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# China-to-FOB Price Transmission in the Rare Earth Elements Market and the End of Chinese Export Restrictions

Volker Seiler\*

## Abstract

This paper investigates the impact of the end of the export quota system (EQS) on China-to-export price transmission in the rare earth elements market, taking into account threshold effects and price transmission asymmetries. The results indicate that export prices became more responsive to changes of Chinese prices after the Chinese Ministry of Commerce (MOFCOM) abandoned the export quota policy. While price shocks wash out much quicker in the Post-EQS period, we do not find evidence for rockets and feathers-type of behaviour.

**JEL Classification:** C32, Q02, Q37, Q38

**Keywords:** Rare Earth Elements, Export Quotas, Asymmetric Price Transmission, Threshold Autoregression (TAR), Threshold Error Correction Model (TECM)

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## 1. Introduction

Rare earth elements (REEs) are key for the transition towards a low-carbon economy and clean energy technologies such as electric and hybrid vehicles, wind turbines and photovoltaic cells (Bauer et al., 2010; MIT Energy Initiative et al., 2010; APS and MRS, 2011; Alonso et al., 2012; Van Gosen et al., 2014; Schmalensee, 2015; Apergis and Apergis, 2017; Steinbuks et al., 2017; Deetman et al., 2018), consumer electronics ranging from smartphones to CD and DVD players, and military defence applications (Hedrick, 2004; Hurst, 2010; Bailey Grasso, 2013). The recent escalation of the US-Chinese trade conflict further underlines the economic and strategic importance of REEs due to fears of potential supply cuts and increasing export prices (Bloomberg News, 2019; Liu and Ruwitch, 2019; Schmid, 2019b). Such fears came true in the past when the Chinese Ministry of Commerce (MOFCOM) heavily intervened in the REEs market by setting export quotas, thus regulating supply. The price peaks observed in 2011 led to accusations of China strategically using the export quotas to manipulate prices (see e.g. Gavin, 2013), culminating in the EU, Japan and the U.S. jointly filing a complaint at the World Trade Organization (WTO) on March 13, 2012 (European Commission, 2012) which eventually led to the abolishment of the export quotas on January 7, 2015 (MOFCOM, 2015; see Charlier and Guillou, 2014, for a theoretical analysis of the export quota policy and the dispute resolution case, and Proelss et al., 2018, for a detailed empirical analysis of the WTO trial).

Given that the Chinese policy was geared towards controlling supply, it comes as little surprise that papers analyzing the rare earth elements market mainly focus on mitigation of supply risks (Schmid, 2019a) and rare earth supply chains (Golev et al., 2014; Keilhacker and Minner, 2017; Mancheri et al., 2019). Economic analyses of the Chinese REEs export policies are provided by Zhang et al. (2015), Müller et al. (2016) and Proelss et al. (2018): Müller et al. (2016) assess potential wealth transfer effects of the export quota announcements by examining share price reactions of Chinese REEs suppliers, U.S. users and rest of the world refiners. While the analysis of the individual export quota announcements does not lend support for the wealth transfer motive, the authors do find evidence of changes due to the WTO trial. This is in line with the results of Proelss et al. (2018) who show that even the announcement of the WTO trial triggered changes of market dynamics. While their analysis of REEs prices shows that the launch of the WTO dispute resolution case increased market efficiency, the majority of their analyses centers around the analysis of stock price synchronicity.

To the best of our knowledge, the only study of the impact of the Chinese REEs policy directly focusing on REEs prices as of now is Zhang et al. (2015) who find the export quotas to have significantly increased China's market power and thus price sensitivity. However, one aspect that has been overlooked so far is the relationship between domestic and export prices. The dual pricing structure with much lower domestic prices (inside China) compared to export (FOB, free on board) prices for the same elements creates incentives for companies to form Sino-foreign joint ventures and shift production to China in order to get access to REEs and benefit from cost advantages (Charlier and Guillou, 2014; Müller et al., 2016). Accordingly, MOFCOM might have used the export quota policy as a tool to strategically manipulate prices. In that case, we expect to observe a change in the domestic-to-export price transmission mechanism after the end of the export quota scheme. In particular, we should be able to observe rockets and feathers-type behaviour (Bacon, 1991), i.e. asymmetric price adjustment, with FOB prices adjusting much quicker to domestic price increases than to price decreases during the export quota scheme (EQS), implying a redistribution of welfare from user industries outside China (buyers) to Chinese REEs suppliers (sellers) (Meyer and von Cramon-Taubadel, 2004). Theoretically, the end of the EQS should have increased supply of REEs outside China, thereby reducing export prices. A complete reversal of the price transmission and potential welfare redistribution pattern after MOFCOM stopped its export quota policy arguably would be the strongest evidence of the EQS scheme having been used for strategic manipulation of export prices. Hence, our study connects and contributes to different strands of literature such as the effects of export quotas, price transmission and economic analysis of the rare earth elements market.

We find the empirical evidence to be mixed: While we have to reject the notion of asymmetric price transmission and rockets and-feathers due to the export quota announcements, we find shocks to be absorbed much faster in the Post-EQS period. Moreover, the size of deviations from the long-run equilibrium required to trigger price adjustments is much smaller compared to the EQS period indicating that export prices became more sensitive to changes of domestic prices after MOFCOM stopped the export quota announcements.

The remainder of this paper is structured as follows: Section 2 provides a short overview of the theoretical explanations for price transmission asymmetries. Section 3 explains the methodology used for the analysis of price transmission during the EQS and Post-EQS periods. Section 4 describes the dataset. In Section 5, we present the empirical results, while Section 6 concludes.

## 2. Theoretical Background

One of the main theoretical explanations for asymmetric price transmission are deviations from the ideal of competitive markets and can be traced back at least to early works on price rigidities and sticky prices. One of the pioneering analyses is Galbraith (1936) who puts forward the idea of monopoly power as an explanation of price rigidities. Arrow (1959) extends this strand of literature by considering inventory as a potential explanation and shows that that prices will be the more rigid the lower the storability of the considered good and the larger the inventory costs. Moreover, in case of a disequilibrium between supply and demand, the more concentrated side of the market will be the main driver of any price changes so that for most commodities price adjustments are triggered by monopolistic behaviour of suppliers. Besides, prices adjust slower (quicker) during times of excess capacity (full capacity utilization). Further reasoning along these lines is provided by Reagan (1982) who shows that price rigidities might be due to stockouts, as the price reactions to demand shocks are more pronounced in this case: If inventories are exhausted, prices have to increase in order to clear the market. In a similar vein, Blinder (1982) shows that price rigidities are to be expected if firms can adjust their inventory levels as a reaction to demand shocks. More precisely, in case of a positive (negative) demand shock, firms increase (decrease) prices and reduce (increase) investment in inventory, thereby reducing price flexibility and hindering adjustment, with the price reaction being stronger (smaller) for demand increases (decreases). Furthermore, firms that produce outputs that are easier to store are especially prone to price rigidities.

A closely connected stream of theoretical literature using Stackelberg competition (von Stackelberg, 1934), i.e. price leader-price follower models, attributes price rigidity to coordination failure (see for example Ball and Romer, 1991). However, the argument can be reversed: Using a model based on Bertrand competition (Bertrand, 1883), Mischel (1998) shows that rather than being the result of coordination failure, price rigidities might be due to coordination success. A similar argument is put forward by Damania and Yang (1998) who explicitly consider punishment as a way to ensure coordination success and collusive pricing: While firms are free to increase prices in case of high demand, they refrain from lowering prices in case of low demand for fear of punishment from their competition, giving rise to asymmetric price reaction. Recently, Ahrens et al. (2017) extended the idea of monopolistic competition by introducing prospect theory (Kahneman and Tversky, 1979) into the theoretical analysis, arguing

that consumers form expectations with regards to reference prices based on past observed prices. Accordingly, firms take the impact of possible price changes on future reference points into account when adjusting prices. Moreover, due to loss aversion (Tversky and Kahneman, 1991), consumers will suffer larger utility losses from price increases than utility gains from price decreases. The analysis of Ahrens et al.'s (2017) model yields that price rigidity depends on whether demand shocks are transitory or permanent: Prices are slower to adjust upwards than downwards (downwards than upwards) in case of temporary (permanent) demand shocks.

The second strand of literature links asymmetric price transmission to adjustment costs associated with price changes, so-called menu costs (Barro, 1972; Sheshinski and Weiss, 1977). While menu costs in a narrow sense refer to the costs of having to reprint price lists in order to inform customers about a price change, a broader definition considers price adjustment costs in general. Thus, the main theoretical argument why price convergence across markets is limited focuses on adjustment costs due to costs of transportation and trade barriers (i.e. menu costs in a wider sense), which serve as a threshold, so-called “commodity points” (Heckscher, 1916; Obstfeld and Taylor, 1997; Al-Abri and Goodwin, 2009): While there is no or only slow price convergence within the threshold interval (referred to “bands of inaction” by Obstfeld and Taylor, 1997), any price differential outside this band will move back towards equilibrium more rapidly, as only then do the benefits of price adjustment exceed the associated transaction costs.

The theoretical underpinning of price rigidity is corroborated by empirical evidence. Using survey data, Blinder (1994) finds that firms accounting for about 78% of U.S. GDP reprice their products at a quarterly frequency or less often. Moreover, firms adjust their prices quicker upwards in case of cost increases (a lag of 2.76 months on average) than downwards in case of cost decreases (a lag of 3.27 months on average), underlining the importance of asymmetric price adjustment. One of the main reasons why the sample firms do not change their prices more frequently are costs associated with price changes, menu costs in particular: About 64% of surveyed firms acknowledged that they have explicit costs of price adjustment, which mainly are due to the frequency rather than the size of price changes. These findings are corroborated by Peltzman (2000) who documents that price changes for industrial goods are about twice as large for increases of input prices versus decreases of input prices. Further evidence along these lines is provided by Schoenle (2017) who shows that there are systematic differences between firms' pricing behaviour in domestic vs. export markets with regards to size, timing and frequency of price adjustments, with changes of domestic prices being substantially smaller but at least twice

as often than changes of export prices. The results indicate a 21% probability of synchronized price changes in case of upward adjustments which compares to a probability of 14% for downward adjustments. Looking at menu costs as such, Schoenle (2017) finds that export market menu costs are three times the size of domestic menu costs.

Given this background, it is illustrative to take a look at the rare earth elements market, where China still has a quasi-monopoly in terms of REEs supply (Müller et al., 2016; Shen et al., 2020). Only companies that are granted the status of qualified export enterprises by MOFCOM are allowed to export REEs. Thus, buyers outside China have no other chance than sourcing from these companies (abstracting from illegal mining and smuggling). In an attempt to consolidate the industry and exercise greater control, MOFCOM gradually reduced the number of qualified export companies from 47 enterprises at the beginning of 2006 to 28 companies at the end of 2013 (Müller et al., 2016). Likewise, recent policies encourage industry consolidation and reorganization via mergers and acquisitions as well as establishment of six dominant state-owned REEs conglomerates. As of 2017, these six conglomerates hold 77 of 78 REEs mining licenses (Shen et al., 2020). While China abandoned the export quota policy and previous regulations targeted reorganization of the industry within China itself, the Chinese Ministry of Industry and Information Technology (MIIT) issued a draft version for further regulation of the rare earth elements industry on 15 January 2021 (MIIT, 2021) which will affect the entire supply chain, including trading and exports of REEs. This industry structure and the recent legislative efforts point to REEs exporters having some degree of monopolistic power with the above mentioned implications for price adjustment. More specifically, we expect export prices to react much quicker to increases than to decreases of domestic prices, i.e. rockets and feathers-type price adjustment (Bacon, 1991). If MOFCOM was able to use the export quotas as a tool to strategically influence the price transmission mechanism, we expect a pronounced change thereof in the Post-EQS period.

### **3. Methodology**

#### *3.1 Threshold Cointegration Analysis*

The concept of cointegration rests on the idea that integrated time series might have a linear combination that is stationary, i.e. the time series have a long-run equilibrium relationship and thus tend to move together in the long-run (Granger, 1986; Engle and Granger, 1987). The two

“classic” approaches to cointegration analysis<sup>1</sup> assume a symmetric relationship between the time series and linear adjustment. Moreover, they implicitly assume that that in case of deviations from the long-run equilibrium, adjustment takes place in every period (Balke and Fomby, 1997). However, in case of market power and transaction costs, these assumptions are invalidated and price rigidities are to be expected. Likewise, discrete policy interventions such as commodity price stabilization schemes (Balke and Fomby, 1997) will result in a discrete rather than a continuous price adjustment process. Taking the industry structure of the REEs market and the MOFCOM export quota announcements into consideration, the usage of linear cointegration analysis does not seem to be adequate. Instead, we resort to the idea of threshold cointegration for our analysis. Building on Tong (1983, 1990), Enders and Granger (1998) and Enders and Siklos (2001) suggest a two-regime threshold autoregressive (TAR) model:

$$\Delta\mu_t = \rho_1 I_t \mu_{t-1} + \rho_2 (1 - I_t) \mu_{t-1} + \sum_{i=1}^p \gamma_i \Delta\mu_{t-i} + \varepsilon_t, \quad (1)$$

$$I_t = \begin{cases} 1 & \text{if } \mu_{t-1} \geq \tau \\ 0 & \text{otherwise} \end{cases}, \quad (2)$$

where  $\mu_t$  denotes the residual from the long-run equilibrium cointegration relationship,  $\rho_1$  and  $\rho_2$  are coefficients of the adjustment towards equilibrium,  $I_t$  is the Heaviside indicator,  $\varepsilon_t$  is the error term and  $\tau$  the value of the threshold. We use Schwarz’ (1978) Bayesian information criterion (BIC) to determine the lag length  $p$  and Chan’s (1993) grid search method to determine the threshold value by minimizing the sum of squared errors from fitting the model over different values for  $\tau$ . Accordingly, the TAR model separates the autoregressive process of  $\mu_t$  into an *OUT* regime (i.e. deviations from the long-run equilibrium outside the threshold interval  $[-\tau, \tau]$ ) and an *IN* regime (i.e. deviations from the long-run equilibrium inside the threshold interval) depending on whether it exceeds the threshold  $\tau$  or not (Lee and Gómez, 2013).

### 3.2 Asymmetric Error Correction Model with Threshold Cointegration

While the TAR model provides information with regards to adjustment to the long-run equilibrium, the error correction formulation allows us to assess the short-run dynamics. Granger and Lee (1989) propose to allow for asymmetric adjustment towards equilibrium by decomposing the error correction terms and first differences of the variables into positive and negative components. Moreover, cointegration tests might be misspecified in case of threshold effects

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<sup>1</sup> I.e. the two-step approach proposed by Engle and Granger (1987) and the maximum likelihood (ML) approach to cointegration proposed by Johansen (1988, 1991, 1995).



(Balke and Fomby, 1997) so that further modification of the error correction terms is warranted. Thus, we follow Sun (2011) and estimate the following asymmetric error correction model with threshold cointegration:

$$\begin{aligned} \Delta EP_t = & \theta + \delta^+ ECT_{t-1}^+ + \delta^- ECT_{t-1}^- + \sum_{j=1}^J \alpha_j^+ \Delta EP_{t-j}^+ + \sum_{j=1}^J \alpha_j^- \Delta EP_{t-j}^- \\ & + \sum_{j=1}^J \beta_j^+ \Delta DP_{t-j}^+ + \sum_{j=1}^J \beta_j^- \Delta DP_{t-j}^- + \vartheta_t, \end{aligned} \quad (3)$$

where  $\Delta EP$  and  $\Delta DP$  denote the first differences of the export (FOB) and domestic (inside China) REEs prices,  $\theta$  represents the constant term,  $\delta$ ,  $\alpha$  and  $\beta$  are coefficients capturing the sensitivity with regards to the respective variables and  $\vartheta$  is the error term. To capture potential asymmetries, the first differences of the lagged price variables are separated into positive and negative components so that  $\Delta EP_{t-j}^+$  is equal to  $EP_{t-1} - EP_{t-2}$  if  $EP_{t-1} > EP_{t-2}$  and equal to 0 otherwise; likewise,  $\Delta EP_{t-j}^-$  is equal to  $EP_{t-1} - EP_{t-2}$  if  $EP_{t-1} < EP_{t-2}$  and equal to 0 otherwise. The same logic applies to the domestic prices. The error correction terms  $ECT$  are defined as  $ECT_{t-1}^+ = I_t \mu_{t-1}$  and  $ECT_{t-1}^- = (1 - I_t) \mu_{t-1}$  using the previous threshold cointegration regressions. Thus, the error correction terms consider both, potential asymmetric adjustment to positive and negative shocks and the impact of threshold effects via the Heaviside indicator. Accordingly, price adjustments occur only if the benefits exceed the associated transaction costs, i.e. deviations from the long-run equilibrium outside the threshold interval  $[-\tau, \tau]$  (Balke and Fomby, 1997; Meyer and von Cramon-Taubadel, 2004; Frey and Manera, 2007; Lee and Gómez, 2013).

#### 4. Data and Sample

For our analyses, we use monthly domestic (inside China) and export (FOB, free on board) prices (CNY/t) for the three most important REEs as to their overall usage (cerium: 42,200t, 32.94%; lanthanum: 38,655t, 30.16%; neodymium: 22,868t, 17.84%) thereby covering about 80% of actively used REEs (Goonan, 2011; Müller et al., 2016; Proelss et al., 2018; Proelss et al., 2020). Data for the period July 2008 to February 2020 is obtained from the Asian Metal database via Bloomberg. We split our sample into the export quota scheme (EQS) period (July 2008 to January 2015) and the Post-EQS period (February 2015 to February 2020) after the Chinese Ministry of Commerce (MOFCOM) officially declared on 7 January 2015 to abide by the WTO's ruling to abolish the export quotas as they are at odds with GATT (MOFCOM, 2015; see Proelss et al., 2018, for a detailed analysis of the WTO dispute resolution case).

Table 1 presents the descriptive statistics for the full period (EQS period) [Post-EQS period] in Section 1 (Section 2) [Section 3]. It sticks to the eye that FOB prices for the three elements are higher and more volatile than their domestic counterparts. This holds true for the full sample as well as for the two sub-periods (see Panel A in each Section). Moreover, FOB prices show much larger price increases and decreases as indicated by the much larger maximum and minimum returns in the full sample and during the EQS period (see Panel C).<sup>2</sup> After the end of the export quota scheme, we still find larger negative returns for FOB prices, neodymium being the exception. However, with the exception of lanthanum, we find domestic prices to exhibit larger positive price changes in the Post-EQS period. Moreover, prices have come down considerably in the Post-EQS period and the gap between export and domestic prices narrowed: While the difference of the mean prices (median prices) was CNY/t 113,703 for cerium, CNY/t 146,200 for lanthanum and CNY/t 215,031 for neodymium (CNY/t 16,526 for cerium, CNY/t 32,582 for lanthanum and CNY/t for 134,622 neodymium) during the EQS period, these numbers compare to CNY/t 1,426 for cerium, CNY/t 2,823 for lanthanum and CNY/t 6,806 for neodymium (CNY/t 1,181 for cerium, CNY/t 3,378 for lanthanum and CNY/t for 4,982 neodymium) during the Post-EQS period. Thus, the descriptive statistics provide a first hint that the end of the MOFCOM export quota announcements has triggered changes in the REEs market.

– Please insert Table 1 about here –

We continue our analysis by examining whether the individual time series contain a unit root. Given our interest in non-linear price transmission, we employ the Perron and Vogelsang (1992) unit root test which allows for the presence of a structural break in the time series as well as the extension allowing for two structural breaks suggested by Clemente et al. (1998).<sup>3</sup> These unit root tests allow to account for either a sudden change (additional outliers, AO) or a gradual shift (innovational outliers, IO) in the mean of the time series. We follow the recommendation of Vogelsang and Perron (1998) and use the additional outliers model as it is robust against misspecification: Even in case the data generating process follows the IO model, application of the AO model nevertheless yields reliable tests, as they have less size distortions.

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<sup>2</sup> Only for neodymium do we observe a larger maximum return for the domestic price in the full sample and the two subsamples.

<sup>3</sup> We thank one anonymous reviewer for drawing our attention to this strand of literature. The results of the modified Dickey-Fuller DF-GLS test (Dickey and Fuller, 1979; Elliott et al., 1996) and the KPSS test (Kwiatkowski et al., 1992) corroborate these results and are available from the authors on request.

Table 2 presents the results for REEs prices (log prices) in Panel A (Panel B). The results show that we are not able to reject the null hypothesis of a unit root for both, FOB and domestic prices and log prices during the EQS period, even when controlling for the possibility of one or two structural breaks. A similar picture emerges during the Post-EQS period, neodymium being the only exception.

– Please insert Table 2 about here –

## 5. Results

### 5.1 Non-Linear Cointegration Analysis

Given that domestic and export prices contain a unit root and thus are integrated, we proceed our assessment of the impact of the end of the MOFCOM export quota scheme by checking for asymmetric price transmission, i.e. non-linear cointegration. We use the threshold autoregressive (TAR) model setting the threshold equal to  $\tau = 0$  as well as its consistent counterpart when estimating  $\tau$  using Chan's (1993) grid search method that yields a super-consistent estimate of the threshold for the non-linear cointegration analysis. We use Schwarz' (1978) Bayesian information criterion (BIC) to select the number of lags in the regressions.

Table 3 presents the results for log prices of cerium (lanthanum) [neodymium] in Panel A (Panel B) [Panel C]. Irrespective of the model, we have to reject the null hypothesis of no cointegration ( $H_0: \rho_1 = \rho_2 = 0$ ) during both, the EQS period and the Post-EQS period. However, we are not able to reject the null hypothesis of symmetric price adjustment ( $H_0: \rho_1 = \rho_2$ ). The point estimates of the adjustment for positive shocks for cerium do not differ much between the TAR model and the consistent TAR model during the EQS period ( $\rho_1 = -0.085$  vs.  $\rho_1 = -0.088$ ) and are statistically significant at the 5% level. Thus, positive deviations from the long-run equilibrium due to increases in export prices or decreases in domestic prices are eliminated by 8.5% to 8.8% per month and persist for 11 to 12 months ( $1/0.088 = 11.36$ ,  $1/0.085 = 11.76$ ). For negative shocks, the coefficient of  $\rho_2$  ranges from  $-0.038$  (consistent TAR model) to  $-0.055$  (TAR model) during the EQS period so that negative deviations due to decreases in export prices or increases in domestic prices are eliminated by 3.8% to 5.5% per month which translates into 18 to 26 months until they are fully absorbed. Please note that the point estimates of  $\rho_2$  are not statistically significant so that this result needs to be considered with great caution. In the Post-EQS period, a similar picture emerges: We find statistically significant estimates of

$\rho_1$  ranging from  $-0.255$  (consistent TAR model) to  $-0.326$  (TAR model) while the estimates of  $\rho_2$  ranging from  $-0.125$  (consistent TAR model) to  $-0.130$  (TAR model) lack statistical significance. Thus, positive shocks wash out in 3 to 4 months, while negative shocks take about 8 months until they are fully absorbed after MOFCOM abandoned the usage of export quotas. As only prices outside the threshold interval  $[-\tau, \tau]$  will adjust towards the long-run equilibrium (Balke and Fomby, 1997), the consistent TAR model indicates that the magnitude of deviations necessary to trigger price adjustments is lower in the Post-EQS period ( $\tau_{EQS} = -0.2922$  vs.  $\tau_{Post-EQS} = -0.0234$ ) which supports our finding of much faster return to the long-run equilibrium. Thus, a smaller change of domestic cerium prices will lead to an adjustment of export prices. In line with this reasoning, the results for the consistent TAR model show that the percentage of observations inside the threshold interval dropped from 41.77% in the EQS period to 31.15% in the Post-EQS period which indicates more frequent price adjustments. It seems the decision to abolish the usage of export quotas triggered a change in the price transmission mechanism for cerium so that prices return much quicker to their long-run equilibrium.

Turning to the results for lanthanum in Panel B, we have to reject the null hypothesis of no cointegration ( $H_0: \rho_1 = \rho_2 = 0$ ) during both periods. Similar to our results for cerium, we are not able to reject the null of symmetric price adjustment. Taking a look at the estimates of  $\rho_1$  and  $\rho_2$  further underlines this finding: For the TAR and consistent TAR model, we find the adjustments for positive shocks to be statistically significant during both, the EQS and the Post-EQS period while the adjustment for negative shocks lacks statistical significance. Again, we find positive deviations from the long-run equilibrium to adjust much faster in the Post-EQS period: While it took about 10 months for positive shocks to wash out during the EQS period ( $\rho_1$  ranges from  $-0.098$  to  $-0.101$ ), the end of the export quotas reduced the persistence of positive deviations from the long-run equilibrium to 3 months ( $\rho_1$  ranges from  $-0.372$  to  $-0.377$ ). This faster adjustment is also indicated by a drop in the threshold from  $\tau = -0.2729$  during the EQS period to  $\tau = -0.0186$  during the Post-EQS period so that smaller changes of Chinese prices lead to changes of FOB prices, i.e. export prices seem to be more sensitive to changes of domestic prices. In line with the observation of a lower threshold triggering price adjustments we note a drop in the number of deviations from the long-run equilibrium within the threshold interval  $[-\tau, \tau]$  from 74.68% in the EQS period to 42.62% in the Post-EQS period which lends further support to the notion that the end of the MOFCOM export quota announcements triggered changes in the price transmission mechanism for lanthanum.

Panel C shows the results of the threshold cointegration tests for neodymium. The  $F$ -test statistics show that export and domestic prices are cointegrated. Similar to our results for cerium and lanthanum, the findings for  $H_0: \rho_1 = \rho_2$  are inconclusive: While the TAR model indicates asymmetric price adjustment in the Post-EQS period, the consistent TAR model indicates asymmetric price adjustment in the EQS period. Moreover, with the exception of  $\rho_2$  in the Post-EQS period (consistent TAR), all point estimates of the adjustment coefficients are statistically significant. The findings indicate that positive shocks persisted for 6 to 8 months in the EQS period ( $\rho_1$  ranges from  $-0.122$  to  $-0.177$ ) while negative shocks washed out after 2 to 4 months ( $\rho_2$  ranges from  $-0.279$  to  $-0.556$ ). After the abandonment of the export quota scheme, this pattern reversed, i.e. positive shocks adjust much quicker than negative deviations from the long-run equilibrium: Given that the point estimates for  $\rho_1$  range from  $-0.271$  to  $-0.709$ , positive shocks persist for 1 to 4 months. This compares to point estimates in the range from  $-0.199$  to  $-0.225$  for  $\rho_2$  so that negative shocks persist between 4 and 5 months. Similar to our findings for cerium and lanthanum, our results show a lower threshold in the Post-EQS period (reduction from  $-0.1098$  to  $-0.0136$ ) so that smaller changes of domestic prices trigger an adjustment of export prices. Likewise, the amount of deviations from the long-run equilibrium inside the threshold interval decreased from 62.03% to 36.07% indicating that adjustments happen more frequently.

– Please insert Table 3 about here –

### 5.2 Threshold Error Correction Model

Following the threshold cointegration analysis, we estimate the error correction terms in order to assess the dynamics of short-run deviations from equilibrium and report the results of the threshold error correction models (TECM) in Table 4. The estimates mirror our findings from the threshold cointegration analysis: We are not able to reject the null hypothesis of a symmetric adjustment path of the error correction terms ( $H_0: ECT_{t-1}^+ = ECT_{t-1}^-$ ) for any of the REEs in our sample, neither in the EQS period nor in the Post-EQS period, no matter which model specification (symmetric or asymmetric TECM, TAR or consistent TAR model) we use. Likewise, we generally find no evidence for distributed lag asymmetry effects for the asymmetric TECM specifications, neither for domestic prices ( $H_0: \Delta^+ DP_{t-1} = \Delta^- DP_{t-1}$ ) nor for export prices ( $H_0: \Delta^+ EP_{t-1} = \Delta^- EP_{t-1}$ ). This is further supported by the BIC favouring the symmetric

TECM over the asymmetric counterpart for the three REEs during both periods. Moreover, the only element for which we find strong evidence for Chinese prices Granger-causing FOB prices is Cerium.

Turning to the point estimates of the error correction terms, the results are mixed. For cerium, we find the coefficients to be insignificant for positive ( $ECT_{t-1}^+$ ) and negative ( $ECT_{t-1}^-$ ) deviations from equilibrium during the EQS period. While both coefficients are much larger (in absolute terms) during the Post-EQS period, only the estimate of  $ECT_{t-1}^+$  is statistically significant. Thus, the FOB price of cerium responds to positive deviations by about 34% per month so that it takes 3 months for the price to return to equilibrium, which is in line with the results from the threshold autoregressive models. For lanthanum, the estimates of  $ECT_{t-1}^+$  are statistically significant during both, the EQS and the Post-EQS period, while the estimates of  $ECT_{t-1}^-$  are insignificant. Again, the absolute magnitude of the error correction terms is larger after MOFCOM decided to abandon the use of export quotas so that the export price of lanthanum reacts by 38% to positive deviations indicating that it takes about 2.6 months until shocks are fully digested. For neodymium, we again find the absolute magnitude of  $ECT_{t-1}^+$  and  $ECT_{t-1}^-$  to be larger during the Post-EQS period. However, our findings for neodymium are opposite to those for cerium and lanthanum: While the error correction term for positive deviations from equilibrium is not statistically significant during both periods, the estimates for  $ECT_{t-1}^-$  are generally significant at the 5% level. The size of the coefficient indicates that negative deviations return to the equilibrium in about half a month after the end of the MOFCOM export quota announcements. In summary, the results from the threshold error correction models indicate that the end of the export quota scheme has changed price transmission in so far as export prices return much faster to their equilibrium after a shock.

– Please insert Table 4 about here –

### 5.3 Robustness Checks

As we do not have any information with regards to the correct specification of the price adjustment mechanism, we run a sensitivity analysis and specify the Heaviside indicator  $I_t$  in (2) to depend on the change in the previous period rather than the level so that

$$I_t = \begin{cases} 1 & \text{if } \Delta\mu_{t-1} \geq \tau \\ 0 & \text{otherwise} \end{cases}, \quad (4)$$

which gives rise to the momentum threshold autoregressive (MTAR) model that allows to capture steep variations in residuals, i.e.  $\mu_t$  having more momentum in one direction (Enders and Granger, 1998; Enders and Siklos, 2001). To be consistent with our previous analyses, we use the grid search procedure of Chan (1993) to estimate the threshold value  $\tau$ .

The results of this robustness check are presented in Table 5. Again, we find support for cointegration of export and domestic prices for all elements during both, the EQS and Post-EQS period. However, with regards to asymmetric price transmission, the results are mixed: While we are able to reject the null hypothesis of symmetric price adjustment for cerium during the Post-EQS period, the results for lanthanum indicate the opposite, i.e. asymmetric price transmission during the EQS period but symmetric adjustment after the end of the MOFCOM export quota scheme. Only for neodymium do we find support for asymmetric price adjustment during both periods.

Turning to the estimates of the adjustment coefficients  $\rho_1$  and  $\rho_2$  confirms our previous findings: Positive deviations from the long-run equilibrium revert much quicker after the end of the MOFCOM export quota scheme. As documented before, we again find the threshold to be larger in the EQS period than in the Post-EQS period so that smaller changes of domestic prices suffice to trigger a reaction of export prices. However, only for neodymium is the number of deviations from the long-run equilibrium inside the threshold interval  $[-\tau, \tau]$  smaller in the Post-EQS period (a reduction from 5.06% to 1.64%) so that price adjustments take place more frequently.

*– Please insert Table 5 about here –*

Likewise, we re-estimate the threshold error correction models (TECM) for the MTAR and consistent MTAR specifications. Allowing for momentum in the threshold autoregressions slightly changes our results: While we are not able to reject the null hypothesis of a symmetric adjustment path of the error correction terms for lanthanum and neodymium in both periods, we find strong evidence for asymmetric adjustment paths in the Post-EQS period for cerium. In line with our main results, we only find evidence of domestic prices Granger-causing export prices for cerium. Overall, the robustness checks validate our findings.

*– Please insert Table 6 about here –*

#### *5.4 Discussion*

Our findings support the view that the end of the MOFCOM export quota announcements in response to the WTO's ruling changed market dynamics as both, the long-run and the short-run dynamics indicate that prices adjust much quicker to equilibrium during the Post-EQS period. Moreover, we find adjustment towards the long-run equilibrium to be facilitated after the end of the MOFCOM export quota scheme, as a lower threshold allows more frequent adjustment. Following the reasoning of Balke and Fomby (1997), the end of EQS seems to have triggered a reduction in transaction costs. These results are in line with previous evidence documented by Müller et al. (2016) who show that stock prices of companies active in the REEs industry react differently after the beginning of the WTO trial. In a similar vein, our results corroborate the findings of Proelss et al. (2018) that the WTO trial changed market dynamics as evidenced by increases in stock price informativeness and market efficiency.

However, contrary to our expectations we do not find evidence for asymmetric price transmission with export prices quickly adjusting to increases of domestic prices but not decreases, i.e. rockets and feather-type of behaviour, which could be interpreted as an indication that MOFCOM strategically used the export quotas to extract rents from overseas industries that rely on REEs as inputs in the production process. The most likely explanations for this result are illegal mining and smuggling (Bradsher, 2010; Rathi, 2010; Baili, 2018; Shen et al., 2020) so that actual shipments by far exceed the official quotas announced by MOFCOM, as well as inventory stockpiles companies might have used in order to cope with export quota reductions (Brown and Eggert, 2018; Mancheri et al., 2019; Reuters, 2019). While we are not able to control for these potential confounders, the economically meaningful and statistically significant results using different specifications strengthen our confidence in our results.

## **6. Conclusion**

Rare earth elements are essential for the exit from fossil fuel and the transition towards clean energy sources such as wind and solar energy. One of the major constraints to accelerated expansion of solar photovoltaics are availability and high costs associated with these mission-critical elements (MIT Energy Initiative et al., 2010; Schmalensee, 2015; Apergis and Apergis, 2017; Steinbuks et al., 2017).



The WTO dispute resolution case against the Chinese practice of using export quotas to regulate supply in the rare earth elements market has been subject of several studies in the recent past (see Charlier and Guillou, 2014; Zhang et al., 2015; Müller et al., 2016; Proelss et al., 2018). We complement the literature on the economic analysis of rare earth elements markets by providing an assessment of domestic-to-export price transmission effects during the EQS and Post-EQS period. The results point to greater integration between Chinese and overseas markets after the end of the export quota scheme, as prices return much faster to equilibrium due to export prices becoming more sensitive to changes of domestic prices and price adjustments taking place more frequently. However, while China has a quasi-monopoly on REEs supply (Müller et al., 2016), we do not find evidence for MOFCOM having exploited its market power by using the export quotas to trigger rockets and feathers-type price adjustment.

Whereas our findings are of interest to academics, market participants and policymakers alike, they might be subject to demand and supply factors such as illegal mining and smuggling, companies building strategic stockpiles, recycling and urban mining, and the search for substitutes that might explain changes in price transmission. We leave these limitations as avenues for future research. Moreover, in order to foster our understanding of the connection between macroeconomic factors and the REEs market, future research might want to investigate the impact of macroeconomic variables such as the business cycle, exchange rates and interest rates on REEs prices and volatility. Previous research from other commodity markets (see e.g. Batten et al., 2010; O'Connor, et al., 2015; Schaleck and Chenavaz, 2015; Vigne et al., 2017) and the resources finance literature (Lucey et al., 2018) might serve as a starting point.

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**Table 1: Descriptive Statistics**

Section 1: Full Sample		N	Mean	SD	Skew	Kurt	Median	Min	Max
Panel A: Prices									
Cerium	FOB	140	96,287	190,446	3.0881	12.4494	23,238	9,939	974,752
	Domestic	140	31,506	39,361	2.5130	8.6080	14,654	9,050	187,500
Lanthanum	FOB	140	141,329	218,820	2.7441	9.8924	55,290	29,725	1,043,057
	Domestic	140	57,599	41,578	2.4000	8.4483	41,016	28,500	231,619
Neodymium	FOB	140	454,891	422,521	2.6477	9.9397	325,894	87,981	2,301,402
	Domestic	140	330,586	227,522	2.8865	13.3400	292,200	70,111	1,499,000
Panel B: Log Prices									
Cerium	FOB	140	10.4420	1.2412	1.2239	3.4285	10.0535	9.2042	13.7899
	Domestic	140	9.9302	0.8052	1.3229	3.7189	9.5925	9.1105	12.1415
Lanthanum	FOB	140	11.2380	0.9568	1.3158	3.7286	10.9204	10.2998	13.8577
	Domestic	140	10.8024	0.5062	1.4059	4.2239	10.6217	10.2577	12.3529
Neodymium	FOB	140	12.7614	0.6894	0.4624	3.8638	12.6943	11.3849	14.6490
	Domestic	140	12.5389	0.5836	-0.1979	4.3908	12.5852	11.1578	14.2203
Panel C: Log Returns									
Cerium	FOB	139	-0.8267	15.1567	4.1529	36.3907	-0.7485	-36.0187	125.1720
	Domestic	139	-0.2197	10.0022	4.1091	28.8901	-0.9244	-18.5098	73.6167
Lanthanum	FOB	139	-0.7357	11.2176	3.3221	25.3320	-0.4525	-27.9296	82.4487
	Domestic	139	-0.4588	8.3354	5.6541	48.3061	-0.7744	-17.6110	73.4852
Neodymium	FOB	139	0.2781	10.4174	0.7886	4.6916	-0.4494	-25.3535	32.5771
	Domestic	139	0.4319	10.6063	1.3187	8.1675	0.0000	-24.8339	53.9080
Section 2: EQS									
Panel A: Prices									
Cerium	FOB	79	160,469	234,636	2.1393	6.8541	41,003	19,520	974,752
	Domestic	79	46,767	47,080	1.6707	4.6802	24,477	11,167	187,500
Lanthanum	FOB	79	222,209	264,775	1.8656	5.3798	85,583	51,440	1,043,057
	Domestic	79	76,009	47,800	1.7045	5.0454	53,000	36,143	231,619
Neodymium	FOB	79	571,012	533,758	1.7022	5.2058	427,122	87,981	2,301,402
	Domestic	79	355,980	298,347	2.0331	7.3421	292,500	70,111	1,499,000
Panel B: Log Prices									
Cerium	FOB	79	11.1933	1.1869	0.8062	2.2702	10.6214	9.8792	13.7899
	Domestic	79	10.3723	0.8252	0.7455	2.3376	10.1055	9.3207	12.1415
Lanthanum	FOB	79	11.8081	0.9297	0.9030	2.4716	11.3572	10.8482	13.8577
	Domestic	79	11.0960	0.4992	1.0524	2.9129	10.8781	10.4952	12.3529
Neodymium	FOB	79	12.8750	0.8938	0.0056	2.3449	12.9648	11.3849	14.6490
	Domestic	79	12.4975	0.7655	-0.0046	2.6319	12.5862	11.1578	14.2203
Panel C: Log Returns									
Cerium	FOB	78	-0.7223	19.6026	3.4740	23.2800	-2.0823	-36.0187	125.1720
	Domestic	78	-0.2783	12.8549	3.4379	19.0651	-2.3323	-18.5098	73.6167
Lanthanum	FOB	78	-0.7775	14.6423	2.7154	15.7272	-0.8104	-27.9296	82.4487
	Domestic	78	-0.6815	11.0126	4.4615	28.9329	-1.6979	-17.6110	73.4852
Neodymium	FOB	78	0.7085	12.1271	0.7207	3.7433	-0.9239	-25.3535	32.5771
	Domestic	78	0.7159	12.4952	1.2688	6.8195	-0.0135	-24.8339	53.9080

*(continued)*

**Table 1: Descriptive Statistics – *continued***

Section 3: Post-EQS		N	Mean	SD	Skew	Kurt	Median	Min	Max
Panel A: Prices									
Cerium	FOB	61	13,167	2,553	1.4291	5.5522	12,969	9,939	21,928
	Domestic	61	11,741	1,964	0.7795	3.7414	11,788	9,050	17,607
Lanthanum	FOB	61	36,581	4,614	0.6698	3.6556	37,178	29,725	50,378
	Domestic	61	33,758	3,228	-0.1563	1.7736	33,800	28,500	39,500
Neodymium	FOB	61	304,505	49,670	1.1769	4.6244	296,882	230,361	478,294
	Domestic	61	297,699	47,566	1.4789	6.2445	291,900	229,500	480,000
Panel B: Log Prices									
Cerium	FOB	61	9.4690	0.1786	0.8030	3.9008	9.4703	9.2042	9.9955
	Domestic	61	9.3577	0.1622	0.3302	2.8001	9.3748	9.1105	9.7761
Lanthanum	FOB	61	10.4997	0.1234	0.3069	2.9235	10.5235	10.2998	10.8273
	Domestic	61	10.4224	0.0969	-0.2626	1.7996	10.4282	10.2577	10.5841
Neodymium	FOB	61	12.6144	0.1535	0.7257	3.3516	12.6011	12.3474	13.0780
	Domestic	61	12.5925	0.1483	0.8884	4.2289	12.5842	12.3437	13.0815
Panel C: Log Returns									
Cerium	FOB	61	-0.9603	5.9330	-1.7812	13.3565	-0.4472	-30.8095	15.4010
	Domestic	61	-0.1447	4.2455	1.9045	8.9738	-0.5248	-10.6723	16.1124
Lanthanum	FOB	61	-0.6822	3.7776	-1.6917	9.5097	-0.4525	-17.5495	8.7946
	Domestic	61	-0.1742	2.0041	0.8790	4.3815	0.0000	-4.5382	6.1864
Neodymium	FOB	61	-0.2722	7.7664	0.5597	5.8768	-0.2855	-18.2966	28.0269
	Domestic	61	0.0688	7.6242	0.7782	6.6729	0.0000	-20.0113	29.2636

This table presents the descriptive statistics for rare earth elements (REEs) prices (log prices) [log returns] in Panel A (Panel B) [Panel C] during the period July 2008 to February 2020. Log returns are calculated as  $R_t = (\ln P_t - \ln P_{t-1}) \times 100$ , where  $P_t$  denotes the price in period  $t$ . We report the statistics for the full sample (EQS period) [Post-EQS period] in Section 1 (Section 2) [Section 3]. EQS period: July 2008 to January 2015. Post-EQS period: February 2015 to February 2020. All prices in CNY/t. Domestic denotes REEs prices within China while FOB denotes export prices (free on board). Monthly data is obtained from Asian Metal via Bloomberg.

**Table 2: Additive Outlier (AO) Unit Root Tests**

Test	Period	Cerium		Lanthanum		Neodymium	
		FOB	Domestic	FOB	Domestic	FOB	Domestic
Panel A: Prices							
AO(1)	EQS	0.971 (7)	0.152 (10)	-0.040 (12)	-1.108 (5)	0.409 (12)	-0.051 (7)
AO(2)		-1.099 (12)	-0.092 (11)	-1.361 (11)	-2.004 (5)	-1.346 (12)	-0.313 (8)
AO(1)	Post-EQS	-1.320 (4)	-0.489 (4)	-2.257 (3)	-2.983 (8)	-6.361*** (2)	-1.074 (5)
AO(2)		-4.429 (10)	-1.757 (7)	-3.440 (0)	-3.183 (0)	-2.718 (5)	-4.929 (2)
Panel B: Log Prices							
AO(1)	EQS	-1.574 (1)	-1.143 (7)	-1.624 (1)	-2.516 (1)	-2.721 (1)	-3.136 (1)
AO(2)		-2.451 (3)	-2.116 (2)	-2.744 (6)	-2.463 (3)	-4.322 (1)	-3.869 (1)
AO(1)	Post-EQS	-1.599 (4)	-2.086 (11)	-2.400 (3)	-3.188 (8)	-5.824*** (2)	-1.627 (8)
AO(2)		-4.763 (10)	-2.050 (6)	-3.045 (0)	-3.509 (1)	-2.997 (5)	-6.456*** (1)

This table presents the test statistic of the additive outlier (AO) unit root tests for rare earth elements (REEs) prices (log prices) in Panel A (Panel B). AO(1): Perron and Vogelsang (1992) test allowing for one structural break. AO(2): Clemente et al. (1998) test allowing for two structural breaks. Number of lags selected via series of sequential *F*-tests. EQS period: July 2008 to January 2015. Post-EQS period: February 2015 to February 2020. Domestic denotes REEs prices within China while FOB denotes export prices (free on board). \*\*\*/\*\*/\* denotes statistical significance at the 1%/5%/10% level. Number of lags in parenthesis.

**Table 3: Threshold Cointegration Tests**

	TAR		Consistent TAR	
	EQS	Post-EQS	EQS	Post-EQS
Panel A: Cerium				
$\tau$	0	0	-0.2922 (41.77%)	-0.0234 (31.15%)
Lags	1	1	1	0
$\rho_1$	-0.085** (2.165)	-0.326*** (5.739)	-0.088** (2.290)	-0.255*** (5.543)
$\rho_2$	-0.055 (0.770)	-0.130 (1.108)	-0.038 (0.500)	-0.125 (1.012)
$F(H_0: \rho_1 = \rho_2 = 0)$	2.628* (0.079)	17.299** (0.000)	2.740* (0.071)	15.874*** (0.000)
$F(H_0: \rho_1 = \rho_2)$	0.132 (0.718)	2.219 (0.142)	0.341 (0.561)	0.983 (0.326)
Panel B: Lanthanum				
$\tau$	0	0	-0.2729 (74.68%)	-0.0186 (42.62%)
Lags	1	1	1	1
$\rho_1$	-0.101** (2.398)	-0.372*** (5.092)	-0.098** (2.434)	-0.377*** (5.224)
$\rho_2$	-0.098 (1.060)	-0.199* (1.737)	-0.130 (1.022)	-0.182 (1.590)
$F(H_0: \rho_1 = \rho_2 = 0)$	3.419** (0.038)	14.733*** (0.000)	3.451** (0.037)	15.067*** (0.000)
$F(H_0: \rho_1 = \rho_2)$	0.001 (0.978)	1.572 (0.215)	0.059 (0.808)	2.022 (0.161)
Panel C: Neodymium				
$\tau$	0	0	-0.1098 (62.03%)	-0.0136 (36.07%)
Lags	1	2	3	0
$\rho_1$	-0.122* (1.988)	-0.709*** (11.916)	-0.177*** (3.014)	-0.271*** (4.428)
$\rho_2$	-0.279** (2.621)	-0.225** (2.270)	-0.556*** (4.197)	-0.199 (1.229)
$F(H_0: \rho_1 = \rho_2 = 0)$	5.209*** (0.008)	73.831*** (0.000)	11.568*** (0.000)	10.560*** (0.000)
$F(H_0: \rho_1 = \rho_2)$	1.692 (0.197)	17.462*** (0.000)	7.810*** (0.007)	0.172 (0.680)

This table presents the estimates of the threshold autoregressive (TAR) models for cerium (lanthanum) [neodymium] in Panel A (Panel B) [Panel C]. Threshold  $\tau$  for the cointegration regression selected according to lowest sum of squared errors using Chan's (1993) grid search method in case of the consistent TAR model. Number of lags selected according to Schwarz' (1978) Bayesian information criterion (BIC). For  $\rho_1$  and  $\rho_2$ , we report the coefficients in the main rows and the  $t$ -statistics in parenthesis. For the hypothesis tests, we report the  $F$ -statistics in the main rows and the  $p$ -values in parenthesis. EQS period: July 2008 to January 2015. Post-EQS period: February 2015 to February 2020. \*\*\*/\*\*/\* denotes statistical significance at the 1%/5%/10% level.

**Table 4: Threshold Error Correction Models**

	TAR				Consistent TAR			
	Symmetric		Asymmetric		Symmetric		Asymmetric	
	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS
Panel A: Cerium								
<i>Const.</i>	-0.008 (0.222)	-0.010 (1.217)	0.048 (1.106)	-0.001 (0.154)	-0.006 (0.230)	-0.010 (1.424)	0.048 (1.324)	-0.002 (0.297)
$ECT_{t-1}^+$	0.010 (0.186)	-0.344*** (5.879)	0.018 (0.342)	-0.340*** (5.874)	0.009 (0.178)	-0.341*** (5.913)	0.020 (0.416)	-0.336*** (5.899)
$ECT_{t-1}^-$	-0.015 (0.125)	-0.337 (1.550)	-0.001 (0.012)	-0.211 (0.919)	-0.013 (0.123)	-0.362* (1.784)	-0.009 (0.092)	-0.244 (1.140)
$\Delta EP_{t-1}$	0.391*** (3.174)	0.088 (0.857)			0.391*** (3.182)	0.089 (0.870)		
$\Delta^+ EP_{t-1}$			0.256* (1.761)	-0.608* (1.729)			0.254* (1.750)	-0.595* (1.686)
$\Delta^- EP_{t-1}$			0.526* (1.861)	0.180 (1.628)			0.527* (1.863)	0.179 (1.616)
$\Delta DP_{t-1}$	0.304* (1.707)	0.601*** (3.700)			0.303* (1.705)	0.590*** (3.666)		
$\Delta^+ DP_{t-1}$			0.092 (0.454)	1.133*** (3.222)			0.091 (0.450)	1.109*** (3.166)
$\Delta^- DP_{t-1}$			1.091** (2.036)	0.674** (2.577)			1.093** (2.043)	0.672** (2.568)
$R^2$	0.272	0.706	0.320	0.732	0.272	0.706	0.321	0.732
$R_{adj}^2$	0.231	0.685	0.262	0.701	0.231	0.685	0.262	0.701
$F$	6.707*** (0.000)	32.460*** (0.000)	5.491*** (0.000)	23.670*** (0.000)	6.708*** (0.000)	32.470*** (0.000)	5.502*** (0.000)	23.610*** (0.000)
BIC	-30.82	-213.21	-27.45	-210.47	-30.83	-213.22	-27.50	-210.35
$F_1$	0.028 (0.867)	0.001 (0.975)	0.018 (0.894)	0.264 (0.609)	0.032 (0.859)	0.009 (0.924)	0.062 (0.804)	0.155 (0.695)
$F_2$	2.913* (0.092)	13.691*** (0.001)	2.360 (0.102)	9.459*** (0.000)	2.905* (0.093)	13.440*** (0.001)	2.368 (0.101)	9.235*** (0.000)
$F_3$			2.783 (0.100)	1.000 (0.322)			2.808* (0.098)	0.909 (0.345)
$F_4$			0.688 (0.410)	4.197** (0.046)			0.697 (0.407)	4.028* (0.050)

(continued)

**Table 4: Threshold Error Correction Models – *continued***

	TAR				Consistent TAR			
	Symmetric		Asymmetric		Symmetric		Asymmetric	
	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS
Panel B: Lanthanum								
<i>Const.</i>	-0.033 (1.161)	0.000 (0.034)	-0.001 (0.022)	0.005 (0.717)	-0.006 (0.348)	-0.000 (0.061)	0.023 (1.078)	0.006 (0.806)
$ECT_{t-1}^+$	0.091* (1.949)	-0.381*** (4.857)	0.099** (2.083)	-0.383*** (4.904)	0.060 (1.539)	-0.381*** (5.043)	0.074* (1.840)	-0.386*** (5.147)
$ECT_{t-1}^-$	-0.093 (0.677)	-0.133 (0.901)	-0.058 (0.414)	-0.070 (0.436)	0.047 (0.421)	-0.132 (0.958)	0.052 (0.459)	-0.051 (0.338)
$\Delta EP_{t-1}$	0.391*** (3.074)	0.353*** (3.373)			0.399*** (3.110)	0.359*** (3.473)		
$\Delta^+ EP_{t-1}$			0.255 (1.615)	0.516* (1.845)			0.265 (1.663)	0.526* (1.914)
$\Delta^- EP_{t-1}$			0.473* (1.758)	0.312** (2.532)			0.447 (1.614)	0.318** (2.608)
$\Delta DP_{t-1}$	0.034 (0.235)	0.341* (1.724)			0.027 (0.185)	0.317 (1.615)		
$\Delta^+ DP_{t-1}$			-0.075 (0.480)	-0.053 (0.165)			-0.092 (0.585)	-0.121 (0.376)
$\Delta^- DP_{t-1}$			0.590 (1.247)	0.800** (2.175)			0.667 (1.411)	0.821** (2.258)
$R^2$	0.308	0.560	0.340	0.581	0.295	0.563	0.331	0.587
$R_{adj}^2$	0.269	0.527	0.283	0.532	0.256	0.530	0.274	0.540
$F$	8.000*** (0.000)	17.160*** (0.000)	6.001*** (0.000)	12.000*** (0.000)	7.536*** (0.000)	17.370*** (0.000)	5.777*** (0.000)	12.340*** (0.000)
BIC	-79.61	-242.69	-74.56	-237.40	-78.22	-243.09	-73.58	-238.36
$F_1$	1.319 (0.255)	1.789 (0.187)	0.931 (0.338)	2.579 (0.114)	0.011 (0.916)	2.170 (0.147)	0.033 (0.857)	3.470* (0.068)
$F_2$	0.055 (0.815)	2.971* (0.090)	0.841 (0.436)	2.399 (0.101)	0.034 (0.853)	2.609 (0.112)	1.107 (0.336)	2.557* (0.087)
$F_3$			1.680 (0.199)	2.560 (0.116)			2.213 (0.141)	3.081* (0.085)
$F_4$			0.471 (0.495)	0.391 (0.534)			0.313 (0.578)	0.417 (0.521)

(continued)

**Table 4: Threshold Error Correction Models – *continued***

	TAR				Consistent TAR			
	Symmetric		Asymmetric		Symmetric		Asymmetric	
	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS
Panel C: Neodymium								
<i>Const.</i>	-0.015 (0.706)	-0.026 (1.594)	-0.002 (0.062)	-0.021 (1.054)	-0.003 (0.263)	-0.021 (1.606)	0.009 (0.522)	-0.016 (1.001)
$ECT_{t-1}^+$	0.179 (1.593)	-0.344 (1.366)	0.181 (1.547)	-0.356 (1.383)	0.131 (1.646)	-0.372 (1.579)	0.152* (1.794)	-0.380 (1.581)
$ECT_{t-1}^-$	-0.156 (0.661)	-1.922** (2.199)	-0.111 (0.461)	-1.832* (1.963)	-0.130 (0.673)	-1.813** (2.469)	-0.128 (0.667)	-1.756** (2.227)
$\Delta EP_{t-1}$	0.379** (2.286)	0.518 (1.460)			0.402** (2.435)	0.537 (1.518)		
$\Delta^+ EP_{t-1}$			0.397* (1.758)	0.317 (0.351)			0.416* (1.871)	0.401 (0.441)
$\Delta^- EP_{t-1}$			0.289 (1.005)	0.567 (1.420)			0.305 (1.064)	0.572 (1.441)
$\Delta DP_{t-1}$	0.202 (1.253)	-0.338 (0.912)			0.198 (1.232)	-0.346 (0.941)		
$\Delta^+ DP_{t-1}$			0.097 (0.494)	-0.210 (0.236)			0.068 (0.347)	-0.280 (0.315)
$\Delta^- DP_{t-1}$			0.463 (1.571)	-0.291 (0.667)			0.486* (1.708)	-0.289 (0.667)
$R^2$	0.443	0.251	0.454	0.255	0.446	0.259	0.460	0.262
$R_{adj}^2$	0.412	0.196	0.407	0.169	0.415	0.204	0.414	0.177
$F$	14.330*** (0.000)	4.529*** (0.003)	9.699*** (0.000)	2.969** (0.014)	14.460*** (0.000)	4.715*** (0.002)	9.935*** (0.000)	3.081** (0.012)
BIC	-127.28	-126.79	-120.08	-118.94	-127.58	-127.39	-120.93	-119.51
$F_1$	1.141 (0.289)	2.546 (0.116)	0.832 (0.365)	1.963 (0.167)	1.433 (0.235)	3.127* (0.083)	1.617 (0.208)	2.483 (0.121)
$F_2$	1.570 (0.214)	0.832 (0.366)	1.364 (0.262)	0.247 (0.782)	1.518 (0.222)	0.885 (0.351)	1.527 (0.224)	0.269 (0.765)
$F_3$			1.064 (0.306)	0.007 (0.934)			1.436 (0.235)	0.000 (0.992)
$F_4$			0.079 (0.779)	0.062 (0.804)			0.086 (0.771)	0.029 (0.865)

This table presents the estimates of the threshold error correction models for cerium (lanthanum) [neodymium] in Panel A (Panel B) [Panel C]. Threshold  $\tau$  in case of the consistent TAR model as to Table 3. Number of lags selected according to Schwarz' (1978) Bayesian information criterion (BIC). For the point estimates, we report the coefficients in the main rows and the  $t$ -statistics in parenthesis. For the hypothesis tests, we report the  $F$ -statistics in the main rows and the  $p$ -values in parenthesis. EQS period: July 2008 to January 2015. Post-EQS period: February 2015 to February 2020.  $ECT$ : Error correction term.  $EP$ : Export price.  $DP$ : Domestic price.  $H_0^{F_1}$ :  $ECT_{t-1}^+ = ECT_{t-1}^-$ .  $H_0^{F_2}$ :  $DP$  does not Granger-cause  $EP$ .  $H_0^{F_3}$ :  $\Delta^+ DP_{t-1} = \Delta^- DP_{t-1}$ .  $H_0^{F_4}$ :  $\Delta^+ EP_{t-1} = \Delta^- EP_{t-1}$ . \*\*\*/\*\*/\* denotes statistical significance at the 1%/5%/10% level.

**Table 5: Robustness Checks – Momentum Threshold Cointegration Tests**

	MTAR		Consistent MTAR	
	EQS	Post-EQS	EQS	Post-EQS
Panel A: Cerium				
$\tau$	0	0	0.0084 (1.27%)	0.0049 (8.20%)
Lags	1	0	1	0
$\rho_1$	-0.035 (0.764)	-0.621*** (12.632)	-0.032 (0.688)	-0.641*** (13.420)
$\rho_2$	-0.134** (2.548)	-0.038 (0.859)	-0.135** (2.609)	-0.038 (0.906)
$F(H_0: \rho_1 = \rho_2 = 0)$	3.599** (0.032)	80.154*** (0.000)	3.696** (0.030)	90.459*** (0.000)
$F(H_0: \rho_1 = \rho_2)$	1.948 (0.167)	76.833*** (0.000)	2.130 (0.149)	89.526*** (0.000)
Panel B: Lanthanum				
$\tau$	0	0	-0.0523 (3.80%)	0.0089 (21.31%)
Lags	1	0	1	0
$\rho_1$	0.020 (0.523)	-0.393** (2.427)	0.018 (0.485)	-0.575*** (2.951)
$\rho_2$	-0.400*** (6.407)	-0.310*** (4.458)	-0.468*** (7.009)	-0.293*** (4.410)
$F(H_0: \rho_1 = \rho_2 = 0)$	20.549*** (0.000)	12.883*** (0.000)	24.561*** (0.000)	14.079*** (0.000)
$F(H_0: \rho_1 = \rho_2)$	31.363*** (0.000)	0.222 (0.640)	38.710*** (0.000)	1.875 (0.176)
Panel C: Neodymium				
$\tau$	0	0	-0.0124 (5.06%)	-0.0014 (1.64%)
Lags	3	0	3	0
$\rho_1$	-0.138* (1.990)	-0.643*** (8.789)	-0.136** (2.022)	-0.646*** (8.949)
$\rho_2$	-0.363*** (4.174)	-0.066 (0.921)	-0.387*** (4.320)	-0.059 (0.835)
$F(H_0: \rho_1 = \rho_2 = 0)$	9.734*** (0.000)	39.048*** (0.000)	10.364*** (0.000)	40.394*** (0.000)
$F(H_0: \rho_1 = \rho_2)$	4.745** (0.033)	31.963*** (0.000)	5.798** (0.019)	33.735*** (0.000)

This table presents the estimates of the momentum threshold autoregressive (MTAR) models for cerium (lanthanum) [neodymium] in Panel A (Panel B) [Panel C]. Threshold  $\tau$  for the cointegration regression selected according to lowest sum of squared errors using Chan's (1993) grid search method in case of the consistent MTAR model. Number of lags selected according to Schwarz' (1978) Bayesian information criterion (BIC). For  $\rho_1$  and  $\rho_2$ , we report the coefficients in the main rows and the  $t$ -statistics in parenthesis. For the hypothesis tests, we report the  $F$ -statistics in the main rows and the  $p$ -values in parenthesis. EQS period: July 2008 to January 2015. Post-EQS period: February 2015 to February 2020. \*\*\*/\*\*/\* denotes statistical significance at the 1%/5%/10% level.



**Table 6: Robustness Checks – Momentum Threshold Error Correction Models**

	MTAR				Consistent MTAR			
	Symmetric		Asymmetric		Symmetric		Asymmetric	
	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS
Panel A: Cerium								
<i>Const.</i>	-0.003 (0.147)	-0.008** (2.013)	0.052 (1.665)	-0.004 (0.957)	-0.003 (0.153)	-0.007* (1.706)	0.052 (1.661)	-0.002 (0.463)
$ECT_{t-1}^+$	0.007 (0.142)	-0.535*** (8.372)	0.015 (0.298)	-0.570*** (9.855)	0.009 (0.186)	-0.551*** (8.579)	0.015 (0.293)	-0.590*** (10.359)
$ECT_{t-1}^-$	-0.001 (0.009)	-0.170*** (2.791)	0.011 (0.183)	-0.094 (1.669)	-0.004 (0.060)	-0.165*** (2.771)	0.011 (0.190)	-0.086 (1.594)
$\Delta EP_{t-1}$	0.391*** (3.156)	0.180* (1.980)			0.389*** (3.133)	0.190** (2.110)		
$\Delta^+ EP_{t-1}$			0.255* (1.697)	-0.906*** (3.417)			0.256* (1.699)	-0.934*** (3.634)
$\Delta^- EP_{t-1}$			0.531* (1.801)	0.378*** (4.082)			0.531* (1.808)	0.396*** (4.389)
$\Delta DP_{t-1}$	0.309 (1.655)	0.495*** (4.014)			0.312* (1.682)	0.480*** (3.930)		
$\Delta^+ DP_{t-1}$			0.095 (0.439)	1.368*** (5.773)			0.094 (0.437)	1.369*** (5.982)
$\Delta^- DP_{t-1}$			1.087* (1.991)	0.207 (0.949)			1.086* (1.979)	0.210 (1.004)
$R^2$	0.271	0.780	0.320	0.837	0.272	0.786	0.320	0.848
$R_{adj}^2$	0.231	0.763	0.262	0.819	0.231	0.770	0.262	0.830
$F$	6.701*** (0.000)	47.790*** (0.000)	5.488*** (0.000)	44.630*** (0.000)	6.708*** (0.000)	49.620*** (0.000)	5.487*** (0.000)	48.220*** (0.000)
BIC	-30.80	-230.19	-27.43	-239.94	-30.83	-231.92	-27.43	-243.79
$F_1$	0.011 (0.917)	18.010*** (0.000)	0.003 (0.956)	34.132*** (0.000)	0.032 (0.858)	20.160*** (0.000)	0.003 (0.958)	39.936*** (0.000)
$F_2$	2.740 (0.102)	16.113*** (0.000)	2.348 (0.103)	19.431*** (0.000)	2.830* (0.097)	15.448*** (0.000)	2.338 (0.104)	20.820*** (0.000)
$F_3$			2.515 (0.117)	10.562*** (0.002)			2.474 (0.120)	11.375*** (0.001)
$F_4$			0.623 (0.433)	18.437*** (0.000)			0.627 (0.431)	20.960*** (0.000)

(continued)

**Table 6: Robustness Checks – Momentum Threshold Error Correction Models – *continued***

	MTAR				Consistent MTAR			
	Symmetric		Asymmetric		Symmetric		Asymmetric	
	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS
Panel B: Lanthanum								
<i>Const.</i>	-0.008 (0.551)	-0.005 (1.270)	0.018 (0.829)	-0.003 (0.564)	-0.003 (0.239)	-0.004 (1.259)	0.023 (1.077)	-0.004 (0.707)
$ECT_{t-1}^+$	0.079** (1.998)	-0.389** (2.551)	0.085** (2.078)	-0.363** (2.231)	0.072* (1.860)	-0.525*** (2.862)	0.081** (2.027)	-0.503** (2.554)
$ECT_{t-1}^-$	-0.031 (0.426)	-0.299*** (4.512)	0.010 (0.123)	-0.300*** (4.412)	-0.031 (0.382)	-0.289*** (4.536)	0.010 (0.110)	-0.291*** (4.439)
$\Delta EP_{t-1}$	0.410*** (3.243)	0.382*** (3.661)			0.414*** (3.252)	0.390*** (3.772)		
$\Delta^+ EP_{t-1}$			0.279* (1.762)	0.616** (2.192)			0.278* (1.753)	0.636** (2.280)
$\Delta^- EP_{t-1}$			0.506* (1.820)	0.325** (2.583)			0.499* (1.790)	0.328** (2.633)
$\Delta DP_{t-1}$	0.117 (0.751)	0.312 (1.566)			0.118 (0.732)	0.300 (1.519)		
$\Delta^+ DP_{t-1}$			-0.004 (0.020)	-0.017 (0.052)			-0.010 (0.056)	0.004 (0.011)
$\Delta^- DP_{t-1}$			0.543 (1.110)	0.595 (1.627)			0.595 (1.245)	0.526 (1.435)
$R^2$	0.315	0.548	0.338	0.561	0.310	0.557	0.337	0.569
$R_{adj}^2$	0.277	0.514	0.282	0.510	0.271	0.525	0.280	0.519
$F$	8.277*** (0.000)	16.340*** (0.000)	5.968*** (0.000)	11.070*** (0.000)	8.076*** (0.000)	17.000*** (4.447)	5.925*** (0.000)	11.440*** (0.000)
BIC	-80.43	-241.08	-74.42	-234.70	-79.84	-242.38	-74.23	-235.77
$F_1$	2.100 (0.152)	0.290 (0.592)	0.797 (0.375)	0.134 (0.716)	1.536 (0.219)	1.493 (0.227)	0.626 (0.431)	1.093 (0.301)
$F_2$	0.564 (0.455)	2.453 (0.123)	0.646 (0.527)	1.366 (0.264)	0.536 (0.467)	2.308 (0.135)	0.793 (0.457)	1.080 (0.347)
$F_3$			0.948 (0.333)	1.276 (0.264)			1.234 (0.270)	0.937 (0.338)
$F_4$			0.504 (0.480)	0.777 (0.382)			0.475 (0.493)	0.880 (0.352)

(continued)

**Table 6: Robustness Checks – Momentum Threshold Error Correction Models – *continued***

	MTAR				Consistent MTAR			
	Symmetric		Asymmetric		Symmetric		Asymmetric	
	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS	EQS	Post-EQS
Panel C: Neodymium								
<i>Const.</i>	0.001 (0.083)	-0.003 (0.353)	0.012 (0.704)	0.002 (0.170)	0.002 (0.210)	-0.004 (0.385)	0.013 (0.802)	0.002 (0.136)
$ECT_{t-1}^+$	0.155* (1.703)	-0.772** (2.536)	0.158 (1.660)	-0.814** (2.629)	0.139 (1.589)	-0.753** (2.476)	0.145 (1.576)	-0.793** (2.562)
$ECT_{t-1}^-$	-0.014 (0.133)	-0.374 (1.259)	0.014 (0.125)	-0.306 (0.990)	-0.005 (0.047)	-0.391 (1.314)	0.022 (0.193)	-0.325 (1.052)
$\Delta EP_{t-1}$	0.362** (2.165)	0.507 (1.403)			0.373** (2.239)	0.502 (1.388)		
$\Delta^+ EP_{t-1}$			0.379 (1.660)	-0.266 (0.302)			0.390* (1.713)	-0.252 (0.285)
$\Delta^- EP_{t-1}$			0.282 (0.986)	0.703* (1.703)			0.287 (0.998)	0.693* (1.677)
$\Delta DP_{t-1}$	0.274* (1.748)	-0.245 (0.663)			0.268* (1.705)	-0.240 (0.650)		
$\Delta^+ DP_{t-1}$			0.165 (0.826)	0.403 (0.474)			0.155 (0.777)	0.390 (0.458)
$\Delta^- DP_{t-1}$			0.512* (1.804)	-0.335 (0.746)			0.517* (1.819)	-0.326 (0.725)
$R^2$	0.446	0.228	0.455	0.246	0.443	0.226	0.453	0.243
$R_{adj}^2$	0.415	0.171	0.408	0.159	0.412	0.169	0.406	0.156
$F$	14.460*** (0.000)	3.996*** (0.007)	9.745*** (0.000)	2.827** (0.019)	14.290*** (0.000)	3.948*** (0.007)	9.667*** (0.000)	2.784** (0.020)
BIC	-127.59	-125.01	-120.25	-118.22	-127.19	-124.85	-119.97	-118.00
$F_1$	1.435 (0.235)	0.873 (0.354)	0.986 (0.324)	1.304 (0.259)	1.056 (0.308)	0.723 (0.399)	0.727 (0.397)	1.103 (0.298)
$F_2$	3.054* (0.085)	0.440 (0.510)	2.069 (0.134)	0.368 (0.694)	2.907* (0.093)	0.423 (0.518)	2.046 (0.137)	0.346 (0.709)
$F_3$			0.942 (0.335)	0.558 (0.459)			1.030 (0.314)	0.523 (0.473)
$F_4$			0.063 (0.802)	0.945 (0.335)			0.072 (0.790)	0.894 (0.349)

This table presents the estimates of the threshold error correction models for cerium (lanthanum) [neodymium] in Panel A (Panel B) [Panel C]. Threshold  $\tau$  in case of the consistent MTAR model as to Table 5. Number of lags selected according to Schwarz' (1978) Bayesian information criterion (BIC). For the point estimates, we report the coefficients in the main rows and the  $t$ -statistics in parenthesis. For the hypothesis tests, we report the  $F$ -statistics in the main rows and the  $p$ -values in parenthesis. EQS period: July 2008 to January 2015. Post-EQS period: February 2015 to February 2020.  $ECT$ : Error correction term.  $EP$ : Export price.  $DP$ : Domestic price.  $H_0^{F_1}$ :  $ECT_{t-1}^+ = ECT_{t-1}^-$ .  $H_0^{F_2}$ :  $DP$  does not Granger-cause  $EP$ .  $H_0^{F_3}$ :  $\Delta^+ DP_{t-1} = \Delta^- DP_{t-1}$ .  $H_0^{F_4}$ :  $\Delta^+ EP_{t-1} = \Delta^- EP_{t-1}$ . \*\*\*/\*\*/\* denotes statistical significance at the 1%/5%/10% level.