Noname manuscript No.
(will be inserted by the editor)

Materials abundance, price, and availability data from the years 1998 to 2015

Brennan Theler · Steven K. Kauwe · Taylor D. Sparks

Received: date / Accepted: date

Abstract Materials researchers are paying ever more attention to sustainability, criticality, availability, and other industrial ecology metrics and concepts as they develop new materials. Previous reports for these metrics have typically been either for a few specific compositions or for a single year. In this work, we present a new curated dataset which reports the global elemental production on a per country basis from the years 1998 to 2015 alongside elemental prices over this same time period. The data is taken from United States Geological Survey Minerals Yearbook entries. In addition to the raw data, analysis of the Herfindahl-Hirschman Index has been carried out and is reported alongside market share of each element for each year in the range provided. Lastly, we present a few possible scenarios for data utility such as exploring trends over the time period, correlating volatility with availability, or examining abrupt changes in the Herfindahl-Hirschman Index and how these may or may not relate to geopolitical events such as wars in mineral producing countries.

Keywords sustainability · availability · criticality · Herfindahl-Hirschman Index

1 Introduction

In the late 20th century the concept of Industrial Ecology was formalized into a discipline wherein industrial processes were treated like an ecosystem. The inputs and outputs such as raw materials, products, recycled goods, pollution, waste, and heat are quantified and the impacts of these on related systems are analyzed. This field has expanded the way that scientists, engineers, and

University of Utah
Department of Materials Science & Engineering
Tel.: +1-801-581-8632
E-mail: sparks@eng.utah.edu

researchers are able to quantitatively describe concepts that they were aware of qualitatively.[1]

In recent years, corporations and even governments have used industrial ecology metrics to assess the impact that material flows can have on production. For example, in 2010 and 2011 the Department of Energy developed its first-ever Critical Materials Strategy based on three strategic pillars: 1) diversifying global supply chains to mitigate supply risk; 2) developing material and technology substitutes; and 3) promoting recycling, reuse and more efficient use to significantly lower global demand for critical materials.[2] In that work the various technologies such as wind turbines, electric vehicles, photovoltaic films, lighting and others were analyzed and the impact of materials criticality was assessed. In some instances it was shown that materials critical to a given technology faced a critical supply risk due to availability or production limitations.

An example of how materials criticality can impact a technology can be seen in an analysis of rare earth metals used in permanent magnet generator systems for wind turbines and other applications. Figure 1 shows the cost of rare earth metals neodymium and dysprosium vs gold all normalized by their prices as of January 2008. A sudden spike in the price of rare earths occurred in the first quarter of 2011 after China implemented export quotas and taxes on rare earths. The severity in the price spike was due to the fact that China produced 97% of the world's rare earths at the time. It wasn't until a trade dispute was filed with the World Trade Organization in 2012 and finally settled in 2015 that prices began to normalize once again[3]. This is just one instance, but Silberglitt and coworkers have suggested that China's role as a major resource producer will continue to have wide implications as China's role, policies, and customers are further refined [4].

There are several important takeaways from the rare earths trade dispute example. First, price alone is a poor measure of criticality. A commodity such as gold or other coin metals might trade at a very high value but be relatively immutable and therefore provide the stability needed for industrial reliance. Second, economic metrics that assess the diversity, or lack thereof, in monopolistic production or known reserves are useful for identifying commodities which might be subject to volatility in price or availability. Finally, data from any single year may be insufficient to predict materials criticality. It is likely that some geopolitical events, such as a trade dispute, may be short-lived in their impact on material flows compared to other events, such as civil wars, which could have decades-long impact or greater.

One economic metric which can help provide a quantifiable measure of monopoly when it comes to resource reserves or production is the so-called Herfindahl-Hirschman Index (HHI, see Equation 1) [6, 7]. This metric considers the market fraction of production or known reserves for a given entity, such as a country or a corporation, and then sums the square of all the market fraction values. Therefore, an HHI value would approach 0 for an infinitely disperse (unconcentrated) market and 1 for a complete monopoly (values range between 0 and 10,000 if percentage market share is used instead of market fraction.)

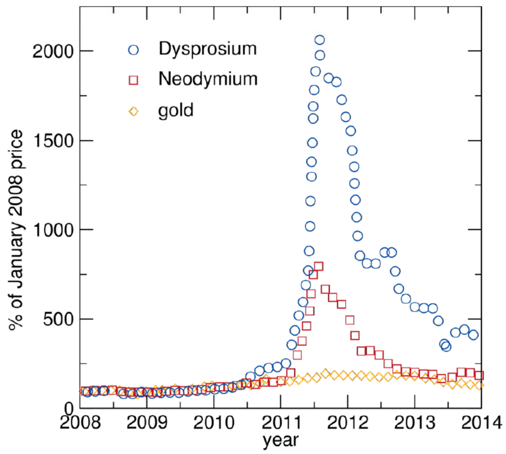

Fig. 1 Price of dysprosium, neodymium, and gold normalized by their January 2008 price between 2008 and 2014 replotted from [5]. The spike in price coincides with export restrictions from the primary producer of rare earth elements.

In recent years materials researchers have implemented HHI calculations to generate quantitative resource metrics. Gaultois *et al.* performed a first of its kind analysis for thermoelectrics where performance and resource metrics were simultaneously compared quantitatively[8]. In that work the HHI for elemental production (HHI_P) and known reserves (HHI_R) were calculated using 2010 data taken from the 2010 United States Geological Survey (USGS) Mineral Resource Data System (MRDS)[9]. The USGS is a bureau of the United States Department of the Interior and publishes in depth mineral analyses each year such as the total production values for different commodities as a function of country of origin, known reserves for different countries, general commodity uses, and some essential trends. Subsequent similar approaches were carried out on lithium ion batteries by Ghadbeigi *et al.* [10], high entropy alloys by Fu *et al.*[11], superhard materials by Tehrani *et al.*[12], photovoltaics by Goe *et al.* [13] and others.

A problem with these recent approaches is their reliance on HHI_P and HHI_R values calculated from 2010 data despite the fact that the global reserve estimates and production values are changing every year and therefore HHI_R and HHI_P should be updated each year. Moreover, if these values were calculated over many different years it would be possible to generate a time series of HHI data which could then be used as the basis for geopolitical stability studies and more. In this data descriptor article we describe how we calculate HHI for all available USGS data providing HHI_P and HHI_R values spanning from 1998 up until 2015. Using this dataset we illustrate diverse trends possible over time with different materials and point to a few obvious instances where geopolitical instability disrupted material flows in ways that would impact technology development.

2 Materials, methods, and data description

The dataset collated data from several sources. Raw materials production data by country was taken from the USGS Minerals Yearbook. At the time of accessing, data was only available through 2014 fully, with the 2015 summary partially published. Each summary summarizes data from that year and the four years prior with corrections from previous years; to ensure accuracy, data was taken from the most recent year still containing that data (for example, 1998 data was taken from the 2002 Minerals Yearbook) when possible. For years more recent than 2010, the data was taken from the 2014 or 2015 Minerals Yearbook up to 2015. Market share percentages and HHI values were directly calculated from this data. Price figures were taken from the USGS Minerals Yearbook where available, with notations on type of product being priced. The USD inflation index was taken from the Bureau of Labor Statistics Consumer CPI-U-RS[14]. Price indices were directly calculated from this data.

2.1 Availability of supporting data and citing a data descriptor article

The datasets supporting the results of this article are available online[15]. When using the results of the present work, please cite the dataset and this manuscript as they are mutually dependent on one another for meaning.

The datasets include 18 .CSV files named '#### Data.CSV' where #### is a year ranging from 1998 to 2015. Each of these files features 7 columns ('Element', 'HHI Contribution', 'HHI', 'Country Production', 'Market Share', 'Total World Production'). The rows then show the seven columns of information for each element arranged alphabetically. The dataset includes a 'Notes by Element.CSV' file which includes 6 columns ('Red=No Price data, Yellow= only partially included on price sheet, Green=on both sheets', 'Element', 'Notes', 'production', 'Are Production figures unavailable?', 'Other') with general notes and information taken from the USGS data such as the units for production *e.g.* kg vs metric tons. The dataset includes a 'Summary- HHI.CSV' file which contains 22 columns ('Element', 'Unnamed: 1', 'HHI-1998', 'HHI-1999', 'HHI-2000', 'HHI-2001', 'HHI-2002', 'HHI-2003', 'HHI-2004', 'HHI-2005', 'HHI-2006', 'HHI-2007', 'HHI-2008', 'HHI-2009', 'HHI-2010', 'HHI-2011', 'HHI-2012', 'HHI-2013', 'HHI-2014', 'HHI-2015') summarizing the HHI for each element for each year in the range provided. The dataset contains a 'Summary-Market Share (%).CSV' file with 21 columns ('Element', 'Notes', 'Country', '1998', '1999', '2000', '2001', '2002', '2003', '2004', '2005', '2006', '2007', '2008', '2009', '2010', '2011', '2012', '2013', '2014', '2015) which summarizes the market share by element on a per country basis for each year in the range provided. Finally, the data includes a 'prices.CSV' file with 10 columns ('Element', 'Year', 'Dollars', 'Change in Absolute Dollars', 'Change in Absolute Dollars (%)', 'Price Index', '1998 Dollars', 'Change in 1998 Dollars', 'Change in 1998 Dollars (%)', and 'Notes').

Table 1 General HHI categories, elements in each category, and standard deviations as well as average annual percent change

HHI Category	elements	$\bar{x}$	$\bar{j}$
High HHI	platinum group metals, Pt, He, Be, Nb, Sb, W, rare-earth metals	637	5.6%
Moderate HHI	V, Cr, Se, Br, Zr, Mo, Pd, Sn, I, Ba, Re	349	6.4%
Low HHI	Al, N, K, S, Ti, Mn, Fe, Ni, Cu, Zn, Ag, Cd, Au	172	4.8%
Gradually changing HHI	P, Pb, Li	800	8.7%
Abrupt changing HHI	Bi, Ca, Hg, Co, B, Ga	1539	13.8%
Volatile HHI	As, Sr, Ta, Te, Th	930	13.5%

HHI values were calculated using the following expression,

$$HHI = \sum_{i}^{N} s_i^2 \quad (1)$$

where N is the total number of countries involved, and s_i is the percent market share of country i in the world production or reserves of a given element. The U.S. Department of Justice and the Federal Trade Commission have designated markets as unconcentrated when HHI $<$ 1500, moderately concentrated when the HHI lies between 1500 and 2500, and highly concentrated when HHI $>$ 2500.[16] If a single country controlled the entire market, HHI = 100^2. By these measures more than half of the produced elements would be classified as highly concentrated and very few elements would be unconcentrated.

2.2 Data utility

The goal of this work is not to provide an in-depth analysis of the events and factors that could be correlated or even responsible for all of the trends in HHI for the elements reported. However, we hope that our collection and publication of elemental production data over this time period including the calculation of HHI in a organized data set will enable future reports of this type such as the one recently conducted on supply chain considerations in lithium ion batteries[17].

General trends are observed when we examine the HHI for the elements reported here over the time period of available data (See Figure 2. It can be seen that elements fall into one of 6 different classes. (1) Elements with a consistently high HHI value ($HHI > 5000$), (2) elements with a consistently moderate HHI value ($5000 > HHI > 2000$), (3) elements with a consistently low HHI value ($HHI < 2000$), (4) elements with HHI which is gradually changing over time, (5) elements with HHI featuring an abrupt change in an otherwise more predictable trend, and (6) elements with overall volatile HHI values. The elements which fall into each of these categories are listed in Table 1 along

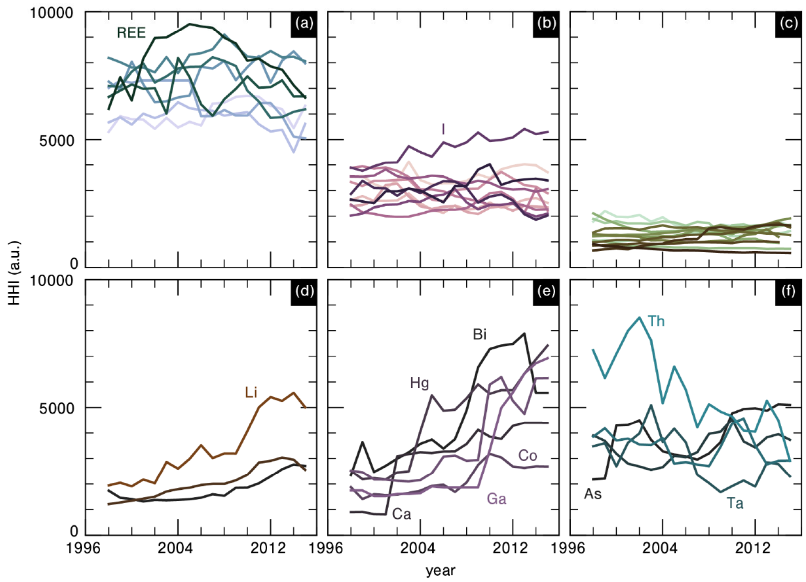

Fig. 2 General trends in HHI for elements. (a) High HHI, (b) moderate HHI, (c) low HHI, (d) gradually changing, (e) abrupt changes in HHI, and (f) overall volatile HHI.

with average standard deviation, $\bar{x}$, and average annual volatility $\bar{j}$ defined as the average of the annual percent change, $\left|\frac{HHI_{presentyear}-HHI_{prioryear}}{HHI_{prioryear}}\right|$.

Comparing categories we note that, in general, higher HHI corresponds to a larger standard deviation over time, $\bar{x}$, compared to moderate and lower HHI values. However, the average annual volatility is approximately the same for each category. On the other hand, much larger standard deviations and average annual volatilities are observed for the gradually changing, abruptly changing, and volatile HHI categories.

The dataset reports not only the annual HHI for each element, but also the production by country of each element over the time span. This allows for a more detailed analysis of any given element. For example, examination of the abruptly changing HHI elements can in some instances be correlated with geopolitical events which could have caused the observed spike in HHI. For example, consider the First and Second Congo Wars which lasted between 1996 and 2003. These wars caused major disruptions in the production of cobalt in the Democratic Republic of Congo[18]. When the annual data for cobalt production calculated as percent market share by different countries is plotted in Figure 3 it is possible to see how Zambia was able to increase market share on account of the turmoil in the Democratic Republic of Congo. The plot also shows how this was gradually returned to normal at the conclusion of the war although ongoing events such as border disputes, resource taxes, illegal mining, and other geopolitical events between the two countries may

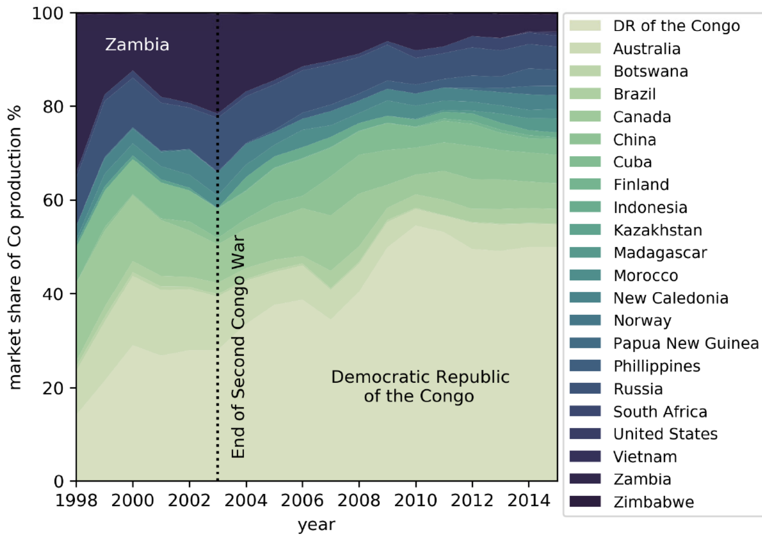

Fig. 3 Market share of global cobalt production between 1998 and 2015 with the end of the Second Congo War marked.

Table 2 General price categories and the elements in each category.

HHI Category	elements
Rare-earth elements	Y, La-Lu
Elements with price $p > \$10^3/kg$	Au, Pt, Pd, Re
Elements with price $\$10^3/kg > p > \$10/kg$	Ga, Ag, Be, Co, V, Ni, Nb, Mo, Sn, Te, I, Ta, W, Hg, Bi, Th
Elements with price $\$10/kg > p > \$10^{-1}/kg$	Cr, Fe, Se, Li, B, N, Al, K, Mn, Cu, Zn, As, Zr, Cd, Sb, Pb
Elements with price $\sim \$10^{-1}/kg > p > \$10^{-3}/kg$	Ca, P, S, Ba, Ti

produce future volatility in cobalt production[19]. A similar analysis could be performed to better understand what was responsible for the spikes in the HHI for boron (2010), gallium (2010), bismuth (2008-2013), calcium (2001), mercury (2003-2005) etc.

The price per kilogram in 1998 US Dollars, p, for the elements in shown in Figure 4. Panel (a) shows the rare-elements and the price volatility from Figure 1 is visible across numerous members of this group. The elements which fall into different price categories are listed in Table 2. Price data is widely varying, with some elements priced as oxides or chlorides, and others as the pure material. Table 3 shows the product and purity for each element price in the data.

Table 3 Product for which price is being considered. *Standard purity of metal products, unless otherwise mentioned, is 99%, or 2N, purity

Element	Product	Purity	Element	Product	Purity
Li	Lithium Carbonate	NA	I	Metal	99
Be	Beryllium Oxide	NA	Ba	Barite	NA
B	Ulexite	NA	Ta	Tantalite Ore	NA
N	Anhydrous Ammonia	NA	W	Ammonium Paratungstate	NA
Al	Metal	99	Re	Metal	99%
P	Phosphate Rock	NA	Au	Ingots	99.5%
S	Elemental Sulfur	99	Hg	Metal	99
K	Potassium Chloride	NA	Pb	Metal	99
Ca	Calcium Carbonate	NA	Bi	Metal	99
Ti	Ilmenite	NA	Th	Thorium Oxide	99.9%
V	Vanadium Pentoxide	NA	Pd	Metal	99
Cr	Chromite Ore	NA	Pt	Metal	99
Mn	Manganese Ore	NA	Ce	Cerium Oxide	99.5%
Fe	Iron Ore	NA	Dy	Dyspropium Oxide	99%
Co	Metal	99.8%	Er	Erbium Oxide	96%
Ni	Metal	99.8%	Eu	Europium Oxide	99.99%
Cu	Metal	99	Gd	Gadolinium Oxide	99.99%
Zn	Metal	99	Ho	Holmium Oxide	99.9%
Ga	Metal	99.99%	La	Lanthanum Oxide	99.99%
As	Arsenic Trioxide	NA	Lu	Lutetium Oxide	99.99%
Se	Metal	99	Nd	Neodymium Oxide	95%
Zr	Zircon	99%	Pr	Praseodymium Oxide	96%
Nb	Ferroniobium	NA	Sm	Samarium Oxide	96-99.9%
Mo	Molybdenum Oxide	NA	Tb	Terbium Oxide	99.9%
Ag	Ingots	99.9%	Tm	Thulium Oxide	99.9%
Cd	Metal	99.95%	Yb	Ytterbium Oxide	99%
Sn	Metal	99	Y	Yttrium Oxide	99.99%
Sb	Metal	99	Sc	Scandium Oxide	99.99%
Te	Metal	99%			

2.3 Future Work

One downside of the original HHI metric is that it considers all entities equally using only market fraction in the HHI calculation. However, some entities could be more susceptible to disruption than others. For example, the think tank Fund For Peace publishes an annual Fragile States Index which attempts to quantify the degree to which a state might face ineffective central government, poor territorial control, absent public services, crime or corruption, refugee immigration, or economic decline. Some scholars have begun to use similar

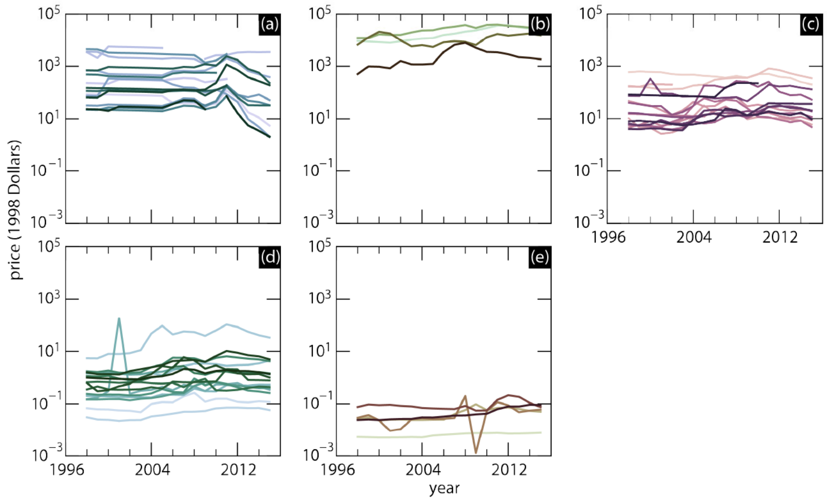

Fig. 4 General trends in price for elements. All prices shown in 1998 US Dollars/kg. (a) Rare-earth elements, (b) elements with price $p > \$10^3/kg$, (c) elements with price $\$10^3/kg > p > \$10/kg$, (d) elements with price $\$10/kg > p > \$10^{-1}/kg$, (e) elements with price $\$10^{-1}/kg > p > \$10^{-3}/kg$.

fragility indices in conjunction with traditional economics metrics [20] but such metrics have not yet been applied to estimate critical material flows.

Acknowledgements The authors gratefully acknowledge support from the National Science Foundation through CAREER Award DMR 1651668 as well as Award CMMI 1562226. T.D.S conceived the study and helped collect data; B.T. collected data; S.K.K. helped process the data. All authors assisted in preparing the manuscript and approved the final manuscript.

2.4 Conflict of Interest Statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Dominique Bourg and Suren Erkman. *Perspectives on industrial ecology.* Routledge, 2017.
2. U.S. Department of Energy. *Critical materials strategy.* DIANE Publishing, 2011.
3. Leslie Hook. China tightens grip on output of rare earths. *Financial Times*, 1, 2010.
4. Richard S Silberglitt, James T Bartis, Brian G Chow, David L An, and Kyle Brady. *Critical Materials: Present Danger to US Manufacturing.* Rand Corporation, 2013.
5. Justin Rowlatt. Rare earths: Neither rare, nor earths. *BBC World Service*, 1, 2014.
6. Orris Clemens Herfindahl. *Concentration in the steel industry.* PhD thesis, Columbia University New York, 1950.

7. Albert O Hirschman. *National power and the structure of foreign trade*, volume 105. Univ of California Press, 1980.
8. Michael W Gaultois, Taylor D Sparks, Christopher KH Borg, Ram Seshadri, William D Bonificio, and David R Clarke. Data-driven review of thermoelectric materials: performance and resource considerations. *Chemistry of Materials*, 25(15):2911–2920, 2013.
9. Mineral Commodity Summaries USGS. *United States Geological Survey, 2015*. 2015.
10. Leila Ghadbeigi, Jaye K Harada, Bethany R Lettiere, and Taylor D Sparks. Performance and resource considerations of li-ion battery electrode materials. *Energy & Environmental Science*, 8(6):1640–1650, 2015.
11. X Fu, CA Schuh, and EA Olivetti. Materials selection considerations for high entropy alloys. *Scripta Materialia*, 138:145–150, 2017.
12. Aria Mansouri Tehrani, Leila Ghadbeigi, Jakoah Brgoch, and Taylor D Sparks. Balancing mechanical properties and sustainability in the search for superhard materials. *Integrating Materials and Manufacturing Innovation*, 6(1):1–8, 2017.
13. Michele Goe and Gabrielle Gaustad. Identifying critical materials for photovoltaics in the us: A multi-metric approach. *Applied Energy*, 123:387–396, 2014.
14. Washington D.C. 20212 U.S. Department of Labor Bureau of Labor Statistics. *Consumer Price Index Research Series Using Current Methods (CPI-U-RS)*.
15. Taylor Sparks. *https://figshare.com/articles/HHI_csv_files_zip/11705445*, 2020.
16. US Department of Justice and Federal Trade Commission. *Horizontal Merger Guidelines of 2010*.
17. Elsa A Olivetti, Gerbrand Ceder, Gabrielle G Gaustad, and Xinkai Fu. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. *Joule*, 1(2):229–243, 2017.
18. John Clark. *The African stakes of the Congo war*. Springer, 2002.
19. Andy Home. Congo and zambia win fight with copper miners but at a cost: Andy home. *Reuters*, 2019.
20. Fabian Kühnhausen. Financial innovation and fragility. *Available at SSRN 2404881*, 2014.