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RESEARCH ARTICLE

Rare Earth Recycling: Forecast of Recoverable Nd from Shredder Scrap and Influence of Recycling Rates on Price Volatility

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Abstract This manuscript quantifies the recoverability of the rare earth (RE) element neodymium from shredder scrap during the next two decades and provides a forecast of recycling rates until 2034 based on these calculations. In combination with this forecast, an analysis of historical price and recycling trends for several critical (i.e., platinum group metals, zinc, tantalum, cobalt, antimony, and tungsten) and non-critical materials (i.e., tin, chromium, gold, and copper) results in general conclusions for the future price volatility of REs in dependence on expected recycling rates.

Keywords Rare earths recycling · Shredder scrap · Price volatility · Critical materials

Introduction

Rare earth (RE) elements are critically important for manufacturing modern materials in the United States and worldwide. Their applications span fuel-efficient vehicles, energy-efficient lighting phosphors, alloys with improved workability, MRI contrast agents, nuclear reactor shieldings, and lasers [1]. Even though REs are not particularly rare (their static depletion index is 870 years) [2], currently operational mining and processing sites are highly localized in one country (China) [2]. Therefore, the 2010 [3] implementation of export restrictions by China had a significant impact on the price development of REs with prices rising from \$80 to \$244 for 1 kg of neodymium oxide within a year [4]. In light of a significant projected growth in demand for REs due to their use in renewable energy technologies and IT/telecommunication devices, RE availability has become a pressing concern in the United States and beyond [2].

Several strategies have been discussed to avoid future price spikes through diversifying the supply of REs, substitution of RE-containing materials [5, 6] as well as reuse [5] and recycling [7] of end-of-life RE-containing products. However, for one particular material application, NdFeB magnets in motors and generators, none of these approaches are currently used. Developing a feasible recycling process for the REs neodymium (Nd) and dysprosium (Dy) is particularly urgent, since NdFeB magnets are not substitutable in motors without a loss in performance [8].

In this report, we provide a forecast for the amount of recoverable Nd from end-of-life motors from shredder facilities over the next 20 years. Based on historical data, we further investigate how recycling rates can influence the price development of critical materials [6, 9]. The results of these analyses are expected to inform decisions about the time frame in which recycling will be commercially feasible as well as advise consumers of RE materials about realistic expectations for future price developments.

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Methodology

Forecast of Recyclable Nd Content in Shredder Scrap Until 2034

The described analysis does not take into account the potential future changes in the processing of end-of-life cars; as such, disassembly before shredding will not be discussed in detail.

Using minimum and maximum values for the Nd content in shredder feed (light duty vehicle/LDVs, household appliances, other sources) as described by us previously [10], two different scenarios were considered in our forecast for the next 20 years: (1) Hybrid vehicle (HEVs) and electric vehicles (EVs) are not shredded with conventional LDVs and household appliances and (2) HEVs and EVs are shredded with conventional LDVs and household appliances. This distinction is important to arrive at accurate conclusions due to the much higher Nd content of HEVs and EVs when compared to conventional vehicles [11].

Several significant variables that affect the final Nd content of these vehicles (Nd content in conventional vehicles; Nd content in HEVs and EVs; market penetration of HEVs and EVs; and Nd content in household appliances) have been approximated as detailed below for the years 2019, 2024, 2029, and 2034 (see SI for detailed calculations).

Nd Content in Conventional LDVs

The calculated average weight of conventional LDVs produced between 2004 and 2013 is 1834 kg [12]. This average weight was used in calculations for the weight of LDVs and was assumed to remain constant between 2014 and 2034.

The weight of Nd in conventional LDVs over time has been considered using two scenarios (a) the Nd content remains constant at 303 g per LDV [10] after 2013 due to a continuous high price of Nd; or (b) the Nd content increases linearly until 2034, continuing the trend before 2014 [10]. These two approximations are illustrated in Fig. 1. The Nd content in conventional LDVs further depends on the age distribution of shredded LDVs, which have been approximated using previously documented age distributions of cars shredded in 1995 and 2007 [10].

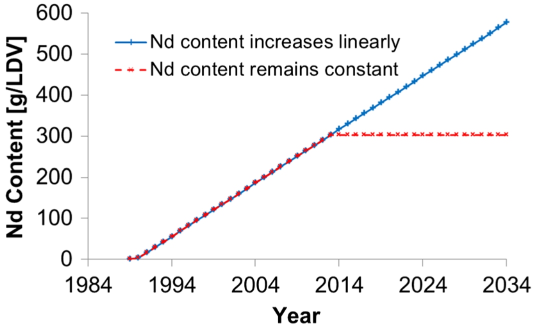

Fig. 1 Minimum (Nd content constant; *red*) and maximum (Nd content increases linearly; *blue*) assumptions used to calculate the total weight of Nd in conventional LDVs

Nd Content in HEVs and EVs

The weight of HEVs/EVs and the weight of Nd in HEVs/EVs need to be approximated in order to arrive at the Nd content of ferrous scrap from HEVs/EVs. The weight of HEVs was assumed to be equal to the average weight (1483 kg) of the four highest selling HEV models in the U.S. (Toyota Prius, Honda Civic, Ford Focus and Chevy Malibu) [13]; similarly, the weight of EVs was assumed to be equal to the average weight of 1570 kg. These average weights of HEVs and EVs as well as the amount of Nd (683 g in HEVs; 756 g in EVs)[2] after removal of the NiMH battery [14] are further postulated to remain constant until 2034 for two major reasons: First, the calculated average weights of the four most common models on the American market produced between 2009 and 2014 remained constant [15]; thus we assume a continuation of this trend. Second, even if lighter vehicles will be produced in the future, it is unlikely that such a weight reduction stems from reduction of functional, moving parts containing motors and Nd magnets. Thus, the overall Nd content of a vehicle per kg ferrous scrap might actually increase; therefore, our assumption of no change in vehicle weight and Nd content is indeed a conservative approximation.

Market Penetration of EVs and HEVs

Various forecasts of EV and HEV market penetration have been made and are illustrated in Fig. 2 [16, 17]. The lowest market share of 8 % HEVs/EVs in 2034 is predicted by the U.S. Energy Information Administration [16], which provides several reasons for its forecast. First, HEVs/EVs have higher purchase prices than conventional LDVs and are more fuel efficient during the time of ownership. Thus, more fuel-efficient conventional LDVs, which are currently developed, and an expected rising price for electricity will result in consumers deciding against the purchase of HEVs/EVs. Second, battery technology is not expected to improve substantially in the near future with respect to battery cost, safety, and performance; all these elements would favor purchases of conventional vehicles.

In contrast, the highest market penetration of 81 % HEVs/EVs in 2034 is predicted by Breker and coworkers [17]. Breker's forecast considers the various beneficial impacts of EVs on the economy (lower oil imports, improved trade deficit, more jobs in battery industry, healthcare cost savings due to less pollution). Since this approach only predicts market shares until 2030, market shares were linearly

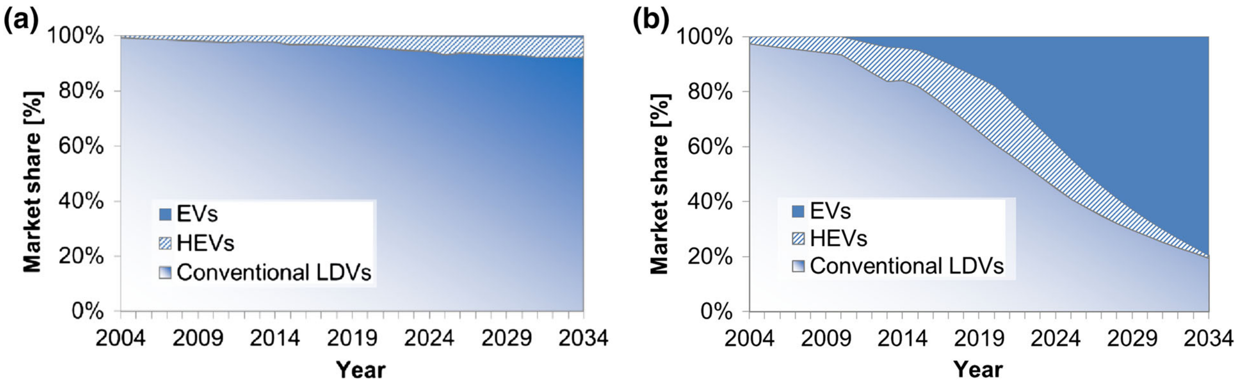

Fig. 2 **a** Minimum and **b** maximum market penetration of HEVs and EVs

extrapolated until 2034. Figure 2 graphically illustrates these minimum and maximum market penetrations of HEVs and EVs, which were used for our calculations.

Calculating the Nd Content in LDVs

As described in detail elsewhere [10], the Nd content in all LDVs (conventional LDVs, HEVs, and EVs) was calculated according to Eq. (1), using the variables $x_{v,i}$, the weight of Nd in ferrous scrap from shredding type v LDVs manufactured in year i, $w_{v,i}$, the percentage of type v LDVs manufactured in year i, $s_{v,i}$, the market penetration of type v LDVs manufactured in year i, and $\bar{x}$, the average Nd content in ferrous scrap.

$$\bar{x} = \frac{\sum w_{v,i} x_{v,i} s_{v,i}}{\sum w_i} \tag{1}$$

$w_{v,i}$ and $x_{v,i}$ were calculated as described previously [10]; $s_{v,i}$ is the market penetration described above. All values for $x_{v,i}$, $w_{v,i}$, $s_{v,i}$, and $\bar{x}$ have been tabulated for the years 2014, 2019, 2024, 2029, and 2034 in the SI.

Nd Content in Household Appliances

The Nd content in household appliances was assumed to increase or stay constant at the same rate with which the Nd content in conventional LDVs increases or stays constant as assumed suggested by a prior analysis (see SI for detailed calculations) [18]. Calculations were performed using 0.70 g Nd/kg ferrous as the maximum Nd content (as reported for U.K. appliances) [10, 19] and 0.61 g Nd/kg ferrous as the minimum Nd content (adjusted for major appliances) [10, 20].

Predicting the Influence of Recycling Rates on Price Volatility

Scope

Initially, we surveyed all metals for which secondary production data are available through the United States Geological Survey (USGS) [21]. These data are exclusively U.S. data, meaning that only U.S. prices and secondary production in the U.S. are analyzed. Our analysis focused on inflation-adjusted prices, as these prices are a better measure of real value than raw price data. The further below illustrated rate of secondary production for the analyzed metals is reported in percentages as the ratio of secondary production divided by the apparent consumption in the U.S. for the same year. Secondary production is defined differently for each metal [21], but in general is the creation of new metal from metal scrap. Apparent consumption is a calculation that takes into account primary and secondary production, imports, and exports. The apparent consumption totals are also calculated by the USGS. We treated secondary production rates as analogous to recycling rates, because secondary production rates compare the amount of new metal created from recycled scrap to the total amount used in the United States. Secondary production and apparent consumption data are both reported in metric tons per year and the axes scales are chosen to suit data and to align the zero points for both graphs; maxima of secondary production rate and inflation-adjusted price in the relevant time period are set to 100 %.

Our study aims to examine the effect of one economic system's response to recycling in relation to its total usage of a material. While prices may be radically different in other markets, we aim to investigate the response of US markets to US recycling rates. Although our study will only analyze the recycling rate in the US, we postulate that the response would be analogous to the way other free markets could react to a locally changing recycling rate.

Our analyses of secondary production and price development focus on the time after 1939. We postulate, based on historical events (such as the first World War and the Great Depression), that the period of price-control during WWII (1939–1943) [22] can be used as a starting point for later price development in a free market, which is the focus of our analyses. This restriction focuses our analyses on modern and currently relevant economic conditions.

Determining Criticality

Next, a criticality analysis was performed for each of the 16 metals with available data for secondary production, inflation-adjusted prices, and apparent consumption [21]. We did not consider data available for iron and steel as iron is not rare per se (iron is the fourth most abundant element in the earth's crust) [23]. Steel was not considered as it consists of a mixture of elements [24]; thus its price can depend on the criticality of each of its components.

The elements of the performed analyses were adopted from the U.S. Department of Energy Critical Materials Strategy (see SI) [6]. This analysis was necessary since the availability of data on secondary consumption is not a factor in previous studies. Based on this analysis, we concluded that Co, Zn, Sb, Ta, W, and platinum group metals (PGMs, including Pt, Pd, Ir, Os, Rh, and Ru) [21] could be considered to be critical materials, while Mg, Al, Cr, Ni, Cu, Ag, Sn, Au, Hg, and Pb were not deemed critical. In order to further elucidate the influence of recycling on price development, we tabulated historical events and the resulting change in price for all 16 metals (see SI). This was necessary as, to the best of our knowledge, other comparative and comprehensive analyses of a series of metals are not available in the prior literature, while more focused analyses (e.g., for Co and REs) are well documented [6, 25]

Price Volatility

In our analyses of price volatility as discussed in the next sections, low price volatility was defined as a change in price of less than 25 % of the overall maximum price during a decade. High price volatility was defined to exist when the price changes were larger than 25 % of the overall maximum, inflation-adjusted price. As an example, Cobalt (Co) prices change between 20 and 100 % of the maximum inflation-adjusted historical price during the 10 years between 1973 and 1983; during the two decades prior to 1973, the price of Co changes only between 14 and 28 % of the maximum inflation-adjusted historical price [26]. The first scenario (1973–1983) is thus a period with high price volatility (and low price stabilization), while the latter examples (1953–1963 and 1963–1973) represent decades of low price volatility.

In order to elucidate how recycling rates influence the price of critical materials, we first analyzed the available literature on this topic, which is surprisingly limited. Kirchain and coworkers found through simulations that price volatility is more pronounced when recycling rates are low (25 % and lower) [27]. High recycling rates, in contrast, contribute to price stabilization [28]. Despite this prior computational study, the conclusion has not been verified using historical price and recycling rates. Therefore, we decided to analyze historical data for critical metals with a special consideration for the influence of recycling rates on price stability.

Results and Discussion

Forecast of Recyclable Nd Content in Shredder Scrap Until 2034

Nd Content in Ferrous Scrap from LDVs

Based on the assumptions described in detail in 2.1, we are able to provide a forecast for the Nd content in conventional vehicles in the next 20 years (Recycling Scenario 1; see Fig. 3). Furthermore, with our calculations considering the market penetration of HEVs and EVs, we can also predict the average Nd content in all vehicles in case shredder operators decide to shred HEVs and EVs together with conventional LDVs (Recycling Scenario 2; Fig. 3). Based on the these calculations, we can predict that the average Nd content in ferrous scrap from conventional LDVs will rise to 0.24–0.30 g Nd per kg ferrous scrap in 2034; the Nd content in ferrous scrap when all types of vehicles are shredded together will lie between 0.26 and 0.48 g Nd per kg ferrous scrap by 2034. Since the market penetration of HEVs/EVs was low in 2014 (2.4 %) [16], the obtained values for the Nd content in 2014 (0.09–0.11 g Nd per kg ferrous scrap) are not different in both scenarios.

Another option for recycling (Recycling Scenario 3) will be the complete removal of the large traction motors and generator motors from HEVs/EVs before shredding in order to process these RE rich materials in a separate process [11]. In this case, HEVs/EVs contain the same amount of Nd as conventional LDVs [2] and the values given for Scenario 1 are valid for calculations of Scenario 3.

Nd Content in Ferrous Scrap from Household Appliances

Based on the assumptions described in 2.1, the Nd content in ferrous scrap derived from shredding household appliances can be predicted to contain 1.85–2.13 g Nd per kg ferrous scrap by 2034 (Fig. 4).

Nd Content in Ferrous Shredder Scrap

With the values obtained in the calculations described above, the overall Nd content of ferrous shredder scrap can be calculated. Ferrous scrap is generally produced by shredding 40–80 % LDVs, 15–50 % household appliances,

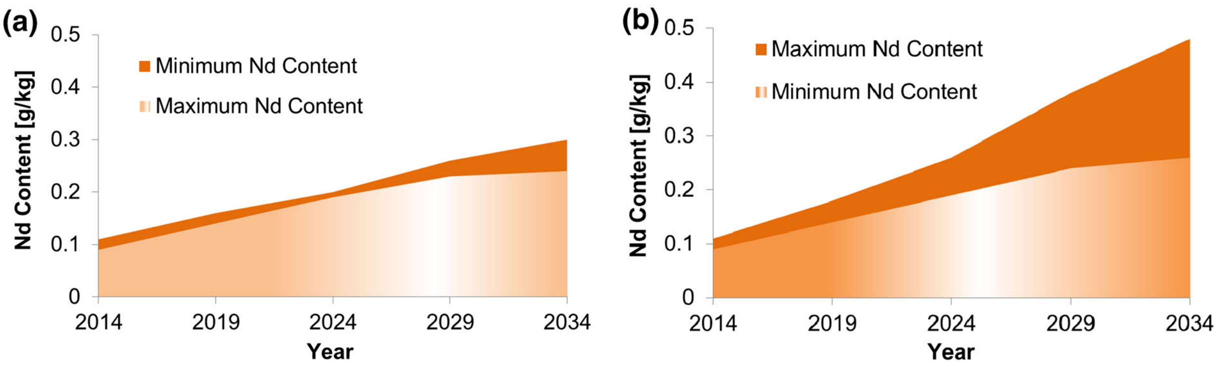

Fig. 3 Nd content in **a** conventional LDVs compared to **b** all LDVs

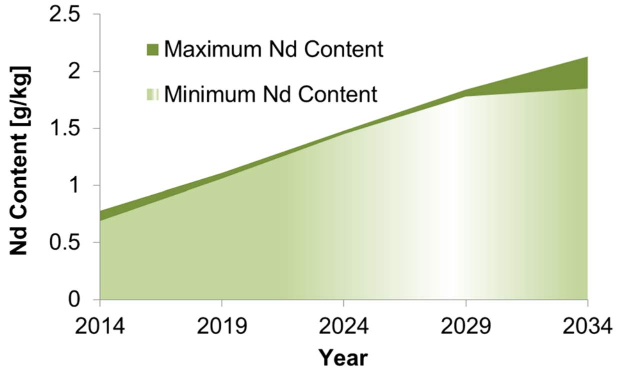

Fig. 4 Forecast of Nd content in household appliances

and 10–15 % other sources (such as dismantled bridges or railroad cars) that do not contain Nd [10]; no change of these currently used ratios is expected for the next 20 years. Due to these ranges of materials in shredder feed that have been established previously in the literature and because of the high Nd content of household appliances and LDVs, the maximum Nd content in ferrous scrap can be expected when 10 % of other sources, 50 % household appliances, and 40 % LDVs are used as shredder feed. In analogy, the minimum Nd content can be expected when using 15 % other sources, 15 % household appliances, and 70 % LDVs [10].

Recycling Scenario 1 (no HEVs/EVs are shredded with conventional LDVs) and Recycling Scenario 2 (HEVs/EVs are shredded with conventional LDVs) are thus forecasted until 2034 (Fig. 5a, b). Interestingly, the numerical outcomes for Nd content in ferrous scrap in 2034 do not differ substantially (0.33–0.89 g Nd/kg ferrous and 0.34–0.97 g Nd/kg ferrous). This suggests that the effect of shredder feed composition (as detailed above) on the Nd content is more substantial than the effect of the different Recycling Scenarios 1 and 2. As such, the increase in the maximum Nd content over time mainly stems from the assumed increase of Nd content in household appliances.

Figure 5c provides an overview of the predicted overall minimum and maximum Nd contents in shredder feed of all potential scenarios; furthermore, the same figure also provides average values for each year, as we find it likely that a combination of the different scenarios with regard to the different factors determining these values (co-processing of HEVs/EVs and conventional LDVs; shredder feed composition; market penetration of HEVs/EVs) will be realized. The increasing distance of the maximum and minimum values from the average values reflects the likely time-dependent growth of uncertainty for developments farther in the future.

Maximum Recycling Rate for Nd in 2034

The global demand for Nd in the next decade has been estimated previously by different groups [2, 29]. With the assumption that the amount of ferrous scrap processed in the US will stay constant during the next decades [21], we can calculate that a minimum of 17,672 t of Nd per year will be recoverable in 2034 from ferrous scrap at an assumed recovery rate of 70 % [30].[1] This amount of Nd is equivalent to 14 % of the global demand for Nd in 2034 [2]. In analogy to these calculations, we predict a maximum secondary production rate of 42 % for the herein outlined Recycling Scenario 2 (see SI for details). To determine if and how these recycling rates might contribute to price stabilization, we will focus on determining the relationship between price developments and recycling rates in the next section using historical data for critical and non-critical materials.

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[1] The recovery rate is primarily dependent on the process that will be used and has been approximated as 70 %. This rate has been chosen based on the recent invention of a process [30] which allows for 80 % recovery of Nd from scrap derived from shredding rare earth motors. Since this scrap derived from motors can be expected to have a higher RE content than ferrous scrap from shredding cars, the recovery rate was adjusted to a lower percentage in order to reflect the likely more challenging recovery.

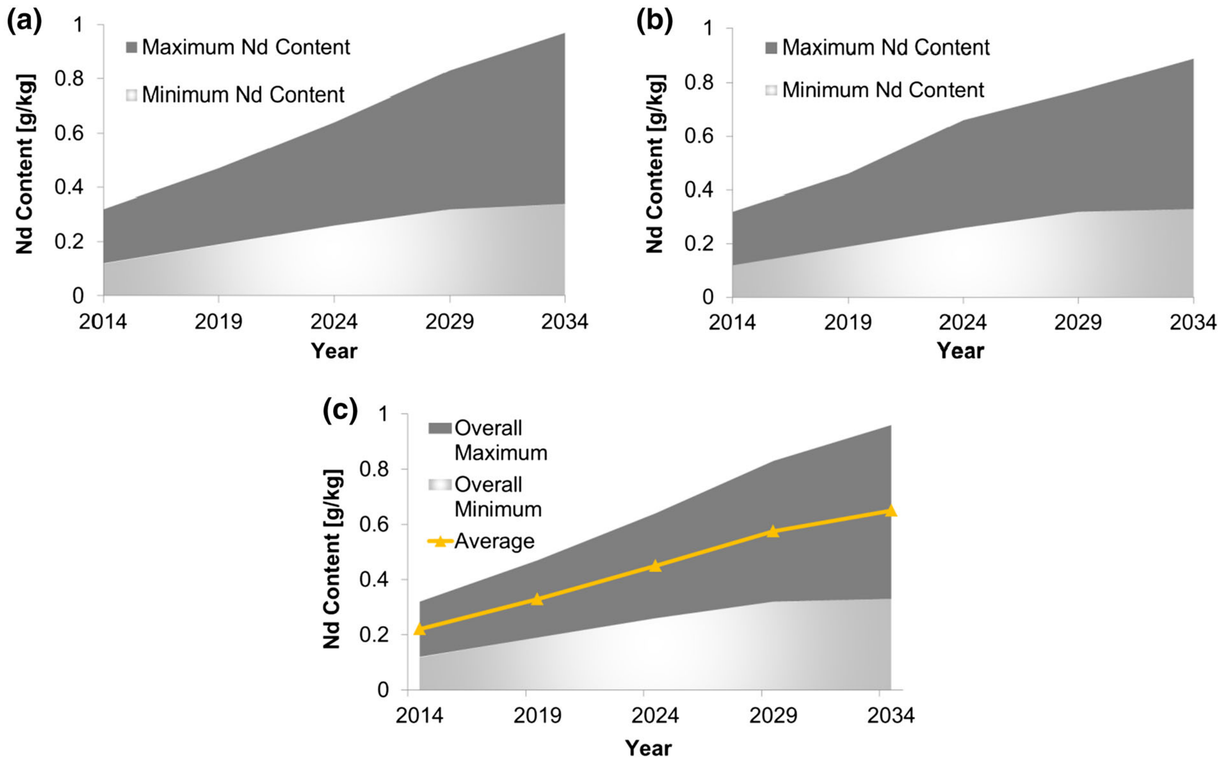

Fig. 5 Nd content in ferrous scrap. **a** Recycling Scenario 1: no HEVs/EVs are shredded with conventional LDVs. **b** Recycling Scenario 2: HEVs/EVs are shredded with conventional LDVs. **c** Overall minimum/maximum Nd content for all scenarios and progression of intermediate values. The intermediate values have been obtained by calculating the average between the overall minimum and overall maximum values for Nd content

Influence of Recycling Rates on Price Stabilization of Critical Materials

As detailed above ("Predicting the influence of recycling rates on price volatility" section), historical secondary production rates as defined by the ratio of secondary production and apparent consumption [21] are only available for six critical materials: Co, Zn, Sb, Ta, W, and PGMs. These six materials can be further differentiated with regard to their recycling rates [27]: (i) critical materials with only low recycling rates (<25 %), which include PGMs, Zn, Ta, and Co and (ii) critical materials with low (<25 %) and high (>25 %) recycling rates (W, Sb).

Price Development of Critical Materials

Figure 6 illustrates the correlation of inflation-adjusted price development versus the secondary production rates for critical materials. All values are shown between 1939 and the latest year for which both inflation-adjusted price data and secondary production totals are available from the USGS [21]. PGMs (6a), Zn (6b), Ta (6c), and Co (6d) exhibit a secondary production rate of consistently lower than 25 % after 1939; for Sb (6e) and W (6f), secondary production rates higher than 25 % are observed for some time frames.

Interestingly, the maximum overall price of a material does not deviate substantially from the first price spike, a phenomenon that has been associated in the literature with a material "becoming critical" [6, 31]. These initial price spikes can be seen in 1974 for PGMs, in 1951 for Zn, in 1979 for Ta, in 1979 for Co, in 1970 for Sb, and in 1956 for W. Another remarkable feature of the graphs in Fig. 6a–d is the price volatility, ranging between 11 and 100 % of the inflation-adjusted price during the illustrated time periods. The price volatility seen in Fig. 6e, f is analogous during times of low secondary production (1993–2012 in 6e for Sb; 1956–1990 in 6f for W) with prices between 10 and 78 %. However, during times of high secondary production rates (1943–1967 in 6e for Sb; 1994–2005 in 6f for W), less price volatility can be seen as characterized by prices ranging mostly under 50 % of the highest inflation-adjusted price (25–43 % of the inflation-adjusted maximum price for Sb between 1943 and 1967; 19–40 % for W between 1994 and 2005).

Based on these data, we suggest in agreement with prior computational investigations [27] that recycling can contribute to the price stabilization of critical materials, in

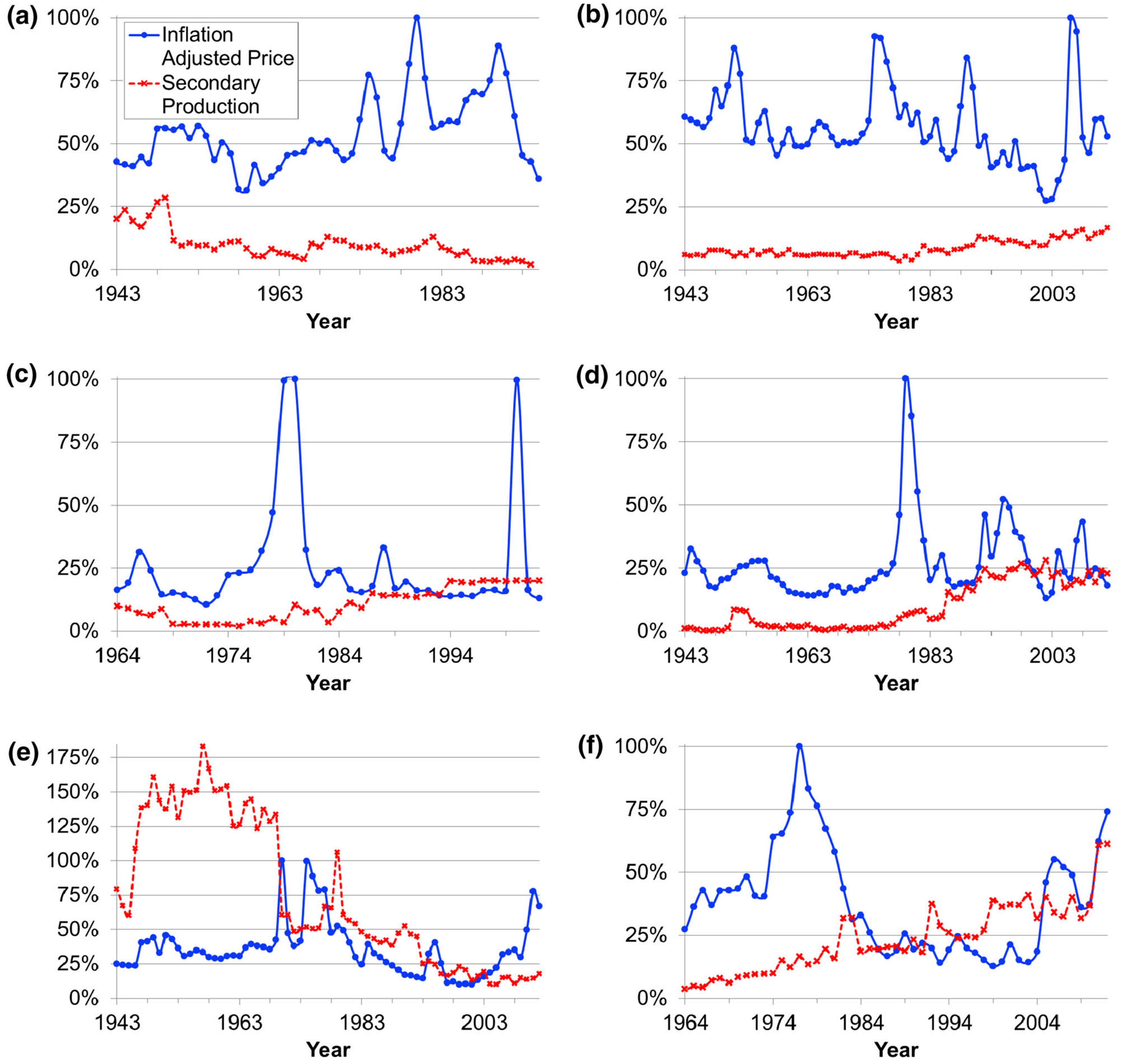

Fig. 6 Inflation-adjusted price versus secondary production rate for critical materials after 1939. **a** PGMs; **b** Zn; **c** Ta; **d** Co; **e** Sb; **f** W

particular, when recycling rates are high. However, prices are still expected to respond to geopolitical stimuli. This effect can not only be observed in the case of W (Fig. 6f) with relatively high secondary production rates (37–61 %) between 1992 and 2006, but also clear rises in the price development, which can be rationalized by the unprecedented growth of the Chinese economy [26].

Price Development of Non-critical Materials

Next, we performed an analogous analysis of the four materials Sn, Cr, Au, and Cu (Fig. 7a–d) in order to investigate if the above described price developments are similar for non-critical materials. Interestingly, no clear commonalities can be observed for the non-critical datasets. Sn pricing (Fig. 7a) behaves in analogy to the critical materials price development discussed above with a consistently low rate of secondary production between 1949 and 2012, resulting in large price differences (12–100 %) during the same period. However, a low secondary production rate below 25 % (1952–2012) for Cu (Fig. 7d) only results in mild price volatilities between 16 and 69 %. The secondary production rates for Cr (Fig. 7b) and Au (Fig. 7c) seem to correlate with the price developments in many events (e.g., 1993–2003 and 2006–2012 for Cr; 1964–1990 and 2006–2012 for Au), while in other periods (e.g., 1962–1993 for Cr; 1990–2006 for Au) price volatility and secondary rate do not show any recognizable

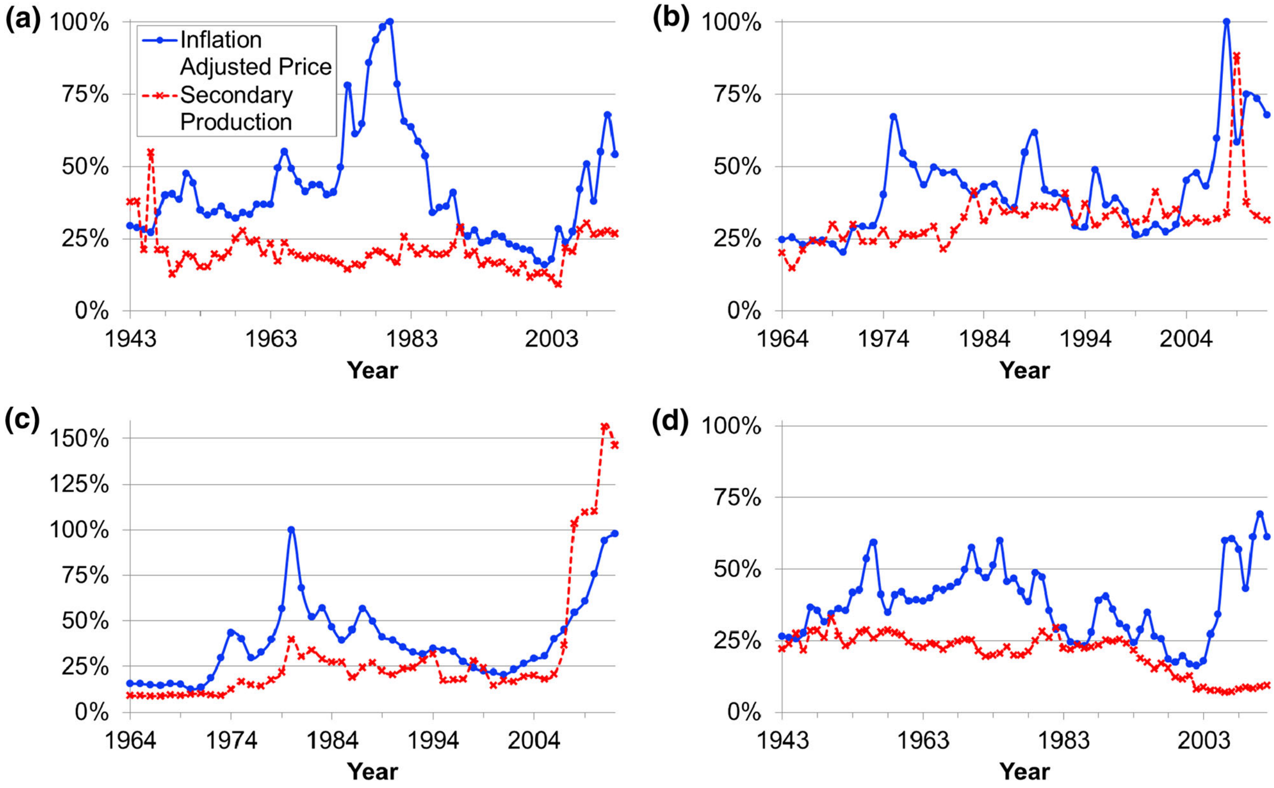

Fig. 7 Inflation-adjusted price versus secondary production rate for non-critical materials after 1939. **a** Sn; **b** Cr; **c** Au; **d** Cu

correlation. Overall, we conclude from this analysis that price responses for non-critical materials are fundamentally more diverse than seen in the last section for critical materials.

Expected Influence of Recycling on RE Price Development

Based on the above analyses, several conclusions for the expected price developments of REs can be made. (i) An extensive price spike as seen for REs in 2011 has been described as the characteristic of materials becoming critical [6, 31]. Based on our analysis of historical data for other critical materials, the inflation-adjusted price for REs in the future is not expected to substantially exceed this mark. (ii) A maximum recycling rate of 42 % of Nd is projected to be achievable in 2034 by recovering and recycling ferrous shredder scrap in the US. However, this rate is too low to have a large stabilizing effect on price volatility [27]. Based on our analysis, a much larger quantity of recycling not stemming from LDV motors or household appliances is required. Thus, end-of-life HD drives or wind generators will have to be recycled to make a sufficiently large impact on price stabilization. (iii) A relaxation of RE prices to pre-2010 levels of inflation-adjusted prices is expected to be possible, based on the historical price development of other critical materials after the criticality price spike (see Fig. 6).

While we observe a correlation between higher recycling rates and increased price stability, other factors clearly also influence price volatility, some of them political (see SI) and others revolving around market maturity. Higher recycling rates are indicative of a more mature market for the material, which in turn creates a mature market for the sale of recycled material. While other factors affect both secondary production and price stability, it is clear that high rates of recycling provide a stabilizing effect on metal prices.

Summary and Conclusions

In conclusion, we have forecasted the Nd content in ferrous shredder scrap during the next 20 years. Based on the obtained value of 0.33–0.97 g Nd/kg ferrous scrap in 2034 and the previously projected future demand, a maximum recycling rate of 42 % of the projected total demand for Nd in 2034 can be expected. However, recoverability of Nd will depend on the treatment and future production methods of ferrous scrap. As such, it is possible that suitable feedstocks for Nd recovery will be located later (e.g., one potential feedstock is slag from electric arc furnaces recycling ferrous scrap [32, 33]) or earlier in the lifecycle (e.g., by disassembly of HEV/EV motors before shredding). Our analysis of the influence of secondary production rates on historical price developments of other critical materials show, however, that this recycling rate might be too low to affect a significant reduction of price volatility. A recycling rate of >50 % over an extended period of time seems to be necessary to achieve that goal. Thus, the recovery of Nd from sources other than LDVs and household appliances will be needed to achieve price stabilization.

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