A Common Market Directive and an Extreme Price Parallelism in the Minerals Industries

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Abstract

Against the backdrop of the 2006 taking effect EU "Restriction of Hazardous Substance" (RoHS) directive, targeted primarily at cutting down e-waste, we study the price dynamics of rare, relevant and regionally restrictedly won metals. The focus of our analysis is on the bivariate study of prices for platinum group metals (PGM) and for the base metal lead. These metals are highly relevant for the production in the automobile industry, which is one of the key sectors of the common market. Platinum and palladium are used in the construction of catalytic converters, while lead is used in manufacturing automotive batteries. We find an extreme form of price parallelism in the aftermath of the RoHS directive. Dynamics do not only begin to move in lock-step but also, whilst before the RoHS directive none of the analyzed price series shows predictive power for the other, lead price series Granger cause relevant PGM prices thereafter. We interpret this result as giving reasonable grounds for an enhanced information value of lead prices as regards key sector production.

JEL classification: C22, D43, O13

Keywords: Platinum, Palladium, Lead, EU directive, Imperfect substitutes, Frequency domain, Rolling trace test

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1 Introduction

This study is an industry analysis at the interface of the automobile sector as a key industry of the European Union (EU), the European common market environmental policy efforts, and the oligopolistic international minerals industries. Using timely time series techniques in the time and frequency domain, we study price parallelism between prices of base metal lead and of Platinum group metals (PGM) platinum and palladium.

Platinum and palladium are used in the construction of catalytic converters, while lead is used in manufacturing automotive batteries. In our identification strategy we consider the 2006 taking effect EU "Restriction of Hazardous Substances" (RoHS) directive, targeted primarily at cutting down end-of-life electronics (henceforth, "e-waste"), as structural break. Figure 1 makes this point. Against the backdrop of the shown development of dynamics of lead prices (solid grey line) and central PGM prices of palladium and platinum (solid black line) over time, our central research questions are:

- Did the RoHS "lead-free e-waste" initiative activate a new relationship between lead prices on the one hand and platinum and palladium prices on the other?
- As suggested by a mere eyeballing of Figure 1, is the profound comovement a product of platinum and palladium prices shadowing lead price dynamics or vice versa?

If we find predictability to run from a perfectly competitive market to one where only a handful of substantial suppliers are present, this could point into a direction that the price information from the perfectly competitive market is used as a signal for the prices in the other market. If this price signal is only present after some specific point in time, this could lead to the conclusion that after this particular point in time the behaviour of some or all market participants has changed.

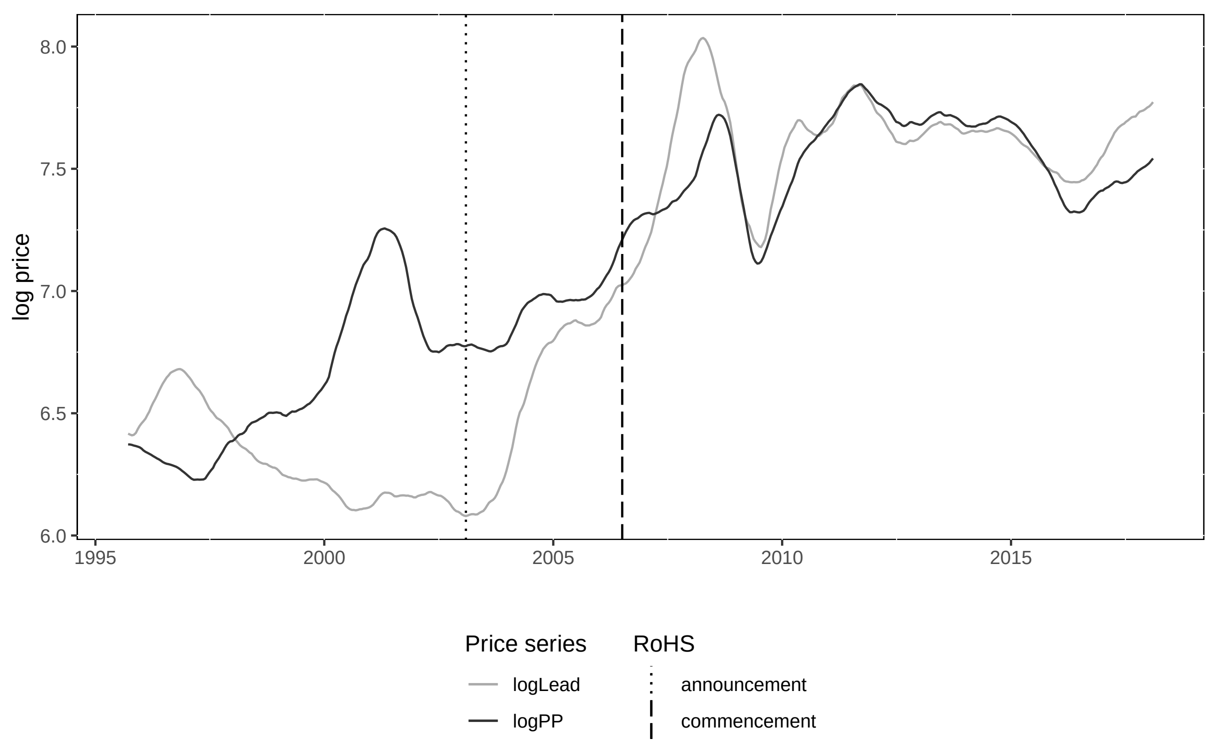
Our study contributes to the literature in several regards.

Using one combined price for the imperfect substitutes platinum and palladium, we are able to show an extreme price parallelism of this combined price to the price of lead.

We are the first to show that the beginning of this price parallelism coincides with the commencement of the RoHS directive. Furthermore we are the first to compare a combined price of two imperfect substitutes with the price of a complementary good that is used with either of them.

The remainder of the paper is organized as follows. Section 2 looks at the automobile market in the EU and the European e-waste policies. In the following section the markets for platinum group metals and lead are described. In section 4 we present our data which are analysed in the next section. Finally, Section 6 concludes.

Figure 1: Lead and central PGM (comprising platinum and palladium) prices



2 The automobile sector and e-waste policies in the EU

2.1 The role of the automobile industry in the EU

Recently, Goolsbee and Krueger (2015) note that even in the "information age" the auto industry remains a major contributor to Western economies. By the beginning of the last decade, there are three (five) EU eonomies in the top-10 (top-15) largest car-producing countries (OECD, 2010). Among them are the two largest economies of the European common market: Germany and France. For the former, i.e. for the largest economy in the EU, the automobile sector is said to be the nation's core industry directly employing about two percent of the working population and showing an annual turnover of about ten percent of GDP (Schweinfurth, 2009; Leuwer and Süssmuth, 2018).

2.2 The role of PGMs and lead in the automobile industry

Two kinds of metals are particularly relevant for the production of the automobile industry: PGM platinum and palladium and the base metal lead which is the main component of storage batteries. For both there are no economically viable alternatives at current prices. Automobile catalysts account for about 70% of the total combined consumption of the PGM metals platinum, palladium and rhodium (Schmidt, 2015 p. 16f.) whereas more than 80% of the supply of lead is used in storage batteries (International Lead Association, 2013 p.14). Platinum and palladium are both used in automobile catalysts but they are not perfect substitutes. Currently platinum is mainly used for catalysts for diesel engines and palladium for gasoline fueled vehicles. Substitution to some extent is possible and depends on the technical design of the catalysts (Schmidt, 2015 p. 17ff.).

2.3 Recent e-waste policies in the EU

Supplementing the "Waste electric and electronic equipment" (WEEE) European Council directive (2002/96/EC amended by 2003/108/EC) entering into force in early 2003, is the

"Restriction of Hazardous Substances" (RoHS) directive 2002/95/EC. It makes the EU hazardous substances and e-waste standards the highest in the world (Selin and VanDeveer, 2006, p. 8). The RoHS directive is often fuzzily referred to as "lead-free directive" of end-of-life electronics and took effect on 1 July 2006 (Williams et al., 2008). An EC directive is binding with regard to the results it sets out to be achieved, but –other than a regulation– gives flexibility to national authorities to choose the specific forms and methods for implementation (Selin and VanDeveer, 2006). The RoHS directive strictly limits the use of the heavy metal lead and five other toxic substances in eight out of ten product groups covered by the WEEE directive. The *ab initio* covered categories are large household appliances, small household appliances, IT and telecommunications equipment, consumer equipment, lighting equipment, electrical and electronic tools, toys, leisure, and sports equipment, and automatic dispensers. Besides medical devices, monitoring and control instruments that are a central component in the assembly of vehicles in the automobile industry are part of the WEEE-regulated product categories but were not covered by the RoHS directive (Selin and VanDeveer, 2006, p. 9) officially up to mid-2011 and effectively up to 2013.[1] This is particularly remarkable as monitoring and control instruments got more computerized in the automobile industry, implying higher contents of lead, especially in the last two decades.

In general, the RoHS directive bans or –as of 2013 through limits– controls lead in electronics for all products sold in the European Community whether made within the EU or imported. However, in a globalized world EU environmental policies also directly through intermediate goods and indirectly through trading up global standards (Vogel, 1997) affect manufacturing goods in markets such as the United States, Japan, and China.

Batteries, and, in particular, automotive batteries, are not included within the scope of the RoHS lead-free directives. It might be objected that in Europe batteries are separately covered by environmental end-of-life battery directives (directives 2006/66/EC, 2003/0282 COD repealing 91/157/EEC) of the European Commission. However, these directives do *not* set any limits on quantities of lead or lead-acid used in automotive batteries. In

[1] The corresponding 2002/95/EC directive-update is directive 2011/65/EU.

accordance with the latest 2006 battery directive (2006/66/EC), lead content in auto batteries is not restricted at all.

3 Market structure of international mineral markets

3.1 Central platinum group metals

PGM are “minor metals” derived from the latter processing stages of heavy non-ferrous metal concentrates (Carvalho, 1991). The PGM class of minerals is composed of six elements: platinum and palladium, the most well known, and iridium, osmium, rhodium and ruthenium.

Because of their chemical and physical properties they are mainly used in the production of all kinds of catalysts and as anti-corrosives in various applications. Besides platinum and palladium being by far the most common PGMs they are also used in the production of jewellery and for investment purposes (Schmidt 2014 p. 11ff.). Only platinum and palladium are publicly traded on metal exchanges whereas for the other PGMs only selling prices of specialized trading companies are available.

3.1.1 Platinum and palladium producing countries

The world mining of platinum and palladium has been relatively stable over the last 15 years with a delivery of about 200,000 kg per year for each of the two metals. Table 1 depicts the geographic origin of the world mining for platinum in 2006 and 2015.

A comparison of Table 1 with Table 2 shows that palladium is produced in the same countries as is platinum. However, production shares differ. While South African mines clearly dominate the production of platinum, Russian and South African producers divide the market for palladium more or less equally with respective market shares of roughly 40 percent.

Table 1: Platinum: total output and production share by country

	Output 2006 (in 1,000 kg)	Share 2006 (percent)	Output 2015 (in 1,000 kg)	Share 2015 (percent)
USA	4.29	1.95	3.67	1.95
Canada	9.00	4.07	7.60	4.02
Russia	29.00	13.12	22.00	11.64
South Africa[2]	170.0	76.92	139.0	73.54
Zimbabwe	5.10	2.31	12.60	6.66
Rest of world	3.29	1.49	4.00	2.12
Total	221.0		189.0	

Source: Own calculations based on US Geological Survey (2008, 2017)

In total, recycled material equals approximately 53,600 kg for platinum and 76,400 kg for palladium in 2015. In contrast to primary production figures, these amounts of recycled material represent estimates (Schmidt, 2015).[3] When jewellery is excluded, the recycling rates for platinum as well as palladium lie between 60 and 70 percent. As a consequence the share of recycled material with respect to the total supply is slowly but constantly growing (Schmidt, 2015).

3.1.2 Platinum and palladium mining companies

As metals of the PGM usually occur together, it is hardly surprising that mines which produce platinum also produce palladium and vice versa. Although there have been mergers and acquisitions in the industry over the years, the main producers of platinum and palladium are more or less the same between the second half of the 2000s and the first half of the 2010s. Even more important, the main producers of platinum are also the main producers of palladium.

[3]For 2013, estimates of recycled platinum (palladium) vary between 43.1 (58.9) and 63 (78.6) 10^3 kg.

Table 2: Palladium: total output and production share by country

	Output 2006 (in 1,000 kg)	Share 2006 (percent)	Output 2015 (in 1,000 kg)	Share 2015 (percent)
USA	14.40	6.43	12.50	5.79
Canada	14.00	6.25	21.00	9.72
Russia	98.40	43.93	81.00	37.5
South Africa	85.00	37.95	83.00	38.43
Zimbabwe	4.00	1.79	10.00	4.63
Rest of world	8.21	3.67	8.30	3.84
Total	224.0		216.0	

Source: Own calculations based on US Geololgical Survey (2008, 2017)

Anglo American Platinum, *Impala Platinum*, *Lonmin*, and *Northam Mining* operate mainly in South Africa and Zimbabwe. *MMC Norilsk Nickel* produces in Russia, and *Stillwater Mining* in the United States. Brazilian company *Vale* mines PGM in Canada. As shown in Table 3, the four largest producers control more than 80 percent of the platinum and palladium production in the year 2006. For the seven largest companies respective shares amount to more than 90 percent. According to calculations of the German Federal Institute of Geosciences and Natural Resources (BGR), in 2013 the Herfindahl-Hirschmann Index reached 1,659 points for the global platinum market and 2,198 points for the global palladium market, respectively. These figures suggest a moderate rather than an alarming level of concentration.

As regards holdings and joint ventures, *MMC Norilsk Nickel* holds a share-capital controling stake of 51 percent of *Stillwater Mining.* Especially the South African based companies show various joint venture constructions, pool-and-share- and concentrate-offtake agreements both with minor producers and among each other. For example, the biggest shareholder of *Lonmin* represents *Glencore* with an equity stake of 24.6 percent. Through its subsidiary *Eastern Platinum Ltd.*, *Lonmin* has an interest of 42.5 percent in joint

Table 3: Major platinum and palladium producers in 2015

	Platinum (in 1,000 kg)	Share (percent)	Palladium (in 1,000 kg)	Share (percent)
Anglo American Platinum	57.10	30.21	38.50	17.82
Impala Platinum	39.69	21.00	22.24	10.30
Lonmin	23.64	12.51	10.89	5.04
MMC Norilsk Nickel	20.40	10.79	83.63	38.72
Northam Mining	7.90	4.18	3.89	1.80
Glencore	4.91	2.60	6.28	2.27
Vale	4.79	2.53	10.61	4.93
Stillwater Mining	3.67	1.94	12.50	5.79

Source: Annual reports of companies referring, as a rule, to financial year 2015

venture *Pandora*. Stakes of the latter are held among others by *Anglo Platinum* and, also through a subsidiary, by *Northam Platinum*. Moreover, *Northam Platinum* is a joint venture partner of *Lonmin* in *Western Platinum Ltd.* (Schmidt, 2015).

Table 3 shows that the largest four companies still control more than 70 percent of the mining of both metals in 2015. Besides mining, most of the companies are also engaged in recycling platinum and palladium from scrap, which for some companies as, for instance, for *Stillwater Mining* roughly corresponds to the amount of primary production.

With the acquisition of *Aquarius Platinum* in April 2016, *Sibanye Gold Ltd.* recently emerged as new player in the PGM market. After the takeover of *Rustenburg Platinum* and *Stillwater Mining*, *Sibanye-Stillwater* is the world's third largest producer of platinum and palladium in 2017. In the same year (on 12/14), the company launched a takeover bid for *Lonmin* which, if successful, will further manifest its dominant position in the market and most likely lead to an additional concentration in the market.

3.1.3 Historical price management

Even during the Soviet Union era and the apartheid regime prevailing in South Africa, there were suspicions of cartel formation in the early 1990s; see, for example, Cramton and Palfrey (1990). It is commonly agreed on among market participants and experts that Russian producers have the ability to influence prices and volatility in the global palladium market and that they have done so in the past; see Lejonhielm and Larsson (2004) for this point and the remaining argumentation of this paragraph. However, "this is not to say that the outcome of these actions necessarily will be as preferred or expected by Russian actors" (Lejonhielm and Larsson, 2004, p. 105). Actions which aimed at maximizing revenue for the Russian state seem not to have been altogether successful in the long run. It is unclear if Russian market participants became aware of the pointlessness of their attempts to control the market and ended their actions.

Contemporaneously, there are still discrepancies in the mined and exported amounts of both platinum and palladium from Russia leaving room for the possibility of concerted action and (cross-border) cartelization in the international PGM industries (Schmidt, 2015). Following the argumentation in Kooroshy et al. (2014), there is, however, no prospect of a widespread revival of 1970s-style cartels in international minerals markets in general. Potash, which is dominated by two state-backed private export corporations, is currently the only openly cartelized global mineral market. According to Kooroshy et al. (2014), for many producer-country governments painful lessons from the attempts to establish cartels in the 1970s serve as "powerful deterrent." And, although Russia and South Africa have recently announced plans for a PGM cartel (officially not the intention to actually cartelize, but the intention to "influence markets"), their exceptional proposal remains vague and its implementation is, according to Kooroshy et al. (2014, p. 2) "unlikely."

As long as the automotive industry is the main buyer of PGMs the demand for platinum and palladium is highly predictable. The lead prices being an indicator for their combined demand. In contrast to e.g. the oil market, output of metals cannot be increased in the short run. As the production of PGM is quite stable, there is no indication that some players are trying to win market share by expanding production. As the development of new mines takes several year. Every attempt of one of the main producers to expand production in the future would be detected by the other market participants well in advance. If tacit collusion can be assumed for the PGM market, any deviation in production could be detected by other market participants years before it would be effective.

With recently stable production quantities for platinum as well as palladium the price is the relevant indicator for the respective demand. Additional demand for one of the metals could in the short run be satisfied by the liquidation of quantities originally bought for investment but also from higher recycling activities. In the long run it will lead to the substitution of palladium through platinum and vice versa. As the process of substitution takes some time the prices of platinum and palladium can fluctuate against each other quite substantially. For the producers that in almost every case produce both metals together in the same mines the combined price of both metals determines their revenues and is thus relevant.

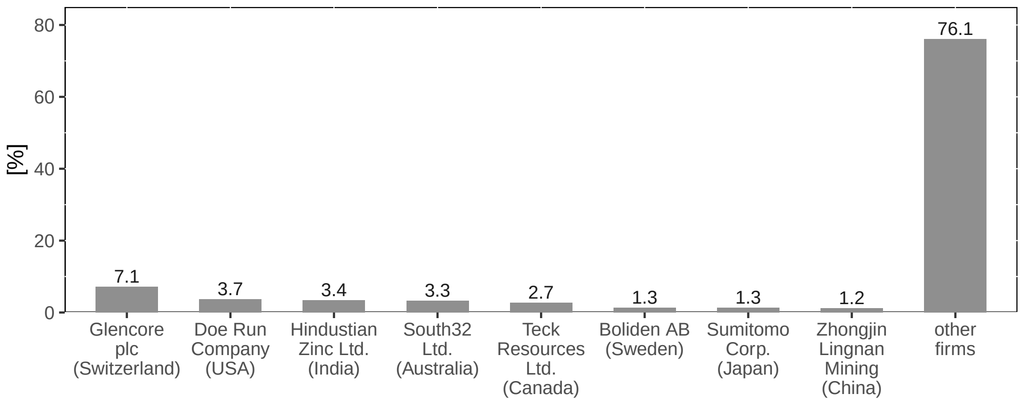
3.2 The lead market

In contrast to the market of auto industry relevant PGM, the lead market is highly competitive. Although roughly half of the mined lead comes from China, the largest lead producer (*Glencore*) only shows a market share of seven percent.

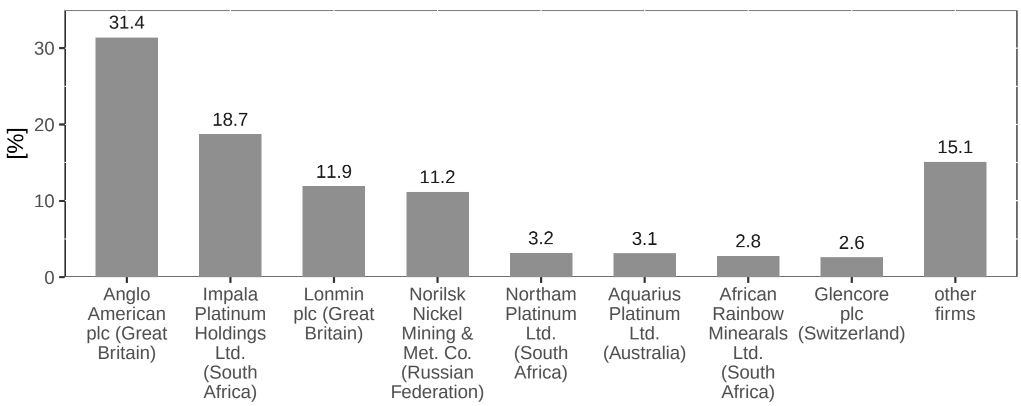
Joint production of the largest four companies represents just about 17 to 18 percent of the mined lead in 2016.

World mining production of lead in 2016 amounts to 4.7 million metric tons. In addition, 6.5 million metric tons are produced through recycling. In 2004, the corresponding figures were 3 million metric tons mined and 3.8 million metric tons recouped from used materials (United Nations, 2006). As can be seen from these figures, the percentage of lead stemming from recycling slightly increased from 54.8 to 57.8 percent.

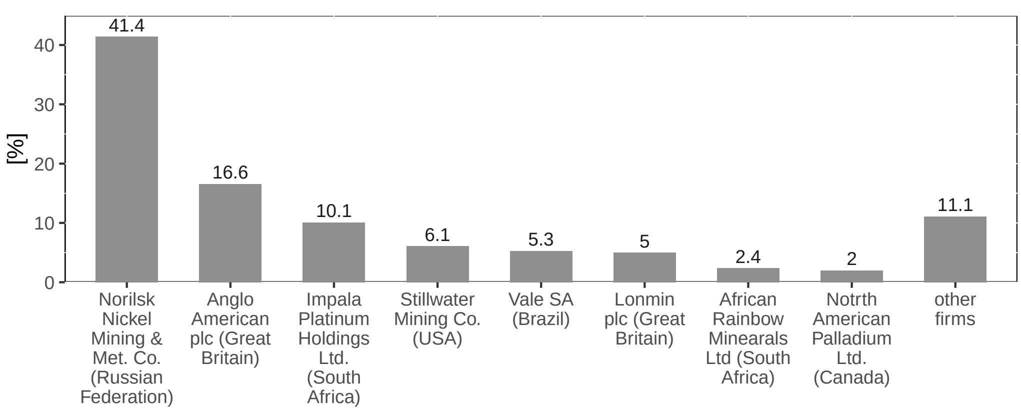
Figure 2: Lead and central PGM production: company-level market shares



(a) Lead production



(b) Palladium production



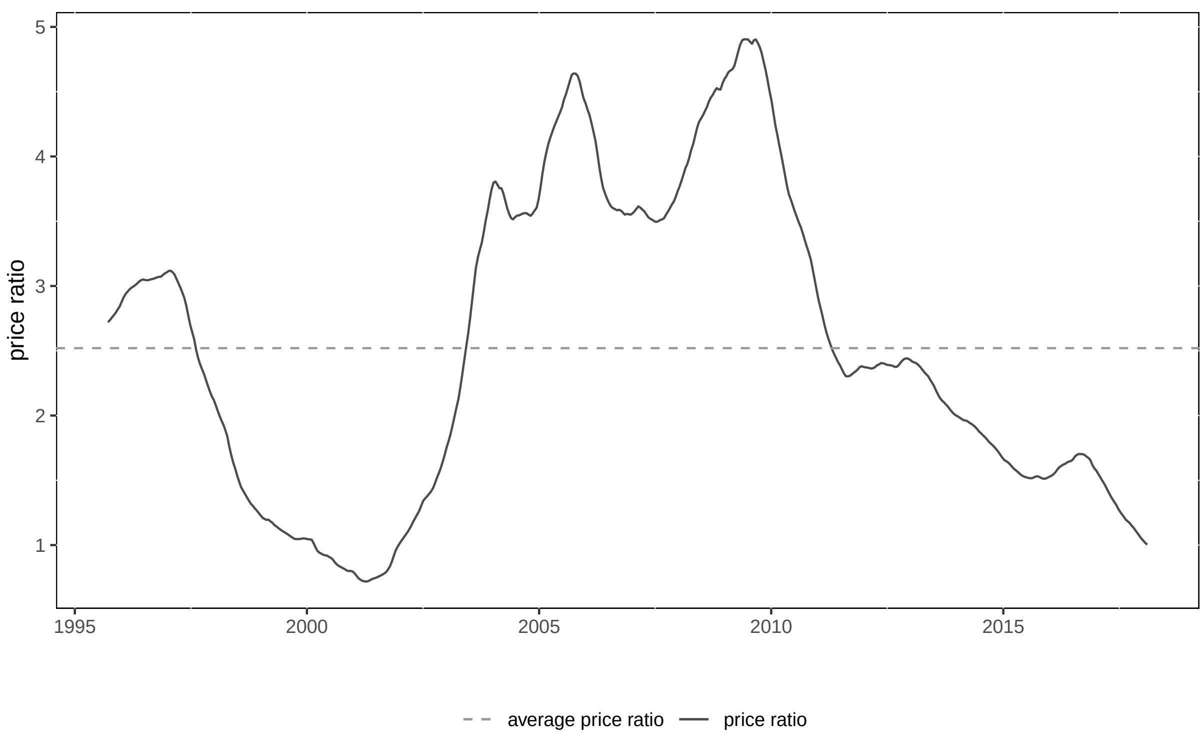
(c) Platinum production

Note: (a) refers to financial year 2016, (b) and (c) to financial year 2013, respectively; Source: BGR

4 Data

Our analysis is based on daily data of prices for lead, palladium, and platinum from December 1, 1994 to February 12, 2018. Price series are retrieved from Thomson-Reuters datastream and provided as listed at the London Metal Exchange. Platinum and palladium prices are expressed in USD per troy ounce. Lead prices are given in USD per metric ton. We smooth price series using 200 days moving averages keeping only every 11th value. By choosing every 11th value we make sure that we deal with roughly two prices at varying weekdays per month.

Figure 3: Platinum/Palladium Price Ratio



As outlined in the preceding sections, we consider platinum and palladium to be imperfect substitutes –both in automobile production and in any other fabrication– and thus expect that both prices do not diverge considerably in the long run. Figure 3 shows the metals' price ratio. Due to the various rigidities in production and consumption, as well as time-wise differences in the construction of mines, differences in product cycles and recycling, the observed price ratio is not perfectly stable and fluctuates around a mean value of 2.5. However, platinum and palladium prices tend to balance in the long run and arguably are influenced by roughly the same factors and events. Therefore, we combine the price series and consider the unweighted sum of platinum and palladium prices (henceforth, PP). To treat PGM minerals jointly is commonly done, for they occur together, in variable proportions, generally associated to large sulphide deposits of nickel and copper (Carvalho, 1991, p. 15). As is common practice, we consider natural log transformations of the resulting two price series, that is, of the lead and PP series, respectively.

Figure 1 in Section 1 shows the trend of both price variables. While in the beginning of the sample PP- and lead prices rather seem to move in opposite directions, the prices begin to converge in 2003. From this point on, PP and lead prices co-move, reach a peak at about the same time in 2007/08 and decline drastically afterwards. Even after this presumably to the financial crisis related development, the graphical representation suggests the price series to be closely related to the end of the sample, only with some drifting apart beginning in 2016.

Conventional unit root tests indicate that the two series are I(1). Table 4 shows the results of the Augmented-Dickey-Fuller (ADF), the Philipps-Perron (P-P), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test for the price series and their respective first difference. As for the ADF test and the P-P test, neither allows us to reject the null hypothesis of a unit root at any reasonable level of significance for the time series in levels. For both time series in first differences, however, we clearly are able to assume stationarity. The KPSS test, which tests for trend stationarity, confirms these results.

Table 4: Unit Root Test Results.

Test	ADF	P-P	KPSS
log lead	−2.67	−1.3	0.3
log PP	−2.72	−1.34	0.3
Δ log lead	−4.42	−3.82	0.1
Δ log PP	−5.65	−3.98	0.04
Critical values			
1%	−3.96	−3.98	0.22
5%	−3.41	−3.42	0.15
10%	−3.12	−3.13	0.12
Trend	✓	✓	✓
Drift	✓	✓	✓
H_0	unit root	unit root	stationarity

Note: Choice of lag length based on information criterion AIC

Table 5: Cointegration test results

Test	Engle-Granger	Johansen trace
Test statistic		
Full sample	−2.48	10.35
Post-announcement	−3.16	12.68
Post-commencement	−4.6	39.09
Critical value		
1%	−3.43	23.52
5%	−2.86	17.95
10%	−2.57	15.66

Note: Engle-Granger critical values taken from MacKinnon (2010)

5 The relationship between lead and PGM prices

5.1 Cointegration

Since both price series are I(1), we are testing for a cointegrating relation. For the whole sample, neither with the Engle-Granger approach nor with the Johansen trace test the null hypothesis of no cointegration is rejected (table 5). If, however, the sample is reduced to the commencement of the RoHS-directive on July 1st 2006, the Johansen trace test rejects the null of zero cointegrating ranks at the one percent level. The Engle-Granger two-step procedure also rejects the null hypothesis of a unit root in the residuals at the five percent level and at the one percent level for the sample beginning with the announcement and the commencement of the RoHS-directive, respectively.

Similar to Peri and Baldi (2013) we perform a rolling trace test in order to date and visualize the emergence and development of the cointegrating relation between lead and PP. The rolling cointegration approach requires the definition of an optimal window size, where results may vary with the chosen window size. Since there is no statistically defined- or rule of thumb-value regarding the optimal size of a rolling window, we choose a window size of 100 days corresponding in our case to roughly 4.5 years, which takes the long-run character of a cointegration relationship into account. Figure 4 displays the trace test statistics of the null hypothesis of $r = 0$ cointegrating vectors, normalized by the 5% critical value (i.e. 17.95), as well as the trace test statistics of the null hypothesis of $r \leq 1$ cointegrating vectors, normalized by the 5% critical value (i.e. 8.18) and plotted against the ending date of the rolling trace test. Thus, if in a time period the null hypothesis of zero cointegrated ranks is rejected, while the null hypothesis of at most one cointegrating ranks is not, there is evidence of cointegration between lead and PP in the recent 4.5 years. The figure indicates a short period of cointegration between lead and PP prices about 2006, comprising the commencement of the RoHS-directive. Further, the larger period, where the null of zero cointegrating ranks is rejected, is observed post-commencement around 2008-2011 and around 2012 to 2016. However, actual cointegration is prevalent only in short windows in 2006, 2008, 2010, 2012 and from 2015 to 2016.

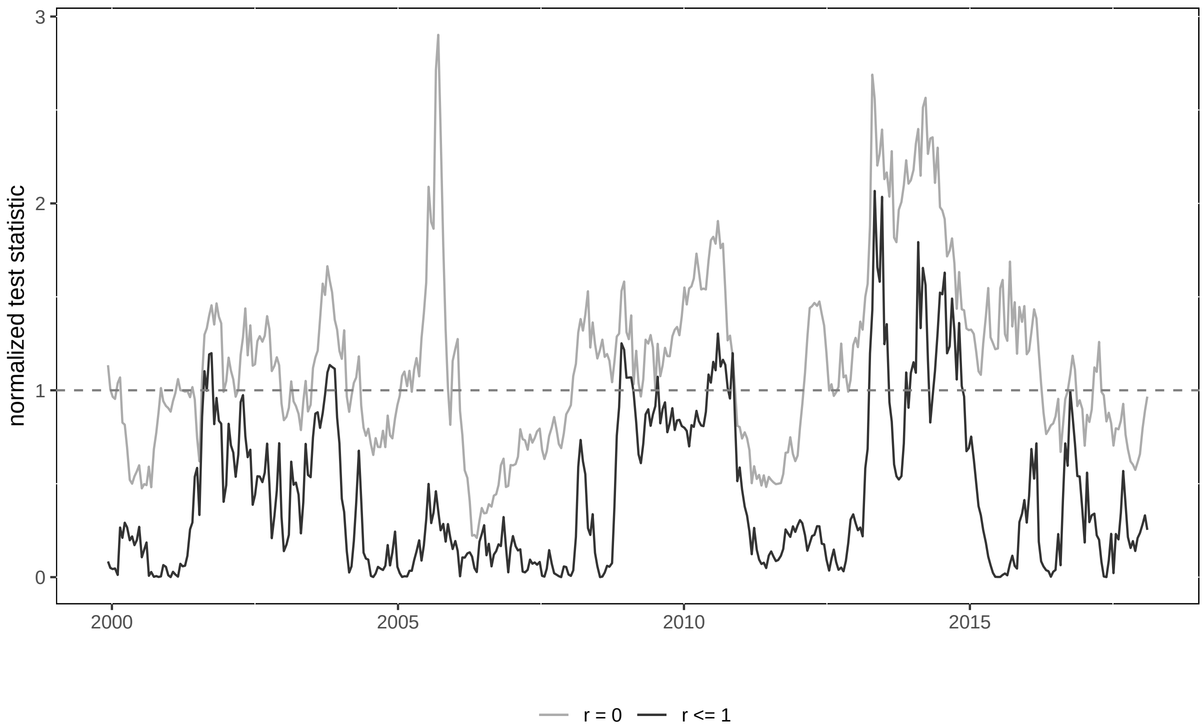
5.2 Granger Causality

Besides addressing the question on the nature and causes of the co-movement of lead- and PP prices, we are especially interested in the industrial economic aspects of this co-movement. As outlined in Section 3, the markets for platinum and palladium are highly interrelated and oligopolistically organized, whereas the market for lead appears to be perfectly competitive. We therefore assume PP prices to shadow lead prices. We perform a Granger causality analysis to shed light on the direction of the feedback between the two price variables.

Table 6 shows the results of a simple VAR-Granger causality test.[4] As expected,

[4] The lag length was chosen according to the AIC and the Granger causality test was adjusted to I(1) variables according to Toda and Yamamoti (1995).

Figure 4: Rolling Johansen trace test



the results suggest unidirectional Granger causality from lead to PP for the sample beginning with the commencement of the RoHS. For the sample ending with the RoHS-commencement, we cannot observe any Granger causality (see Table 7).

To further investigate the nature of the detected Granger causality, that is, to examine whether lead prices influence PP prices both in the short- and long-run, we employ a Granger causality test (BCG) in the frequency domain as proposed by Breitung and Candelon (2006). The BCG test visualizes spectral causality by frequency. It is tested whether a particular component of the "cause variable" helps in predicting the component of an "effect variable" at the same frequency ω one period ahead. Figure 5 shows the results of the BCG test with the null hypothesis of no Granger causality from PP to lead on the left side and from lead to PP on the right side for the post-commencement

Table 6: Granger causality between lead- and PP-prices, lag order 4, post-RoHS commencement.

	chi2	df	p
pplead	6.73	4	0.15
leadpp	16.97	4	0.00

Table 7: Granger causality between lead- and PP-prices, lag order 4, pre-RoHS commencement.

	chi2	df	p
pplead	3.74	4	0.44
leadpp	4.84	4	0.30

period.[5] For Granger causality running from lead to PP, we reject the null of no Granger causality for lower frequencies $\omega \in [0,0.92]$ and frequencies $\omega \in [1.5, 3.12]$ at the 5% level. Further, we reject the null of no Granger causality from lead to PP at the 10% level for all frequencies and at the 5% level for $\omega \in [0,0.11]$, which corresponds to $11 \cdot 2\pi/\omega = 628$ trading days (roughly 2.5 years). BCG causality tests in log differences yield qualitatively similar results (see Figure 6).

Interestingly, for the period before the RoHS-commencement, there is no indication of Granger causality from lead to PP at any frequency for the price series in levels and log differences (Figure 7, Figure 8).

6 Conclusion

Although prices for platinum and palladium are individually fluctuating with regards to each other as well as to other commodities. Their combined price runs parallel with that

[5] We only report results using the Geweke approachas test results according to Hosoya-type conditioning are qualitatively in line.

Figure 5: BCG causality test in levels, lag order 4: post-RoHS

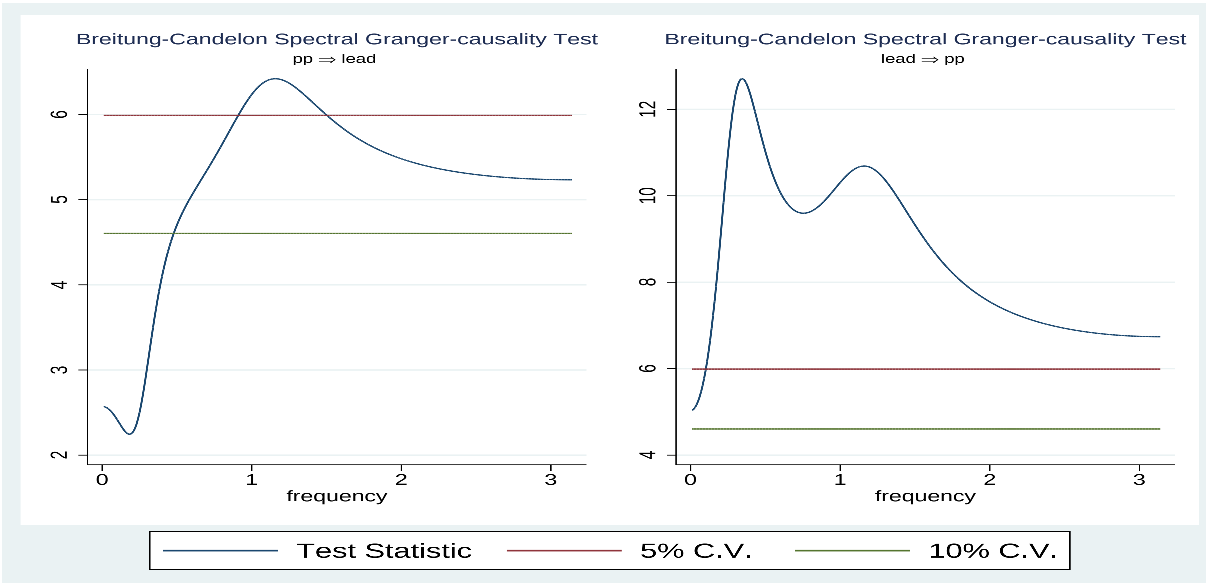


Figure 6: BCG causality test in log differences, lag order 4: post-RoHS

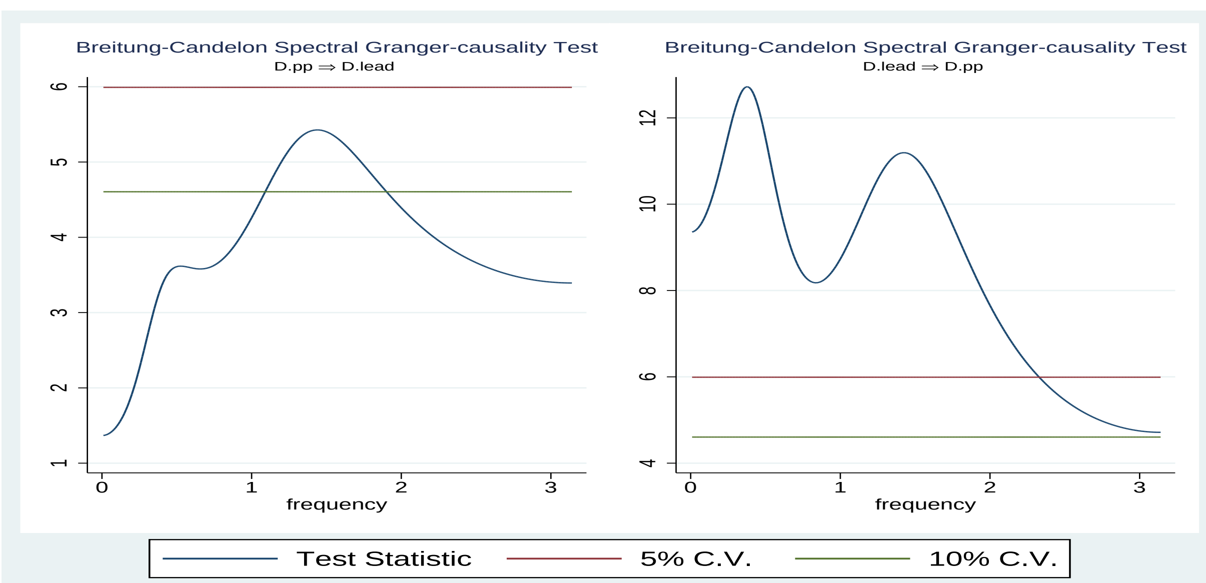


Figure 7: BCG causality test in levels, lag order 4: pre-RoHS

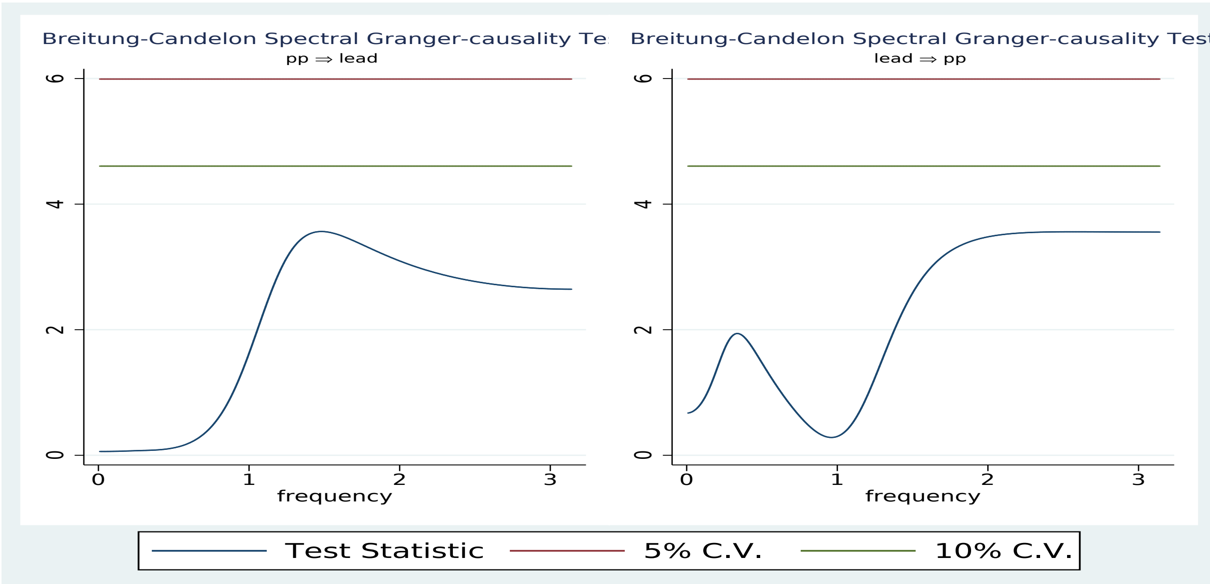
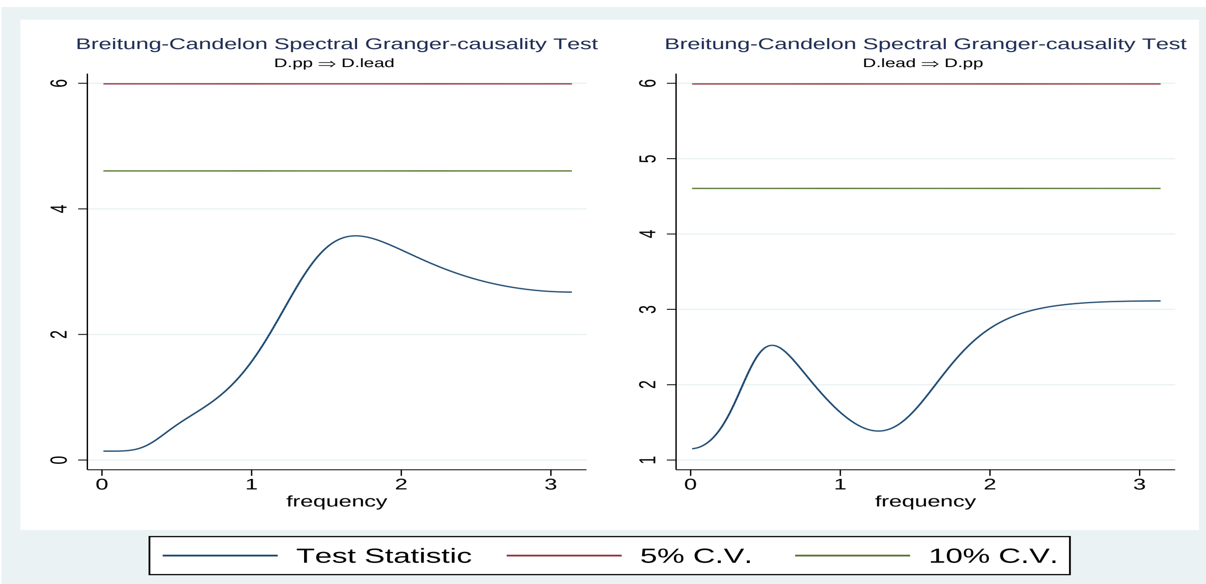


Figure 8: BCG causality test in log differences, lag order 4: pre-RoHS



for lead since the implementation of the RoHS directive in 2006. We were able to show unidirectional Granger causality from lead to platinum/palladium prices beginning with the commencement of the RoHS. This is not the case for the preceding period. With stable output and a combined price of platinum and palladium that shadows the price of lead, the producers are covered against any substitution process between platinum and palladium that occurs.

Since the announcement and implementation of the RoHS the combined price of platinum and palladium has risen substantially, while output of both metals has remained stable. Every attempt by one of the major players to manipulate prices of either palladium or platinum by cutting supply temporarily would in the long run lead to a substitution effect. The price of the substitute will rise and the producer of the substitute will profit from the move. In the end only the relative prices will be affected. Therefore keeping output stable and having a combined price for palladium and platinum that shadows the lead price seems to be the most profitable strategy for all market participants.

References

[1] Breitung, J. and B. Candelon (2006), Testing for short- and long-run causality: a frequency-domain approach, *Journal of Econometrics* 132, 363–378.

[2] Carvalho, O. (1991), *Production and market structure for minor metals: an economic view from the non-ferrous industry*, PhD thesis, University of London, Imperial College, Royal School of Mines, London

[3] Crampton, P.C. and T.R. Palfrey (1990), Cartel enforcement with uncertainty about costs, *International Economic Review* 31, 17–47.

[4] Goolsbee, A.D. and A.B. Krueger (2015), A retrospective look at rescuing and restructuring General Motors and Chrysler, *Journal of Economic Perspectives* 29, 3–24.

[5] Hamilton, J.D. (2017), Why you should never use the Hodrick-Prescott filter, forthcoming in *Review of Economics and Statistics*

[6] International Lead Association (2013), Annual Review 2013, London.

[7] Kooroshy, J., Preston, F., and S. Bradley (2014), Cartels and competition in minerals markets: challenges for global governance, Chatham House Energy, Environment and Resources, The Royal Institute of International Affairs, London

[8] Lejonhielm, J. and R.L. Larsson (2004), Russia's strategic commodities, FOI Swedish Defense Research Agency, Stockholm

[9] Leuwer, D. and B. Süssmuth (2018), The exchange rate susceptibility of European core industries: 1995-2010, *World Economy* 41, 358–392.

[10] MacKinnon, J.G. (2010), Critical values for cointegration tests, Queen's University Economics Department Working Paper, No. 1227

[11] OECD (2010), The automobile industry in and beyond the crisis, OECD Economic Outlook 86, 87–117.

[12] Peri, M. and L. Baldi (2013), The effect of biofuel policies on feedstock market: empirical evidence for rapseed oil prices in EU, *Resource and Energy Economics* 35, 18–37.

[13] Selin, H. and S.D. VanDeveer (2006), Raising global standards: hazardous substances and e-waste management in the European Union, *Environment* 48, 6–17.

[14] Schmidt, M. (2015), Rohstoffrisikobewertung: Platingruppenmetalle, BGR German Federal Institute for Geosciences and Natural Resources, Hannover

[15] Schweinfurth, A. (2009), Car-scrapping schemes: an effective economic rescue policy?, Global Subsidies Initiative (GSI) Policy Brief 12/2009, IISD, Geneva

[16] Toda, H. Y. and T. Yamamoto (1995), Statistical inference in vector autoregressions with possibly integrated processes, *Journal of Econometrics* 66, 225–250.

[17] United Nations (2006), Lead and Zinc Statistics, International Lead and Zinc Study Group, Lisbon

[18] US Geological Survey (2008), Mineral Commodity Summaries 2008, US Department of the Interior, Washington D.C.

[19] US Geological Survey (2017), Mineral Commodity Summaries 2017, US Department of the Interior, Washington D.C.

[20] Vogel, D. (1997), *Trading up: consumer and environmental regulation in a global economy*, Harvard University Press, Cambridge, MA

[21] Williams, E., Kahhat, R., Allenby, B., Kavazanjian, E., Kim, J., and M. Xu (2006), Environmental, social, and economic implications of global reuse and recycling of personal computers, *Environmental Science and Technology* 42, 6446–6454.