Energy Strategy Reviews 26 (2019) 100394

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

The geopolitics of metals and metalloids used for the renewable energy transition

André Månberger, Bengt Johansson*

Environmental and Energy Systems Studies, Lund University, P.O. Box 118, SE-221 00, Lund, Sweden

ARTICLE INFO

Keywords:
Critical material
Geopolitics
Resource curse
Renewable energy
Energy transition

ABSTRACT

This study examines the geopolitical role of 14 metals and metalloids needed for renewable energy technologies. The analysis focuses on three factors with potential geopolitical importance: the geographic concentration of resources, potential revenues of resources rich countries and the size of total global markets.

The geographic concentration of most of the fourteen studied metals and metalloids will be higher than for oil. The only exceptions are tellurium, copper and silicon. The economic revenues as fraction of total economic throughput will be rather low for most of the countries studied. This will reduce the risk for a resource curse to emerge. The exceptions are the Democratic republic of Congo, Chile, Cuba, Madagascar and Zambia. The total economic value of the studied metals and metalloids will also be much smaller than the current oil market.

1. Introduction

Fossil energy, particularly oil, has been linked to geopolitics as a result of the geographical concentration of reserves, the existence of strategic supply chain bottlenecks, the import dependence of several governments, and as a precursor for internal tensions and vulnerabilities (see e.g. Refs. [1–4]). Renewable energy (RE) today contributes with a relatively limited share of the total energy mix, but the share is increasing (see e.g. Ref. [5]) in response to climate mitigation policies, cost reductions, and a desire to diversify energy supply in many countries. Although renewable energy policies are sometimes supported with references to energy security, the exact relation between renewable energy and energy security is not straightforward and depends largely on what aspects of the multifaceted concept that are highlighted (for different conceptual perspectives of energy security, see e.g. Refs. [3,6–8]). Energy security can be approached with technical, economic, political and environmental perspectives, which in different ways interact with each other. In this paper, we concentrate our attention to aspects of energy security that have geopolitical implications. Factors that are central for defining the geopolitics of natural resources are amongst others geography, dependency and economic value.

The growing importance of renewable energy has led to the emergence of new research around the interaction between renewable energy, security and geopolitics (see e.g. Refs. [9–13]). Interests have mainly been directed to the energy resources per se (such as hydro, wind, biomass and solar) and the integration of these sources in various energy systems.

However, in addition a number of previous studies have identified that renewable energy systems can increase the demand for some minerals, e.g. rare earth metals (see e.g. Refs. [14,15]). Although these minerals exist around the globe, the opportunity to extract them varies significantly among countries. This can give rise to a variety of security and geopolitical consequences that need to be explored in order to understand the risks and opportunities of this expansion. A literature on the geopolitical consequences of rare earth metals have started to emerge, often with a broader focus then from the perspective of future energy transitions (see e.g. Refs. [16–22]).

1.1. Geopolitical aspects of energy and other natural resources

The geopolitical aspects of energy and materials can be divided in a number of different categories. Here, we structure the way energy and materials interact with geopolitics according to five different processes:

- Import dependent countries strive to secure an adequate and affordable supply.
- Resource rich countries strive to secure adequate incomes from their resources.
- Countries seek to secure important trade flows.
- Regimes in resource-rich countries strive to use their resources to increase their political influence nationally or in the global arena.
- Resource availability affects internal stability through a variety of

---

* Corresponding author.
E-mail addresses: Andre.Manberger@miljo.lth.se (A. Månberger), Bengt.Johansson@miljo.lth.se (B. Johansson).

https://doi.org/10.1016/j.esr.2019.100394
Received 3 December 2018; Received in revised form 28 June 2019; Accepted 25 July 2019

processes, where those with negative outcomes often are summarised under the term “resource curse”.

First, import dependant countries in different ways strive to secure the supply of energy and other natural resources needed in their economics. The strategies can include diversification, direct ownership (usually through nationally owned companies), through bilateral long-term relations or through international institutions such as free and transparent international markets. Conflicts can arise when competing interests meet in different locations, and through a wish to protect global energy markets as a means to secure supply and protect national industrial interests. Security of supply can be hampered by national unrests in supplying countries and by threats to important trade links. The political stability of important suppliers is thus an important aspect.

Second, resource rich countries may strive to secure incomes that are often key to the national economies and state budgets. Depending on their positions, this can be carried out through attempts to control price setting and gain increased market shares (for a discussion of the strategies used see e.g. Refs. [1,23–25]). These attempts can include measures that interfere with the market and the interests of resource dependent countries, potentially leading to conflicts. The strategies could also include different ways to recover a larger fraction of the rent of investing companies through nationalisation, exploitation taxes etc.

Third, international oil trade has been linked to geopolitics and international conflicts because of its size and economic importance [26,27]. One of the claims is that the economic importance motivates hegemonic actors to use military means and soft power to maintain trade flows. A threat to market domination can trigger military intervention, the prime example being the Carter Doctrine [2]. Furthermore, the combination of perceived global scarcity and local abundance is a prerequisite for resource wars, in which countries use military force to gain access to resources, see e.g. Ref. [28]. A fourth aspect would be that countries use their resources to increase their influence in the global political arena. This influence could be used for realising countries' political and economic ambitions or as a way to strengthen the regime's internal status. Here, the geographical concentration of resources can enable resource-rich countries to gain advantage over import dependent countries, e.g. through the contested energy weapon [29,30]. Similar aspects have been looked into when it comes to minerals, for instance, in the case of China where it has been argued it has used its dominance regarding certain strategic minerals as a tool in their conflict with Japan regarding military strategic islands. This led to disturbance of the supply of rare minerals essential for the Japanese industry [16].

Finally, the resource availability and the revenue of the resources can contribute to the instability of countries and thus geopolitical consequences, often called the resource curse (for typologies defining this correlation see e.g. Refs. [31,32]). There are several reasons for such instabilities. The resources can be targets of different interest groups and lead to conflicts. Rebel groups in weak states can use the revenues from conflict minerals to fund their activities [33], and the dependence on resources can crowd out other sectors of the economy through currency appreciation [34]. The dependence on resources can also make state budgets and national economies vulnerable to fluctuating world market prices. There is also an increased risk for autocracy. If the national elites are independent of tax incomes they tend to be less keen on developing democratic institutions, which in turn can increase tensions. However, high resource rents do not necessarily lead to conflicts. Basedau and Lay [35] argue that the total income level of a country matters, and that high per capita incomes reduce the risks for conflicts. One reason for that could be that low per capita income leads to poor governance capabilities [36]. In addition, Orihuela [32] stresses that also geographic location matters, as there is a path dependency in institution development with an impact on the risk for a resource curse.

1.2. Previous studies on the geopolitics of the renewable energy transition

There is only a limited number of studies looking on the geopolitics of the renewable energy transition. Some go through a broader number of technologies; others concentrate on a few specific technologies. The general conclusion is that the low energy density that characterises renewable energy will reduce the risk for interstate conflict, whereas land use issues grow in importance especially with regard to biomass. The physical differences between renewable and non-renewable energy flows indicate that the transition will reduce the risk for interstate conflict but can increase the risk for local land use conflicts [10]. The potential for excess rents, which could be an important cause of geopolitical tensions, both through conflicts to control the resources or through the resource curse, is generally assumed to be rather limited. An exception could be for hydropower, as the resource is concentrated, can be profitable for the one who controls it and the construction of dams can impact other countries. For example, previous research has identified that large scale hydropower can turn into a “resource curse” [37,38]. In addition, the expansion of renewable energy is often, for efficiency reasons, assumed to be based on the integration of infrastructures. This integration can have geopolitical implications.

The consequence of the renewable energy transitions can diminish the relative importance of fossil fuel exporters, which can get reduced incomes. When, energy importers turn to domestic renewable energy it strengthens the importers' bargaining power vis-a-vis exporters [11]. The potential to exploit the energy weapon diminishes. The geopolitics of oil can, in response to the reduced demand due to energy efficiency and renewable energy, turn from a mind-set of scarcity to abundance where some oil producers have stranded assets [39].

Most existing studies have looked into the direct use of energy sources and only a few have looked into the geopolitics of rare minerals in the context of renewable energy transition, although there are several studies looking into the geopolitics of these materials (see e.g. Refs. [17–19]) and other minerals (see e.g. Ref. [40]) in a broader sense. Holders of these resources would gain economically if the use of renewable energy increase [41]. Riddle et al. [15] have furthermore studied the function of the strategic minerals markets and O'Sullivan et al. [42] argued that mining cartels, similar to OPEC, may develop that would control mining of metals critical for renewable energy. These studies did not, however, go into detail in how the demand for different materials will change, which countries would supply the resource and how much revenues they would make. These shortcomings make it difficult to compare the geopolitics of renewable energy materials with fossil energy resources. On the other hand, another set of literature has quantified how much demand for various metals and metalloids would increase if a renewable energy transition would occur [14,43–45], but this literature has not analysed geo-economic and geopolitical consequences of such changes.

Finally there is a literature that argues that the geopolitics of energy transition should be less about controlling natural resources but more about having access to technology, patents and human knowledge [46,47]. The methods to protect these assets will differ from protecting the physical resources. The long-term impact of the distribution of these softer resources on geopolitics will probably be more difficult to assess than the role of natural resources for which the geographical location is rather well determined.

2. Focus and methodology

In this chapter, the focus of this study and the methodology used is briefly presented. Assumptions and methodological issues are discussed in more detail in the supplementary material.

This study focuses on the geographical concentration of the reserves of metals and metalloids used in renewable energy systems and the economic value of these resources. Geographical concentration of reserves is especially important for the fourth geopolitical process presented in chapter 1.1, i.e. the potential for regimes in resource rich countries to increase their political influence in the global arena but also to the first process that regards the competition around scarce geographically concentrated resources. The economic value of the markets and the relative economic importance of the resources to countries' economies can, on the other hand, have an impact on both the second geopolitical process, presented in chapter 1.1, the desire to act to protect incomes, and the fifth process, i.e. the risk for a resource curse and the connected risks for country instabilities.

In this paper the analysis is based on 14 metals and metalloids identified in a previous study [14]. These metals and metalloids were identified as important for key technologies, producing or using renewable energy, that are assumed to gain significant market shares in low carbon energy transition scenarios. These technologies were described in detail in Ref. [14] and include electric motors for wind power production and electric cars (key materials: neodymium, dysprosium and copper), batteries and fuel cells (key materials: lithium, cobalt, manganese, nickel and platinum) and solar electricity technologies (tellurium, indium, gallium, selenium, silver and silicon). As the electrification of the transportation system plays a central role in many low carbon energy scenarios, technologies for electric vehicles are included, although the technology is not directly dedicated for renewable energy.

This study focuses on the incremental demand of these metals, following the expansion of renewable technologies, acknowledging that there is an additional demand for these metals that is not studied here. For example: copper used in batteries, electric motors and on-board chargers is included, while the copper used in the general wiring harness in vehicles is not, since this use is assumed to be almost equivalent to that of ICE-vehicles.

Two metal demand scenarios[1] are developed, both taking the starting point in IEA:s climate change transition scenario [48] called "beyond 2°" (B2D-scenario). The B2D-scenario shows one way that the energy system can develop in a way that is consistent with meeting the 2° target of the Paris agreement. It stretches to 2060 and illustrates how the use of various renewable production and end-use technologies develop.

The annual flows of material embedded in these technologies were quantified using a previously developed model [14]. The assumptions for material intensity, i.e. how much of each material that is used per kW or kWh as well as technology lifetimes were taken from Ref. [14]. Metal intensities have declined in the past and are assumed to continue to do so, see Ref. [14] and supplementary material.

The two different metal demand scenarios differ from each other regarding the assumed recycling rates. In Scenario 1 current recycling rates are assumed throughout the period while as in scenario 2, recycling rates increase linearly from current levels to 80% in 2040 for all metals and metalloids. Recycling rate is defined here as the quantity recycled as a percent of the material in waste streams for products that have reached their end of life. This study only examines the increased metal demand attributable to energy transition. Recycled material is therefore only used by the model when the examined technologies have reached their end of life.

The concentration of the studied key metals and metalloids are analysed using the Herfindahl-Hirschman Index (HHI) based on the shares of current global reserves for the respective countries and material. The HHI is a standard index used to analyse market concentration for various products.[2] In order to interpret the values for the different materials, we compare them to the corresponding HHI for fossil fuels. The data on reserves are taken from the 2018 United States Geological Survey (USGS) mineral commodity summaries [50] except for indium, gallium and rare earths where other sources are used (see supplementary material).

The annual economic value of the additional metal flows resulting from the energy transition was estimated by multiplying annual metal flows with market prices for refined metal. In lack of any reliable forecasts for all of the studied materials we base our price assumptions on revealed data on last ten years metal prices.[3] The last ten years have experienced a "boom" and "bust" period accompanied by high and low prices in general as well as fluctuating prices for some metals used in renewable energy technologies and batteries (e.g. cobalt). One low price and one high price scenario have been developed based on this. The validity of this approach was tested by comparing these estimates for some of the materials for which estimates of future prices exist [52,53].

It should be noted that market prices for refined metal is used in the estimates (e.g. price of the lithium content in battery grade lithium carbonate). This is sometimes (much) higher than the raw material price at the mine gate. Revenue estimates for countries that sell concentrate rather than pure metal will therefore be higher than what would actually be the case. The reasons why we only use prices for pure metal are twofold. First, this is a good estimate of maximum revenue that the resource rich countries can gain because it takes into account the opportunities to integrate downstream in the supply chain. Second, it is uncertain where future refining industries will be situated and a country rich in resources may choose to invest in such facilitates domestically or abroad.[4]

The quantity of each metal or metalloid produced in a specific country is estimated from the total global demand which is distributed among countries in proportion to their current share of total reserves as reported by Ref. [50]. In other words, a country that today has y% of the reserves of metal x is assumed to extract y% of the primary demand for metal x in all years. The exceptions are indium, gallium and silicon where the shares of various countries future mining are assumed to be the same as the current shares of production, since reserve data for individual countries is not readily available. However, particularly in the short term this is sometimes misleading because countries can choose to support domestic mining (extract more than assumed), engage in producer cartels (extract less) and/or enforce stricter mining regulations (extract less). Mining can also be affected by external events, such as social instability. Still we think using share of reserves as a basis for production assumptions is a feasible approach.

The potential resource revenue is calculated for each country as the sum of the revenues from each of the studied metals and metalloids. Supplied quantities are multiplied with the assumed price for each material. To get a hint of the importance of these revenues for the countries' economies, the revenues are divided by the respective countries' GDP in 2016. Future GDP trajectories for individual countries were not included here due to uncertainties involved. Using current GDP will probably overestimate the relative value of the studied materials for some of these countries' economies. Phasing out fossil energy may negatively affect GDP for some countries. To put these values in relief the economic value of the global metal and metalloid flow is compared with the oil market.

3. How much metals and metalloids would be required to make a renewable transition?

The virgin metal demand in the studied scenarios as share of current

---

[1] The two scenarios shows demand for both metals and metalloids.

[2] For a comparison of the advantages and disadvantages of various indices for resource concentration, see e.g. Ref. [49].

[3] Metal prices are available online from open sources: www.infomine.com and www.metalary.com, previous USGS Mineral Commodity Summaries (e.g. Ref. [50]) and neodymium and dysprosium during the price spike in 2011 from Ref. [51].

[4] An analogy is petroleum exporters' downstream integration. For example, Saudi Arabia has invested in oil refineries and the petrochemical sector domestically as well as abroad.

Table 1

Basic data, assumptions and cumulative demand up to 2060, year of peak primary metal demand and mean annual growth rate up to that year, for two metal demand scenarios. Data on reserves are from Ref. [50] for 2018 unless otherwise stated.

	Cobalt	Copper	Dysprosium	Gallium	Indium	Lithium	Neodymium	Nickel	PGM	Manganese	Selenium	Silver	Tellurium	Silicon
Data and assumptions														
Reserves (ton)	7,100,000	790,000,000	539,000[d]	5,200[e]	47,100[e]	16,000,000	15,900,000[d]	74,000,000	69,000[f]	680,000,000	100,000	530,000	31,000	N/A
Current recycling rate [a]	40%	60%	15%	15%	40%	10%	15%	60%	70%	45%	5%	80%	0%	0%
Recycling rate from 2040 in scenario 2	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
Low price ($/ton)	30,000	5000	360,000	400,000	300,000	20,000	35,000	10,000	30,000,000	2000	22,000	55,000	30,000	15,000
High price ($/ton)	90,000	10,000	2,800,000	1,000,000	600,000	90,000	400,000	30,000	60,000,000	4000	66,000	110,000	450,000	50,000
Scenario 1:														
Cumulative demand [b]	140%	8%	10%	21%	8%	91%	8%	47%	1%	5%	11%	9%	31%	$1.2{\cdot}10^7$ ton
Demand growth (%/y) [c]	5.6%	0.32%	7.4%	0.23%	0.57%	9%	3.1%	1.7%	0.23%	0.25%	0.37%	0.23%	2%	0.2%
Year of demand peak	2043	2045	2027	2042	2043	2047	2049	2045	2045	2045	2043	2043	2043	2042
Scenario 2:														
Cumulative demand [b]	96%	7%	7%	18%	7%	59%	5%	41%	< 0.5%	4%	10%	9%	26%	$1.0{\cdot}10^7$ ton
Demand growth (%/y) [c]	9.5%	0.36%	7.4%	0.23%	0.57%	8.4%	8%	1.6%	0.22%	0.22%	0.03%	0.23%	2%	0.18%
Year of demand peak	2030	2040	2027	2042	2043	2045	2028	2045	2045	2045	2403	2043	2043	2043

Note: The scenarios 1 and 2 are both consistent with a global climate mitigation scenario from IEA [48] that shows renewable energy technologies increasing (e.g. personal electric vehicles increase from 1.5 million to 1.3 billion and solar PV from 220 GW to 6700 GW). A model developed in Ref. [14] was used to quantify incremental metal demand. Scenario 1 adopts estimates of current recycling rates and Scenario 2 assumes that they will increase to 80%.

[a] Recycling is the quantity recycled as a percent of the material in waste streams for products that have reached their end of life. Values from Ref. [55].

[b] Cumulative demand for the modelled period expressed as share of reserve or, for Silicon, in ton.

[c] Growth calculated as mean annual growth of virgin material from 2017 to the year of maximum demand, assuming that demand from other sectors is the same as in 2017. For a more extensive analysis of how modelling assumptions affect cumulative demand, growth and year of demand peak see Ref. [14].

[d] Rare earth reserve estimates are based on interpolation of data from Refs. [50,56]. See supplementary material for information.

[e] Gallium and indium are extracted as by-products. Conventional reserve estimates do not exist. The data is for known extractable amounts from Ref. [55] for 2012. Resources are (much) higher, e.g. Werner, Mudd and Jowitt [57] puts the indium resource figure at 356,000 ton. See also supplementary material.

[f] USGS [50] reports reserves as 69,000 ton for all PGM combined. Platinum and palladium make up a majority of the PGM reserve and most end use applications can substitute one of these for the other, e.g. vehicle catalysts [58] and fuel cells [59]. The PGM reserve figure is therefore used here.

Table 2
Geographical concentration of major reserve holders in 2018, data from Ref. [50]. Oil is provided as a point of reference.

Resource	HHI	Share of reserve					Other countries
Cobalt	2825	DR Congo (49%)	Australia (17%)	Cuba (7%)	Philippines (4%)	Zambia (4%)	19%
Copper	796	Chile (22%)	Australia (11%)	Peru (10%)	Mexico (6%)	US (6%)	45%
Lithium	3039	Chile (47%)	China (20%)	Australia (17%)	Argentina (13%)		3%
Manganese	1880	South Africa (29%)	Ukraine (21%)	Brazil (18%)	US (14%)	China (7%)	11%
Nickel	1880	Australia (26%)	Brazil (16%)	Russia (10%)	Cuba (7%)	Philippines (6%)	35%
PGM	8373	South Africa (91%)	Russia (6%)	Zimbabwe (2%)	US (1%)		< 1%
REE	2287	China (37%)	Brazil (18%)	Vietnam (18%)	Russia (15%)	India (6%)	6%
Selenium	1390	China (26%)	Russia (20%)	Peru (13%)	US (10%)	Canada (6%)	25%
Silver	1148	Peru (18%)	Australia (16%)	Poland (16%)	Russia (10%)	China (7%)	33%
Tellurium	727	China (21%)	Peru (12%)	US (11%)	Canada (3%)	Sweden (2%)	51%
Oil	1119	Venezuela (19%)	Saudi Arabia (17%)	Canada (11%)	Iran (10%)	Iraq (9%)	33%

Note: PGM stands for Platinum group metal, REE stands for Rare earth elements. HHI stands for Herfindahl-Hirschman index. A high value corresponds to a high concentration with the maximum value of 10,000.

reserves is presented in Table 1. It should be noted that reserves are subsets of resources and are therefore likely to grow as a result of improved mining technology and/or higher prices. However, it is useful to compare cumulative demand with current reserves since large price increases are unlikely if reserves are significantly greater than cumulative demand. This is the case for most of the analysed metal and metalloids. Exceptions are cobalt and lithium especially in scenario 1, in which recycling rates remains at the current level. Even with high recycling rates in scenario 2, the cobalt needed for renewable energy technologies will be close to the levels of current reserves.

This study does not include the demand growth in other parts of society and thus understates reserve depletion. This is not problematic for those materials for which the renewable energy sector is a dominating source of increased demand, for example permanent magnets (neodymium and dysprosium) used in generators and motors see Ref. [43]. Other metals are more problematic since competing future demands have not been thoroughly assessed (e.g. the same metalloids can be used to construct solar PV and LED light) and/or remains unknown. Also, demand for many metals is likely to increase as a result of growing population and economic wealth [54].

4. Geographical concentration of reserves

This section analyses the geographical concentration of the reserves of ten of the metals included in this study. Silicon was excluded due to its abundance as was metals mined as by-products (i.e. indium and gallium) for which it is difficult to obtain data. Data for platinum group metals (PGM) was used to analyse platinum, since platinum can be substituted by other PGM (e.g. palladium in fuel cells and catalyser) and USGS [50] provides reserve estimates only for PGM as a group. Neodymium and dysprosium were also studied as one group (rare earth elements, REE) for the same reasons.

The estimates of the geographical resource concentration presented in the form of HHI reveal that only two metals (tellurium and copper) have lower concentration than oil and the remaining eight have higher concentration, see Table 2. The concentration of platinum group metals (PGM) is the highest (HHI = 8373 of maximum 10000) followed by lithium (HHI = 3039) and cobalt (HHI = 2825). Individual countries, rich in these metals, e.g. South Africa in PGM; Chile in Lithium and the Democratic Republic of Congo (DRC) in cobalt, are thus important for the global supply of respective resource, more so than many countries rich in oil.

Six countries (Australia, Chile, DRC, China, Brazil and Russia) together hold a large share of cobalt (66%), copper (33%), lithium (84%), nickel (52%), rare earths (70%) and silver (33%) reserves. These countries are situated in different continents and are heterogeneous concerning level of economic development and political systems and priorities. A cooperation between these countries in a producer cartel similar to OPEC appears unlikely today, and the countries would probably find it difficult to increase market prices in the medium term as a result of the existence of substitutes and potential competition from countries outside of this group.

An area where it could be possible to form a small successful cartel is for lithium, due to lithium's geographical concentration and dominance in current battery technologies. However, the concentrations presented in Table 2 are calculated for reserves, i.e. resources that can be produced economically at today's prices. Higher prices will expand reserves and make new sources available such as extracting lithium from sea water [60] and ocean floor mining [61]. The high price assumption for lithium used in this study is the same as low end estimates of production cost from seawater (US$90-130 k/ton of lithium) as estimated by Jasiński, Meredith and Kirwan [52]. This provides back stop-supply sources that put a ceiling to long term price increases which render the formation of producer cartels that can increase prices above this level difficult in the long term. Also, higher lithium prices and perceptions of market interference incentivise developing batteries that do not contain lithium[5] and other energy technologies such as fuel cells, thus undermining the importance of lithium in the long term.

5. Producer revenues

This section analyses potential revenues, that can be attributed to the increased metal demand following an energy transition, for countries rich in metals used for renewable energy. This is done by calculating potential resource revenues as a share GDP for a number of resource-rich countries for the period 2016–2060. The countries are chosen from the list of countries from Ref. [50].

Starting with the 37 countries existing on the USGS list, 18 countries (see Table 3) were analysed in more detail because these countries hold most of the reserves.[6] Depending on the maximum revenue share of the GDP these countries were divided into three groups: less than 0.5%, between 0.5 and 5% and above 5%. Examples are depicted in Figs. 1–3.

Most countries in the world would belong to the first group, two of which are included in this study (China and the US). Both of these countries are rich in metals used in renewable energy technologies but the size of their economies is large compared to potential revenues. Furthermore, these countries currently have oil related revenues that are higher than the potential mineral revenues for renewable energy. Declining oil revenues would thus not be compensated from increased mineral revenues if a renewable energy transition would occur. One

---

[5] This study only included lithium batteries. Other battery elements may gain market share in the future, such as sodium which is more abundant [62].

[6] Due to the lack of data it was not possible to study minor countries where the reserves are small compared the global total but for which the revenues could be significant and therefore could potentially give rise to the problems defined as the resource curse. Also note that an overview of peak revenues/GDP for all 37 countries is provided in the supplementary material.

Table 3
Basic data on the eighteen studied countries, the resources that are used in renewable energy systems that the respective countries possess, peak revenues attributable to increased metal demand for renewable energy compared to their GDP and estimates of current state stability.

Nation	Population 2018[a] million	GDP/capita 2016 USD[a]	Main metals and metalloids studied	Oil revenue/GDP[b]	Peak metal revenue/GDP[c]	Current state stability[d]
Argentina	44.7	12,499	Li	1.8%	1.07%	More stable
Australia	24.8	54,069	Cu, Co, Li, Nd, Dy, Ag, Ni, Si	0.44%	2.04%	Sustainable
Brazil	211	8649	Li, Nd, Dy, Mn, Ni, Si	2.32%	0.58%	Warning
Canada	37.0	42,154	Cu, Co, Nd, Dy, Pt, Ni, Te, Se, Si	4.66%	0.93%	Sustainable
Chile	18.2	13,794	Cu, Li, Ag	0.03%	10.52%	More stable
China	1415	7993	Cu, Li, Nd, Dy, Ag, Mn, Ni, Te, Se, Si	0.57%	0.17%	Elevated warning
Cuba	11.5	7815	Co, Ni	0.89%	14%	Warning
DR Congo	84.0	512	Cu, Co	9.9%	44%	Very high alert
Madagascar	26.3	451	Co, Ni	0	13%	High Warning
Peru	32.6	6049	Cu, Ag, Te, Se	1.1%	1.2%	High Warning
The Philippines	106.5	2951	Co, Ni	0.1%	1.2%	High Warning
Russia	144	8655	Co, Nd, Dy, Pt, Ag, Ni, Se, Si	14%	0.61%	Elevated warning
South Africa	57.4	5274	Co, Nd, Dy, Pt, Mn, Ni, Si	0.1%	1.5%	Elevated warning
Ukraine	44.0	2099	Mn, Si	0.51%	1.7%	Elevated warning
The US	327	57,808	Cu, Co, Li, Nd, Dy, Pt, Ag, Mn, Ni, Te, Se, Si	1.1%	0.02%	Very stable
Vietnam	96.5	2171	Nd, Dy	2.9%	1.63%	Warning
Zambia	17.6	1270	Cu, Co	0%	8.3%	High Warning
Zimbabwe	16.9	998	Li, Pt	0%	0.50%	High Alert

[a] GDP data from Ref. [63].

[b] Production levels and prices used for these calculations are from 2016 when the price level was the lowest in 10 yrs ($44/barrel). This means that the values are lower than what has been usual.

[c] Taken as the highest level during the studied period. Note that GDP for 2016 is used in all comparisons.

[d] [64]. The fragility of the nations are categorised in 12 groups from very sustainable to very high alert. They can give an indication of current fragilities but their usefulness in long term analyses can be questioned, see e.g. a discussion in Ref. [65].

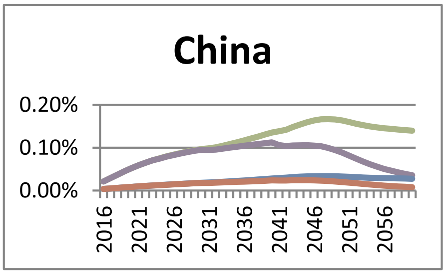

Fig. 1. Revenues attributable to increased metal demand for renewable energy technologies as a share of GDP in 2016 for China (2016–2060). The green line is scenario 1 assuming high prices, the purple line is scenario 2 assuming high prices, the blue line is scenario 1 assuming low prices and the red line is scenario 2 assuming low prices. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

option for these countries to increase revenues and domestic jobs connected to the minerals is to develop downstream integrations following the example of China when they turned from exporting rare earths to manufacturing first permanent magnets and then generators and motors.

The second group contains eleven countries: Argentina, Australia, Brazil, Canada, Peru, the Philippines, Russia, South Africa, Ukraine, Vietnam and Zimbabwe. All of these countries have mining sectors that today make up from slightly less than one percent (Philippines) to almost 10% (Peru) of their GDP and provide resource rents of between 0.3% (Argentina and Vietnam) to 8.3% of their GDP (Peru).[7] Increased use of renewable energy will provide these countries with the opportunity to grow their mining sector and its contribution to export revenues. However, the net effect of a shift to renewable energy is likely to be negative for most countries in this group, since all of them produce fossil energy.

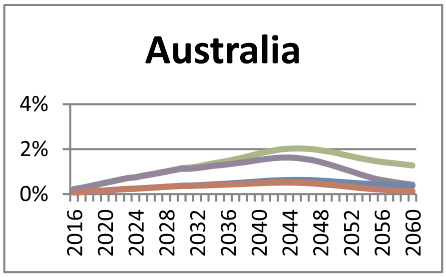

Fig. 2. Revenues attributable to increased metal demand for renewable energy technologies as a share of GDP in 2016 for Australia (2016–2060). The green line is scenario 1 assuming high prices, the purple line is scenario 2 assuming high prices, the blue line is scenario 1 assuming low prices and the red line is scenario 2 assuming low prices. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

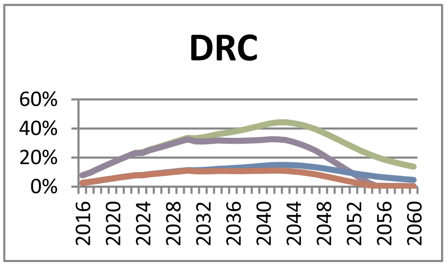

Fig. 3. Revenues attributable to increased metal demand for renewable energy technologies as a share of GDP in 2016 for DRC (2016–2060). The green line is scenario 1 assuming high prices, the purple line is scenario 2 assuming high prices, the blue line is scenario 1 assuming low prices and the red line is scenario 2 assuming low prices. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The third group includes five countries: DRC, Chile, Cuba, Madagascar and Zambia. DRC, Chile and Zambia already have mining sectors that generate resource rents above 10% of their GDP while the

---

[7] Data on mining revenues can be found at https://tradingeconomics.com/country-list/gdp-from-mining and mineral rents at https://data.worldbank.org/indicator/NY.GDP.MINR.RT.ZS.

fractions are much smaller in Cuba (0.2%) and Madagascar (1.3%). In the scenarios, Chile will derive most of its revenues from lithium production and the other four countries from cobalt. These prices have been volatile in the past varying with a factor of four for lithium and three for cobalt. Revenues for these countries are sensitive to the adopted price assumptions, as can be seen in Fig. 3. Revenues could thus fluctuate between the high and low price assumptions, if future price volatility is similar as historically.

A general observation is that producer revenues will increase up to mid-2030 for all scenarios after which they either continue to grow, reach a plateau or decline depending on assumptions for level of recycling. The level of recycling will have limited or no impact on producer revenues for the next twenty years, because the stock in society is expanding. However, recycled material can later meet a growing share of demand to the extent that it will reduce absolute demand levels for virgin material (in the case of cobalt it is reduced by a half during a period of less than ten years assuming that recycling increases). Producers would therefore need to find new markets for their minerals or manage the consequences of reduced revenues.

Only five countries were identified as having the potential to gain revenues corresponding to more than 5% of their current GDP. Prices of minor metals[8] have historically been more volatile than those of oil and the potential revenues from these are therefore very volatile. Average revenues are therefore less likely to stay close to the high estimates for a longer time unless demand from sectors not included in this study contributes to much higher average prices (and revenues). Only one country, DRC, gains revenues corresponding to more than 5% of current GDP also when low price-high recycling assumptions are combined. Mineral revenues for renewable energy are therefore unlikely to provide revenue flows on a country level at similar levels as for some of the important oil exporters such as Saudi Arabia (35% of GDP), Libya (34%) and Iraq (45%) but comparable to oil exporters such as Nigeria (10%).

6. Global market value

The total value of the analysed material demand in mid-2040 would be between 3.2 and 10.4% of the size of the oil market in 2016 (i.e. US$ $5.9*10^{10}$ to $1.9*10^{11}$), see Fig. 4. The market size for materials reaches a plateau after mid-2040 because assumed technological development reduce metal intensities and this more than compensates for the increasing number of vehicles and installed renewable power production. The high and low price assumptions can be compared with price span in the oil market. The magnitude of the price span is about the same for oil and the studied metals and metalloids with slightly more than twice as high price in the boom as in the bust period.

The share of recycled material of total materials grows in both scenarios 1 and 2 as a result of technologies that reach their end of life, see Figs. 5 and 6. In scenario 2, recycled material overtakes mining as the largest source in 2050, in scenario 1 the value of recycled material is lower than primary supply in all years. The total demand of virgin material starts declining in both of the scenarios after 2040 and thus also the revenues from primary supply. It should be remembered that these scenarios do not include other sectors in society and the total demand for virgin metal may therefore continue to increase even if the demand for renewable energy technologies falls. However, the scenarios do illustrate that a new supply source becomes available over time and more so when recycling is improved. The “technosphere source” will increase the number of suppliers.

Five elements (nickel, copper, cobalt, lithium and silicon) together make up 90% of the analysed market value (24%, 21%, 20%, 15% and 9% respectively), assuming low metal prices (see supplementary material for shares in the high price scenario). Four other elements (manganese, neodymium, silver and dysprosium) each represent more than 1% of the market value. The remaining five elements (platinum, indium, gallium, tellurium and selenium) have a combined share of less than 1%. Thus, some of the most expensive metals per tonne (platinum, gallium, and indium) make up small share of the total market since the volume is low.

The value of the cobalt market increases over time because lithium batteries, containing cobalt, are assumed to be used in electric vehicles. Previous studies that have quantified future cobalt demand in global energy transition scenarios provide estimates that are similar to this study or higher, for a comparison of estimates see Ref. [67]. However, the assumed volume of cobalt demanded may be overestimated, since cobalt free lithium batteries (e.g. the lithium iron phosphate-chemistry)

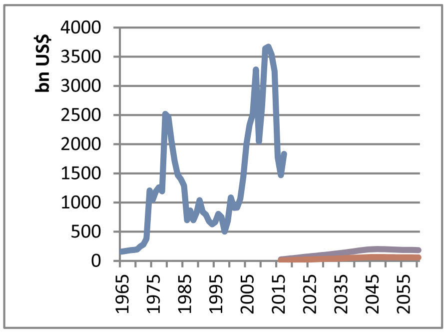

Fig. 4. Inflation adjusted oil market size in blue (1965–2017) in 2017 price level, metal market of scenarios 1 and 2 (2016–2060) for high prices (purple) and low prices (red), prices in billion US$. Oil market data from Ref. [66]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

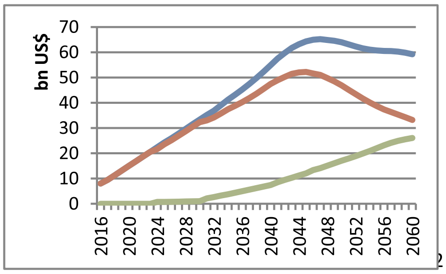

Fig. 5. Global market size of metals demand attributable to the increased demand from renewable energy technologies in scenario 1 (current recycling rate), assuming low prices (in billion US$). Blue line is value of gross demand, red is value of virgin demand and green is the value of recycled material. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

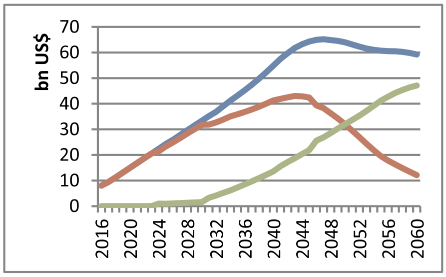

Fig. 6. Global market size of metals demand attributable to the increased demand from renewable energy technologies in scenario 2 (increased recycling rate), assuming low prices (in billion US$). Blue line is value of gross demand, red is value of virgin demand and green is the value of recycled material. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

---

[8] This term is often used for metal that are traded in relatively low volumes compared to base metals such as iron, aluminium, copper etc.

are available today and battery producers develop chemistries that use less cobalt than existing formulas, see e.g. Ref. [68]. Besides incremental improvements, technological disruptions such as solid-state batteries that do not contain cobalt would lower cumulative demand but also cause demand to decline faster than our results show.

The comparison between the current global oil market and future markets for metals and metalloids for renewable energy reveals several differences including: The metal and metalloid market is smaller (3–10% of the oil market), is more heterogeneous (many different elements) and the sources of supply can increase over time as a result of recycling. Recycled metals and metalloids for the renewable technologies could come from within consumer countries which might reduce the need for lengthy supply chains.[9] Taken together, these differences indicate that the global material market for renewable energy will generally be of less geopolitical importance than has been the case for oil.

7. Discussion

This study has looked into a few aspects of the increasing demand of metals and metalloids for renewable energy, aspects that historically have had geopolitical implications when it comes to energy and especially oil, i.e. resource concentration and economic value. There are both similarities and differences between the two aspects. While most of the studied metals and metalloids has a geographical concentration that is as high or higher than oil, the economic value of global markets for metals and metalloids as well as the income for individual countries of these materials are significantly lower than for oil and for many individual oil exporting countries.

The geopolitical risks of the geographical concentration will depend on the availability of substitutes for use in renewable technologies, and the stability as well as geopolitical strategies of exporting countries. If countries choose to restrict supply or if antagonistic attacks and natural disasters in producer countries occur, it can result in physical shortages and price hikes. However, these are likely to have short-term impacts because substitution and alternative supply sources can alleviate shortages of a particular resource. A case in point is China's export restrictions on rare earth metals in 2010, directed towards Japan as a retaliation of a border dispute. The embargo triggered a price spike but this was short lived and showed that it is difficult to successfully utilize supplies of rare earths to gain political leverage [16]. This also holds for other metals and metalloids that can either be replaced by another element, or substituted using another technology design. For example, different metals and metalloids are critical for different solar PV technologies and the reserves of these elements are found in different countries. Therefore, it is unlikely that all solar PV technologies would be affected by a supply shortage at the same time. Batteries are partial exceptions due to lithium's dominance in current technologies used in electric vehicles and reserves' high geographic concentration. The success of a “lithium producer-cartel” would be limited by the opportunities to exploit resources available offshore as well as alternative means to store energy that can provide a backstop to higher prices.

It seems that the substitutability has been rather large historically but it does not guarantee that it will be the case in the future as new lock-ins may be built in the systems similar to the lock-ins of fossil fuels.[10] The relatively low economic value of the metals and the metalloids also indicate that the global economy and also individual economies will be less sensitive to price volatility and price increases due to growing scarcities. Although the study indicates that the demand for the metals and metalloids for energy purposes will, in most cases, be lower than current reserves, especially if recycling is increased, it cannot be excluded that an increased demand for other technologies using the same raw materials can put more strain on the supply, with increasing prices.

Only a handful of countries will have the potential to gain significant new net revenue flows as a result of the increased use of renewable energy. One reason is that many of the countries simultaneously face declining revenues when fossil fuels are phased out. The global transition to a renewable energy system will have an impact on the political economy of the energy system. However, the effect will primarily come from reduced export revenues for fossil energy exporters rather than increased revenues for mineral exporters.

The DRC and to a certain degree Cuba, Chile, Madagascar and Zambia are the main exceptions with regard to the potential economic impact of increasing demand of metals and metalloids for renewable energy. Here the potential revenues from above all cobalt (and for Chile from lithium) will be significant, with the potential opportunities and risks that follow from that. The institutional development of the major exporters will be important to foster sustainable development and avoid the continuation and amplification of current problems.

Mineral revenues can be important for sub-state actors and for regional tax revenues. It can also provide funding opportunities for belligerent groups in conflict areas. According to Ref. [69] this is most likely to occur if the resource is “loothable”, i.e. combining high value per weight and volume and possibility for artisanal mining. Cobalt is therefore more likely to be a conflict mineral than minerals requiring industrial separation processes (e.g. rare earths), produced in small quantities as by products (e.g. indium) or those that have a much lower value (e.g. copper).

Recycled material is insufficient to meet the growing demand in the short to medium term, if the use of renewable energy continues to increase. By mid-2040's, recycled material can meet a growing share of demand causing the demand for virgin materials to reach a plateau and then decline. This will be the case if the technology stock in society grows less rapidly, metal intensity reduces as a result of technological development and recycling increases from today's level. This would enable the number of supply sources to increase over time as well as the proximity to end users. This is the opposite development compared to that of oil reserves that deplete and the remaining reserves are mostly found in remote locations, such as deep offshore. An interesting aspect is that the countries exporting virgin materials might lose significantly of an increase in recycling both due to falling quantities and a downward pressure on price. The interaction between recycling and geopolitics is an area that would benefit from further studies.

There are several methodological problems when trying to evaluate future geopolitical implications of the energy transitions. First, the geopolitical implications depend on the general geopolitical developments, the strategies of central political powers, the long-term development of the global economies and the institutional development of individual states. All of these aspects are inherently difficult to predict. What our study provides, however, are indications what types of and where potential risks and opportunities can arise following the low carbon transition. Hopefully that can provide useful information when designing low carbon systems that are resilient to future geopolitical challenges.

---

[9] “Could” does not, however, necessarily mean “will” as the recycling industry might choose the location abroad due to costs, environmental legislation etc.

[10] Some historic examples of substitutability: In the 1970s′ the first commercial permanent magnets that contained REE (samarium-cobalt magnets, Sm–Co) were introduced to the market. Supply issues of cobalt resulted in higher prices at the end of the decade and neodymium-iron-boron (NdFeB) magnets were invented as a response in early 1980's. NdFeB-magnets replaced Sm-Co-magnets in most applications due to lower cost and higher strength (however less corrosion resistant and heat tolerant). Platinum and palladium have been substituted in catalysts as response to changes in relative price. Copper has to a great extent been replaced by aluminium in transmission wires. Copper has also been replaced by fibre optics in information transmission infrastructures.

Second, in this study we have taken our starting point in current reserves. This is a simplification but it gives a first indication on future geopolitical implications of the increasing demand for metals and metalloids in the scenarios. However, as Habib et al. [40] note "The future geopolitical supply risk is less dependent on the present production distribution and more dependent on the location of current geological resources and the future discoveries, as well as on the technological development to improve profitability of mining the currently sub-economical resources". One example where the location of resources differs significantly from reserves is lithium, which is widely spread in the oceans (see e.g. Ref. [60]). The development of technologies for utilising these resources economically would significantly reduce the dependence of current suppliers but introduce new aspects into the geopolitics of the oceans.

Third, our results are based on one specific energy transition scenario, the IEA beyond 2° scenario. There are other possible pathways with other technological mixes, which for example include a larger share of fuel cells. This could increase the demand of other resources such as platinum at the expense of lithium and affect the revenues for countries that possess these resources.

Finally, in this study resource revenues for 18 countries have been estimated and compared with the countries' current GDP. Only five countries were identified as having the potential to obtain revenues above 5%. Future research could analyse which resource rents and export revenues these countries could gain from this. Also, sensitivity analysis could be conducted for different levels of GDP growth and prices.

To summarise, many metals and metalloids used in renewable energy technologies are more concentrated than oil. Disruptions caused by antagonistic attacks or natural disasters can have short term impacts on market supply and affect production of certain renewable technologies. However, most metals are less likely to provide producers with political leverage and bargaining power, as the importers' adaptive responses, in the medium to long term, would make such behaviour less succesful.

Acknowledgements

This publication is a deliverable of MISTRA GEOPOLITICS, which is funded by the MISTRA – The Swedish Foundation for Strategic Environmental Research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2019.100394.

References

[1] J. Barnes, A.M. Jaffe, The Persian Gulf and the geopolitics of oil, Survival 48 (2006) 143–162 https://doi.org/10.1080/00396330600594348.
[2] J.D. Colgan, Fueling the fire: pathways from oil to war, Int. Secur. 38 (2013) 147–180 https://doi.org/10.1162/ISEC_a_00135.
[3] B. Johansson, A broadened typology on energy and security, Energy 53 (2013) 199–205 https://doi.org/10.1016/j.energy.2013.03.012.
[4] A. Månsson, Energy, conflict and war: towards a conceptual framework, Energy Res. Soc. Sci. 4 (2014) 106–116 https://doi.org/10.1016/j.erss.2014.10.004.
[5] IEA,, World Energy Outlook, OECD, Paris, 2017.
[6] B. Kruyt, D.P. van Vuuren, H.J.M. de Vries, H. Groenenberg, Indicators for energy security, Energy Policy 37 (2009) 2166–2181 https://doi.org/10.1016/j.enpol.2009.02.006.
[7] L. Chester, Conceptualising energy security and making explicit its polysemic nature, Energy Policy 38 (2010) 887–895 https://doi.org/10.1016/j.enpol.2009.10.039.
[8] F. Ciută, Conceptual notes on energy security: total or banal security? Secur. Dialogue 41 (2010) 123–144 https://doi.org/10.1177/0967010610361596.
[9] B. Johansson, Security aspects of future renewable energy systems–A short overview, Energy 61 (2013) 598–605 https://doi.org/10.1016/j.energy.2013.09.023.
[10] A. Månsson, A resource curse for renewables? Conflict and cooperation in the renewable energy sector, Energy Res. Soc. Sci. 10 (2015) 1–9 https://doi.org/10.1016/j.erss.2015.06.008.
[11] D. Scholten, R. Bosman, The geopolitics of renewables; exploring the political implications of renewable energy systems, Technol. Forecast. Soc. Chang. 103 (2016) 273–283 https://doi.org/10.1016/j.techfore.2015.10.014.
[12] S. Paltsev, The complicated geopolitics of renewable energy, Bull. At. Sci. 72 (2016) 390–395 http://doi.org/10.1080/00963402.2016.1240476.
[13] D. Scholten, The Geopolitics of Renewables, Lecture Notes in Energy 61, Springer, Cham, Switzerland, 2018.
[14] A. Månberger, B. Stenqvist, Global metal flows in the renewable energy transition: exploring the effects of substitutes, technological mix and development, Energy Policy 119 (2018) 226–241 https://doi.org/10.1016/j.enpol.2018.04.056.
[15] M. Riddle, C.M. Macal, G. Conzelmann, T.E. Combs, D. Bauer, F. Fields, Global critical materials markets: an agent-based modeling approach, Resour. Policy 45 (2015) 307–321 http://doi.org/10.1016/j.resourpol.2015.01.002.
[16] J.D. Wilson, Whatever Happened to the Rare Earths Weapon? Critical Materials and International Security in Asia, Asian Security, 2017, pp. 1–16 http://doi.org/10.1080/14799855.2017.1397977.
[17] D.S. Abraham, The Elements of Power. Gadgets, Guns, and the Struggle for a Sustainable Future, Yale University Press, New Haven and London, 2015.
[18] K. Veronese, Rare. The High-Stakes Race to Satisfy Our Need for the Scarcest Metals on Earth, Prometheus Books, Amherst, New York, 2015.
[19] P. Klossek, J. Kullik, K.G. van den Boogaart, A systemic approach to the problems of the rare earth market, Resour. Policy 50 (2016) 131–140 http://doi.org/10.1016/j.resourpol.2016.09.005.
[20] S. Kalantzakos, China and the Geopolitics of Rare Earts, (2018) Oxford Scholarship Online https://doi.org/10.1093/oso/9780190670931.001.0001.
[21] K. Smith Stegen, Redrawing the geopolitical map: international relations and renewable energies, in: D. Scholten (Ed.), The Geopolitics of Renewables. Lecture Notes in Energy 61, Springer, Cham, Switzerland, 2018.
[22] M.D. Bazilian, The mineral foundation of the energy transition, Extr. Ind. Soc. 5 (2018) 93–97 http://doi.org/10.1016/j.exis.2017.12.002.
[23] D. Finon, C. Locatelli, Russian and European gas interdependence: could contractual trade channel geopolitics? Energy Policy 36 (2008) 423–442 http://doi.org/10.1016/j.enpol.2007.08.038.
[24] D. Gately, Strategies for OPEC's pricing and output decisions, Energy J. 16 (1995) 1–38.
[25] M.I. Khan, Falling oil prices: causes, consequences and policy implications, J. Pet. Sci. Eng. 149 (2017) 409–427 http://doi.org/10.1016/j.petrol.2016.10.048.
[26] J. Mercille, The radical geopolitics of US foreign policy: the 2003 Iraq War, Geojournal 75 (2010) 327–337 https://doi.org/10.1007/s10708-008-9253-6.
[27] D. Stokes, S. Raphael, Global Energy Security and American Hegemony, The John Hopkins University Press, Baltimore, 2010.
[28] S. Peters, Coercive western energy security strategies: 'resource wars' as a new threat to global security, Geopolitics 9 (2004) 187–212 https://doi.org/10.1080/14650040412331307882.
[29] K. Smith Stegen, Deconstructing the "energy weapon": Russia's threat to Europe as case study, Energy Policy 39 (2011) 6505–6513 https://doi.org/10.1016/j.enpol.2011.07.051.
[30] S. Bouzarovski, M. Bassin, Energy and identity: imagining Russia as a hydrocarbon superpower, Ann. Assoc. Am. Geogr. 101 (2011) 783–794 https://doi.org/10.1080/00045608.2011.567942.
[31] M. Humphreys, Natural resources, conflict, and conflict resolution: uncovering the mechanisms, J. Confl. Resolut. 49 (2005) 508–537 http://doi.org/10.1177/0022002705277545.
[32] J.C. Orihuela, Institutions and place: bringing context back into the study of the resource curse, J. Inst. Econ. 14 (2018) 157–180 http://doi.org/10.1017/s1744137417000236.
[33] P. Collier, A. Hoeffler, Greed and grievance in civil war, Oxf. Econ. Pap. 56 (2004) 563–595 https://doi.org/10.1093/oep/gpf064.
[34] W.M. Corden, Booming sector and Dutch disease economics: survey and consolidation, Oxf. Econ. Pap. 36 (1984) 359–380 http://doi.org/10.1093/oxfordjournals.oep.a041643.
[35] M. Basedau, J. Lay, Resource curse or rentier peace? The ambiguous effects of oil wealth and oil dependence on violent conflict, J. Peace Res. 46 (2009) 757–776 https://doi.org/10.2307/25654495.
[36] J.D. Fearon, Primary commodity exports and civil war, J. Confl. Resolut. 49 (2005) 483–507 http://doi.org/10.1177/0022002705277544.
[37] K.J. Hancock, B.K. Sovacool, International political economy and renewable energy: hydroelectric power and the resource curse, Int. Stud. Rev. vix058, (2018) 1–18 http://doi.org/10.1093/isr/vix058.
[38] L. Eisgruber, The resource curse: analysis of the applicability to the large-scale export of electricity from renewable resources, Energy Policy 57 (2013) 429–440 https://doi.org/10.1016/j.enpol.2013.02.013.
[39] T. Van de Graaf, A. Verbruggen, The oil endgame: strategies of oil exporters in a carbon-constrained world, Environ. Sci. Policy 54 (2015) 456–462 https://doi.org/10.1016/j.envsci.2015.08.004.
[40] K. Habib, L. Hamelin, H. Wenzel, A dynamic perspective of the geopolitical supply risk of metals, J. Clean. Prod. 133 (2016) 850–858 http://doi.org/10.1016/j.jclepro.2016.05.118.
[41] M.d. Ridder, The Geopolitics of Mineral Resources for Renewable Energy Technologies, The Hague Centre for Strategic Studies (HCSS), Haag, 2013.
[42] M. O'Sullivan, I. Overland, D. Sandalow, The Geopolitics of Renewable Energy, Columbia University, New York, 2017.
[43] S. Deetman, S. Pauliuk, D.P. van Vuuren, E. van der Voet, A. Tukker, Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances, Environmental science & technology, 2018, https://doi.org/10.1021/acs.est.7b05549.

[44] T. Fishman, R. Myers, O. Rios, T.E. Graedel, Implications of emerging vehicle technologies on rare earth supply and demand in the United States, Resources 7 (2018) 9 http://doi.org/10.3390/resources7010009.

[45] K. Tokimatsu, H. Wachtmeister, B. McLellan, S. Davidsson, S. Murakami, M. Höök, R. Yasuoka, M. Nishio, Energy modeling approach to the global energy-mineral nexus: a first look at metal requirements and the 2°C target, Appl. Energy 207 (2017) 494–509 http://doi.org/10.1016/j.apenergy.2017.05.151.

[46] E. Hache, Do renewable energies improve energy security in the long run? Int. Econ. (2018), http://doi.org/10.1016/j.inteco.2018.01.005.

[47] D. Crieckemans, Geopolitics of the renewable energy game and its potential impact upon global power relations, in: D. Scholten (Ed.), The Geopolitics of Renewables. Lecture Notes in Energy 61, Springer, Cham, Switzerland, 2018.

[48] IEA, Energy Technology Perspectives, OECD, Paris, 2017.

[49] T. Brown, Measurement of mineral supply diversity and its importance in assessing risk and criticality, Resour. Policy 58 (2018) 202–218 http://doi.org/10.1016/j.resourpol.2018.05.007.

[50] USGS, Mineral commodity summaries 2018, U.S. Geological Survey, Reston, 2018http://doi.org/10.3133/70194932.

[51] F. Wall, Rare earth elements, in: G. Gunn (Ed.), Critical Metals Handbook, Wiley, Oxford, 2014, pp. 312–339.

[52] D. Jasiński, J. Meredith, K. Kirwan, The life cycle impact for platinum group metals and lithium to 2070 via surplus cost potential, Int. J. Life Cycle Assess. 23 (2017) 773–786 https://doi.org/10.1007/s11367-017-1329-4.

[53] M. Lokanc, R. Eggert, M. Redlinger, The Availability of Indium: the Present, Medium Term, and Long Term, National Renewable Energy Laboratory (NREL), Golden, 2015.

[54] A. Elshkaki, T.E. Graedel, L. Ciacci, B.K. Reck, Resource Demand Scenarios for the Major Metals, Environmental science & technology, 2018, http://doi.org/10.1021/acs.est.7b05154.

[55] H.U. Sverdrup, K.V. Ragnarsdottir, D. Koca, An assessment of metal supply sustainability as an input to policy: security of supply extraction rates, stocks-in-use, recycling, and risk of scarcity, J. Clean. Prod. 140 (2017) 359–372 http://doi.org/10.1016/j.jclepro.2015.06.085.

[56] B. Zhou, Z. Li, C. Chen, Global potential of rare earth resources and rare earth demand from clean technologies, Minerals 7 (2017) 203 http://doi.org/10.3390/min7110203.

[57] T.T. Werner, G.M. Mudd, S.M. Jowitt, The world's by-product and critical metal resources part III: a global assessment of indium, Ore Geol. Rev. 86 (2017) 939–956 https://doi.org/10.1016/j.oregeorev.2017.01.015.

[58] G.M. Mudd, S.M. Jowitt, T.T. Werner, Global platinum group element resources, reserves and mining - a critical assessment, Sci. Total Environ. 622–623 (2018) 614–625 https://doi.org/10.1016/j.scitotenv.2017.11.350.

[59] E. Antolini, S.C. Zignani, S.F. Santos, E.R. Gonzalez, Palladium-based electrodes: a way to reduce platinum content in polymer electrolyte membrane fuel cells, Electrochim. Acta 56 (2011) 2299–2305 http://doi.org/10.1016/j.electacta.2010.11.101.

[60] A. Yaksic, J.E. Tilton, Using the cumulative availability curve to assess the threat of mineral depletion: the case of lithium, Resour. Policy 34 (2009) 185–194 http://doi.org/10.1016/j.resourpol.2009.05.002.

[61] Y. Takaya, K. Yasukawa, T. Kawasaki, K. Fujinaga, J. Ohta, Y. Usui, K. Nakamura, J.I. Kimura, Q. Chang, M. Hamada, G. Dodbiba, T. Nozaki, K. Iijima, T. Morisawa, T. Kuwahara, Y. Ishida, T. Ichimura, M. Kitazume, T. Fujita, Y. Kato, The tremendous potential of deep-sea mud as a source of rare-earth elements, Sci. Rep. 8 (2018) 5763 http://doi.org/10.1038/s41598-018-23948-5.

[62] C. Vaalma, D. Buchholz, M. Weil, S. Passerini, A cost and resource analysis of sodium-ion batteries, Nat. Rev. Mater. 3 (2018).

[63] UN, Statistical Yearbook 2018 Edition, sixty-first ed., (2018) United Nations, New York.

[64] Fund for Peace, Fragile States Index 2018, Fund for Peace, Washington D.C., 2018.

[65] B. Johansson, Climate Change, Vulnerability and Security Risks-Methodological Aspects Regarding Identification of Vulnerable Countries and Hotspots, Swedish Defence Research Agency, Stockholm, 2010.

[66] BP, BP Statistical Review of World Energy, BP p.l.c., London, 2018.

[67] D. Giurco, E. Dominish, N. Florin, T. Watari, B. McLellan, Requirements for minerals and metals for 100% renewable scenarios, in: S. Teske (Ed.), Achieving the Paris Climate Agreement Goals, Springer, Cham, 2019, pp. 437–457.

[68] J. Chung, J. Lee, Asian Battery Makers Eye Nickel Top-Up as Cobalt Price Bites, Reuters, 2017, https://www.reuters.com/article/us-southkorea-battery-cobalt/asian-battery-makers-eye-nickel-top-up-as-cobalt-price-bites-idUSKBN1AJ0S8.

[69] P. Le Billon, Wars of Plunder: Conflicts, Profits and the Politics of Resources, C. Hurst & Co., London, 2012.