig. 6f).
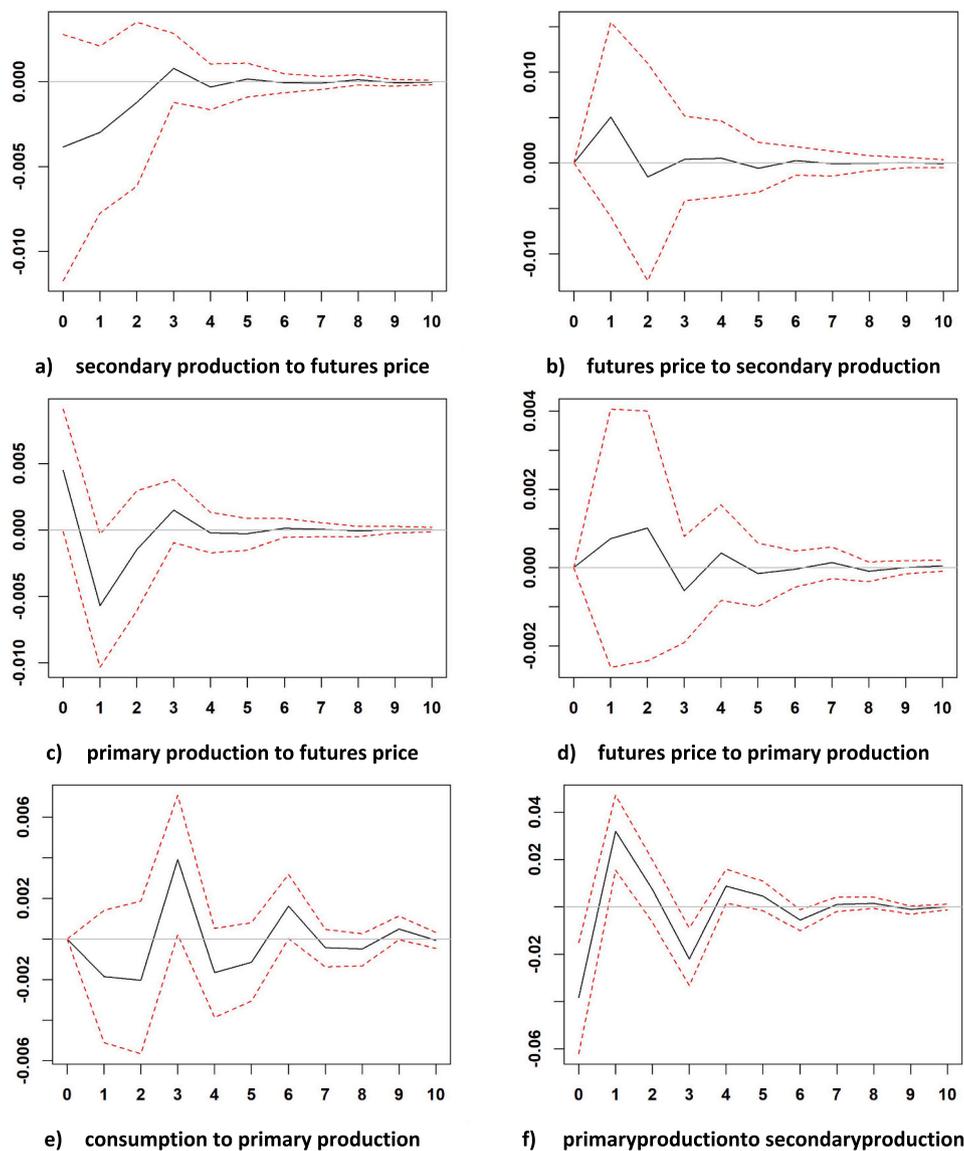
Fig. 4. Key impulse response functions for copper to a one standard deviation shock, with 90% confidence intervals and 1000 bootstrap runs.

4.4. Comparison of the different markets

A comparison of the findings for the three distinct metals reveals that the importance and responsiveness of recycling is greater in markets with a higher share of secondary production. This becomes clear as, in the copper market, recycling has little influence on market dynamics, and recyclers do not significantly adjust their output in response to changes in demand, convenience yield, or price. In contrast, these effects are observable for aluminum and lead.

In detail, the results indicate that secondary production of aluminum and lead influences futures prices, whereby the responses differ in direction. While the futures price of aluminum decreases in response to a positive shock to the secondary production, the opposite is the case for lead. This discrepancy is likely attributable to the vastly different market environment, with more than half of the total refined supply originating from recycled material. However, further research is required to identify the root causes of the observed characteristics. Conversely, the results show that both aluminum and lead recyclers capitalize on rising commodity prices by scaling up production, highlighting their ability to swiftly adapt to favorable market conditions. The analysis also indicates that this adaptation occurs more rapidly for lead, likely due to its more established recycling infrastructure.

Finally, metal-specific material flows between primary and secondary production sites, namely the use of primary aluminum as a sweetener and the inclusion of copper and lead scrap as inputs in the respective primary production processes, can be directly attributed to some of the interactions observed in our analysis.

4.5. Sensitivity analysis

To test the robustness of our results, we conduct a sensitivity analysis by varying certain specifications of our models and comparing the findings with our base models. Following the findings highlighted by Kilian and Lütkepohl (2018), the Akaike Information Criterion is alternatively employed to determine the optimal lag length. This results in a difference in the lag length for aluminum, which is determined to be two instead of four. To test the sensitivity of the model to longer-term funding conditions, we use the yield on U.S. treasury securities at a two-year constant maturity instead of three months. Moreover, the indicator of economic activity is broadened to encompass the industrial production of all OECD countries, rather than solely the United States. Finally, we swap the general global Energy price index for the WTI crude oil futures price.

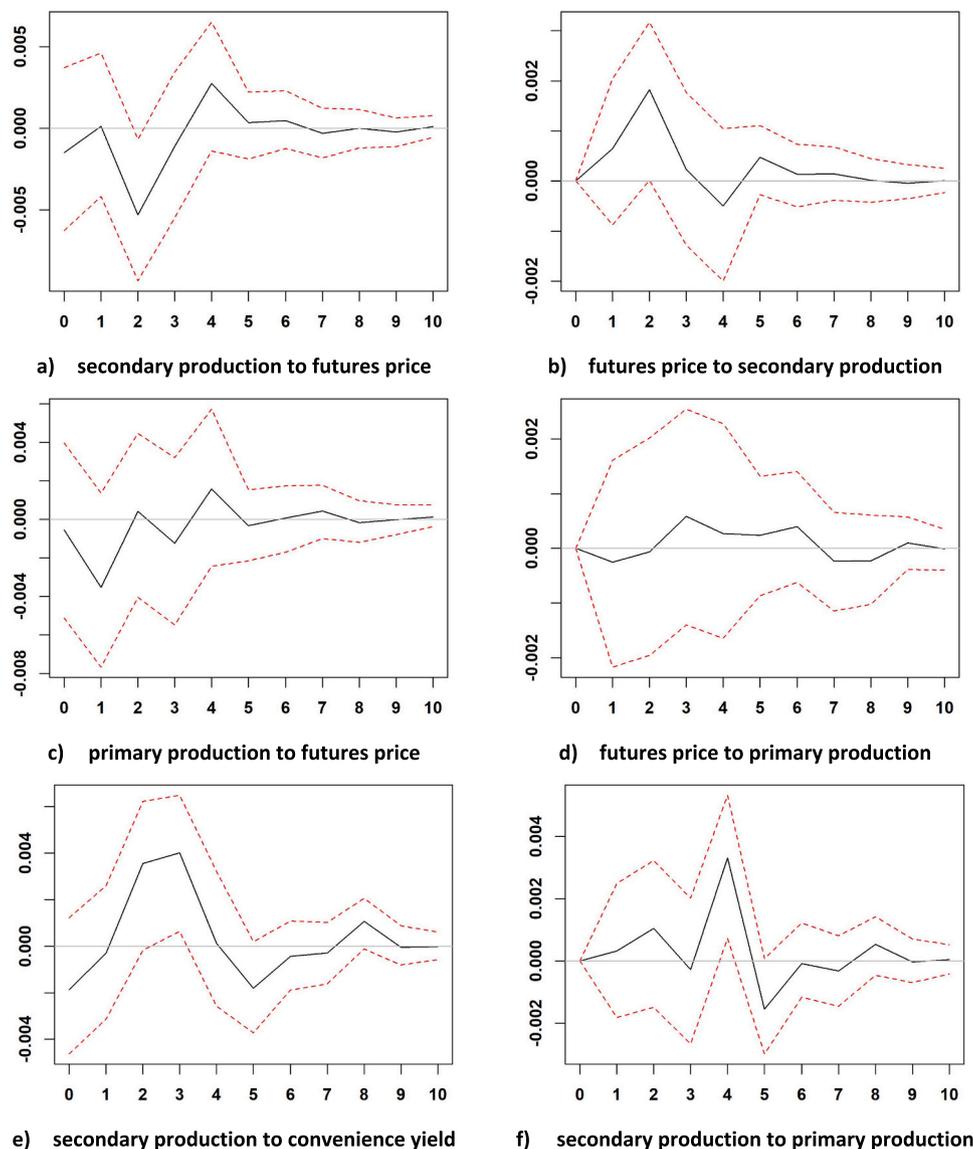The sensitivity analysis (see Appendix B) confirms the robustness of

Fig. 5. Key impulse response functions for aluminum to a one standard deviation shock, with 90% confidence intervals and 1000 bootstrap runs.

the main results across a range of model specifications, thereby reinforcing the reliability of the findings. Firstly, the results appear to be largely unaffected by modifications to the lag order selection. However, the altered aluminum model is unable to detect the fundamental relationship between primary and secondary production by the process of sweetening the scrap when only two lags are included. The significant effect of futures prices on secondary production for aluminum and lead disappears when considering a longer-term economic outlook, as implemented by varying the duration of yields on U.S. Treasuries. This suggests that secondary production is driven more by immediate economic and financing conditions than by medium-term expectations, likely due to its higher short-term flexibility and adaptability. Ultimately, neither the variation in industrial production nor the change in the energy price indicator affects the core conclusions regarding secondary production. However, the sensitivity analysis indicates that the lead model is less robust than those for copper and aluminum. This suggests that lead markets may be more susceptible to external shocks, likely due to the challenging market environment previously described.

5. Conclusion

In pursuit of a more sustainable and circular economy, recycling offers significant potential to reduce the environmental impact of metal production globally and mitigate resource depletion. However, the role of secondary production within metal markets remains largely underexplored. Therefore, we employ SVAR modeling using monthly data from 2010 to 2023 to analyze the interdependencies in the global copper, aluminum, and lead markets.

Collectively, our observations show that, in markets with a higher level of recycling implementation, namely the aluminum and lead markets, recycling significantly affects futures prices, while the convenience yield, as an indicator of scarcity and stock levels, as well as consumption, also exhibit sensitivity to changes in secondary production. This suggests that recycling has the potential to mitigate scarcity and lower commodity prices. In contrast, the copper market, which relies most heavily on primary production, shows no evidence of similar influence from secondary producers at this stage. Additionally, our findings reveal that secondary production is highly responsive to market conditions, with recyclers ramping up production primarily in response to commodity price fluctuations, while also reacting to signs of material scarcity. Meanwhile, primary production tends to adjust volumes more slowly. Finally, certain findings across all observed markets can be linked to the metal-specific material flows between primary and secondary production sites. This underscores the importance of a
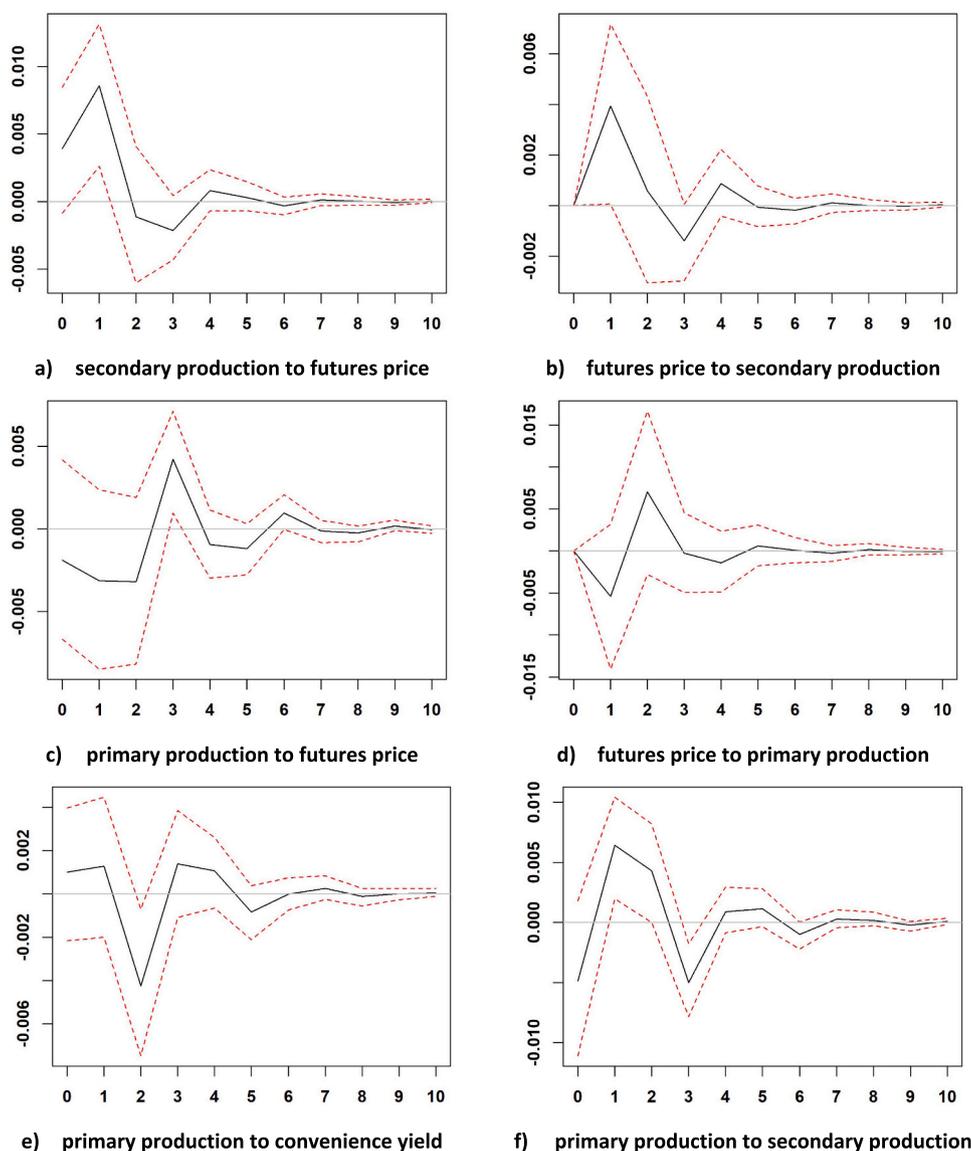
Fig. 6. Key impulse response functions for lead to a one standard deviation shock, with 90% confidence intervals and 1000 bootstrap runs.

multidisciplinary approach when analyzing commodity markets.

This study is subject to a few data-related limitations. In particular, the lack of differentiation between pre- and post-consumer scrap, as well as the exclusion of remelted scrap in the copper and lead data, the latter of which may lead to an underestimation of recycling's influence in these markets. Moreover, the data represents global averages, which prevents the direct examination of regional effects. Nevertheless, even when analyzing these aggregated figures, the importance of recycling in shaping market dynamics is clearly evident. Future research should therefore place greater emphasis on regional analyses, for example by studying more advanced recycling systems, which could provide valuable insights into potential global developments. In addition, distinguishing between pre- and post-consumer scrap would enable interesting analyses of temporal dynamics in recycling flows, especially regarding the time lag between the generation of scrap during manufacturing processes and the end-of-life scrap that may occur many years after the metal's initial consumption.

Our analysis underscores the significant role of recycling in shaping the commodity market environment, even in sectors predominantly controlled by primary producers, and illustrates the crucial impact of recycling practices on market flexibility besides its potential to mitigate the environmental footprint of metal production. Therefore, to promote more sustainable metal production, both voluntary and regulatory measures should be considered. These include the further development and wider deployment of advanced separation and sorting technologies for metal scrap, as advocated by Cullen and Allwood (2013) and others (Modaresi and Müller, 2012; van den Eynde et al., 2022), which have already been successfully implemented in the field of lead recycling. Alternatively, targeted policy measures, such as subsidies aimed at strengthening recycling activities, can also make a significant contribution.

CRediT authorship contribution statement

Michael Straub-Mück: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amelie Schischke:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Andreas W. Rathgeber:** Writing – review & editing, Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Data

Table 2
Variable definitions and sources.

Variable	Name	Source
PP	• WBMS Copper Production Refined Copper World Total (QWBCUPRDREFWW) • WBMS Aluminum Primary Smelter Production World Total (QWBALPRSPALWW) • WBMS Lead Secondary Refined Production World Total (QWBPBPRDRELWW)	(London Stock Exchange Group, 2024)
SP	• WBMS Copper Scrap Recovery Production Of Secondary Refined Copper World Total (QWBMCUSRESRFWWM) • WBMS Aluminum Secondary Production World Total (QWBALSPRSECWW) • WBMS Lead Secondary Refined Production World Total (QWBMPBSRPSRLWWM)	London Stock Exchange Group, 2024)
C	• WBMS Copper Consumption Refined Copper World Total (QWBCUCONREFWW) • WBMS Aluminum Primary Consumption World Total (QWBALCONPALWW) • Refinitiv WBMS Lead Consumption Refined Lead World Total (QWBPBCONRELWW)	London Stock Exchange Group, 2024)
P	• LME Aluminum rolling 3-month (LMAHDS03 Comdty) • LME Copper rolling 3-month (LMCADS03 Comdty) • LME Lead rolling 3-month (LMPBDS03 Comdty)	(London Metal Exchange, 2024)
FX	U.S. Dollar Index (DXY)	(ICE Futures U.S., 2024)
IP	U.S. Industrial Production	(Board of Governors of the Federal Reserve System (US), 2024b)
IR	Market Yield on U.S. Treasury Securities at 3-Month Constant Maturity (DGS3MO)	(Board of Governors of the Federal Reserve System (US), 2024a)
EC	Global price of Energy index (PNRGINDEXM)	(Board of Governors of the Federal Reserve System (US), 2024a)

Note: This table presents the names, descriptions, sources, and dates of availability for each variable included in this study.

Table 3
Descriptive statistics of the variables.

Variable	Min.	5% Q.	Median	Mean	95% Q.	Max.	St.Dev.	Skew.	Kurt.	Obs.
Copper										
PP	−0.093	−0.056	−0.001	0.000	0.047	0.123	0.034	0.315	1.451	167
SP	−0.746	−0.090	0.001	0.001	0.150	0.477	0.117	−1.650	16.27	167
C	−0.172	−0.071	0.001	0.000	0.078	0.157	0.048	0.110	1.063	167
CY	−0.165	−0.020	0.002	0.003	0.032	0.078	0.022	−2.126	21.366	167
P	−0.182	−0.079	0.001	0.001	0.077	0.140	0.048	−0.365	1.014	167
Aluminum										
PP	−0.069	−0.026	−0.001	0.000	0.033	0.070	0.020	0.268	2.282	167
SP	−0.072	−0.026	0.000	0.000	0.024	0.064	0.016	−0.597	4.512	167
C	−0.094	−0.055	−0.001	0.000	0.068	0.135	0.038	0.524	1.006	167
CY	−0.012	−0.043	0.003	0.003	0.050	0.091	0.031	−1.029	4.844	167
P	−0.130	−0.073	0.002	0.000	0.067	0.101	0.044	−0.262	0.087	167
Lead										
PP	−0.317	−0.172	−0.003	0.001	0.156	0.282	0.096	−0.233	1.354	167
SP	−0.097	−0.041	0.001	0.004	0.068	0.145	0.035	0.607	3.842	167
C	−0.161	−0.066	−0.002	0.000	0.079	0.131	0.045	−0.115	0.862	167
CY	−0.218	−0.044	0.003	0.003	0.053	0.163	0.036	−0.971	11.303	167
P	−0.177	−0.092	0.006	0.001	0.069	0.135	0.050	−0.425	0.647	167
Exogenous										
FX	−0.046	−0.023	0.002	0.002	0.028	0.050	0.020	−0.252	−0.008	167
IR	−1.249	−0.025	0.005	0.032	0.037	0.759	0.024	−2.006	9.929	167
IP	−0.144	−0.249	0.001	0.000	0.514	0.058	0.257	−0.377	2.751	167
EC	−0.404	−0.017	0.007	0.004	0.028	0.244	0.013	0.418	0.538	167

Note: This table presents the minimum (Min.), 5 % quantile (5% Q.), median (Median), mean (Mean), 95 % quantile (95% Q.), maximum value (Max.), standard deviation (St.Dev.), skewness (Skew.), excess kurtosis (Kurt.), and number of observations (Obs.) for the variables included in this study.

Appendix B. Sensitivity analysis

Table 4
Sensitivity analysis.

	Copper				Aluminum					Lead			
	Base	2Y	IP OECD	WTI	Base	Lag 2	2Y	IP OECD	WTI	Base	2Y	IP OECD	WTI
Impulse from **PP** to **PP**	+	+	+	+	+	+	+	+	+	+	+	+	+
Impulse from **PP** to **SP**	−	−	−	−	0	0	0	0	0	+	+	+	+
Impulse from **PP** to **C**	+	+	+	+	+	+	+	+	+	+	+	+	+
Impulse from **PP** to **CY**	0	0	0	0	0	0	0	0	0	−	−	−	−
Impulse from **PP** to **P**	−	−	−	+	0	0	0	0	0	+	0	0	+
Impulse from **SP** to **PP**	0	0	0	0	+	0	+	+	+	+	−	−	+
Impulse from **SP** to **SP**	+	+	+	+	+	+	+	+	+	+	+	+	+
Impulse from **SP** to **C**	+	+	+	+	0	0	0	0	0	+	+	+	+
Impulse from **SP** to **CY**	0	0	0	0	+	+	−	+	+	0	+	+	0
Impulse from **SP** to **P**	0	0	0	0	−	−	−	−	−	+	+	+	+
Impulse from **C** to **PP**	+	0	+	+	−	0	−	−	−	0	0	0	0
Impulse from **C** to **SP**	0	0	0	0	0	0	0	0	0	0	0	0	0
Impulse from **C** to **C**	+	+	+	+	+	+	+	+	+	+	+	+	+
Impulse from **C** to **CY**	+	+	+	+	0	0	0	0	0	−	−	−	−
Impulse from **C** to **P**	0	0	−	−	0	0	0	0	0	−	−	−	−
Impulse from **CY** to **PP**	0	0	0	0	+	+	+	−	+	0	+	0	0
Impulse from **CY** to **SP**	0	0	0	0	+	+	+	+	+	0	−	−	0
Impulse from **CY** to **C**	−	−	+	0	0	0	0	0	0	+	+	+	+
Impulse from **CY** to **CY**	+	+	+	+	+	+	+	+	+	+	+	+	+
Impulse from **CY** to **P**	+	+	+	+	+	+	+	+	+	+	+	+	+
Impulse from **P** to **PP**	0	0	0	0	0	0	0	0	0	0	+	+	0
Impulse from **P** to **SP**	0	0	0	0	+	+	+	+	+	+	+	+	+
Impulse from **P** to **C**	0	0	0	0	0	0	0	0	0	0	0	+	0
Impulse from **P** to **CY**	0	0	0	0	+	0	+	+	+	+	0	0	+
Impulse from **P** to **P**	+	+	+	+	+	+	+	+	+	+	+	+	+

Note: The table displays the results from the analysis of the impulse response functions, comparing the outcomes of our base model with those from slightly modified versions. Hereby, we vary the lag length for Aluminum (Lag 2), the treasury yield (2Y), the Industrial Production (IP OECD) and the energy price indicator (WTI). The table displays the first significant responses based on the 90% confidence level. The symbols indicate a positive response (+), a negative response (−), and no significant response (0).

Data availability

The data that support the findings of this study are available from the third-party sources listed in Appendix A. While some parts of the data are publicly accessible, others require a subscription and are subject to the provider's terms and conditions. The code developed for the paper is accessible via the following link: https://github.com/michaelstraubmueck/Recycling-Matters.

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