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Analyzing Changes in Supply Risks for Abiotic Resources over Time with the ESSENZ Method—A Data Update and Critical Reflection

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Abstract: In the last decade, several methods were developed to determine potential supply risks due to short term socio-economic aspects. One of them is the ESSENZ method (comprehensive method to measure and assess resource efficiency of products in the context of sustainable development) developed by the authors. Due to newly available data (e.g., production statistics) the characterization factors (CFs) of the ESSENZ method were updated (based on data from the years 2011 to 2015, with focus on 2014 and 2015) and compared with the original CFs (based on data from the years 2009 to 2013, with focus on 2012 and 2013) for six of the overall eleven categories. The goal of the paper is to analyze if changes in the underlying data are adequately reflected in the CFs of ESSENZ for the considered categories. Further, the updated CFs are provided. The six categories are analyzed by comparing original and updated CFs and clustering them into four groups: declining, emerging, persistent, and non-occurring potential supply risks. Significant differences in the CFs are evaluated by analyzing changes in the underlying data as well as the steps to determine the CFs. It could be shown, that for most of the considered categories and resources changes in the underlying data are reflected adequately in the CFs. However, some methodological challenges of ESSENZ, which limit the reflection of potential supply risks changes, could also be identified.

Keywords: supply risk; socio-economic availability; criticality; abiotic resources

1. Introduction

Resource criticality has become a topic of growing interest in the last decades due to increasing incidents of supply disruptions of abiotic resources (especially metals), e.g., rare earths trade dispute between China and several other developed countries [1–3]. With abiotic resources being vital inputs for a stable economy and society, their supply disruption has been perceived as being particularly relevant [4,5]. Several methods were developed in the past, applying a variety of indicators and approaches to determine potential supply risks of abiotic resources on a micro (product) level [6] (e.g., the. Economic Resource Scarcity Potential [7], the ESSENZ method [8] (comprehensive method to measure and assess resource efficiency of products in the context of sustainable development) and the GeoPolRisk method [9,10]), on a meso (company) level (e.g., [11–13]) as well as on a macro (country) level (e.g., [14–16]). Within the UNEP/SETAC (United Nations Environment Programme/Society of Environmental Toxicology and Chemistry) Task Force "mineral resources" the topic of measuring potential supply risk in the context of life cycle assessment (LCA) was also discussed [17] and recommendations for methods and future method developments are provided [6].

As potential supply risks are caused by economic, socio-economic, geopolitical, technical, and environmental factors, they are defined as short term aspects (3–10 year timeframe [18]) and the associated indicator values have to be updated regularly to adequately reflect potential supply risks. Due to the novelty of the existing methods, few of them have been updated so far (e.g., [19,20]). These methods provide updated results but did not compare the original and updated results to determine if the differences can be explained by changes in the underlying data. By carrying out such a comparison, it can be analyzed whether supply risk changes over time can be reflected adequately by the methods. This paper focuses on the ESSENZ method developed by the authors [8,21]. Due to newly available data (e.g., production statistics or updated indicator values such as the Worldwide Governance Indicators [22]), the characterization factors (CFs) were updated (with data from the years 2011 to 2015, with focus on 2014 and 2015) and are compared with the original CFs published with the corresponding paper [8] in 2016 (based on data from the years 2009 to 2013, with focus on 2012 and 2013). Both sets of CFs can be found under the following link: https://www.see.tu-berlin.de/menue/forschung/ergebnisse/essenz/parameter/en/.

The goal of the paper is to analyze if changes in the underlying data of the updated CFs (for selected categories) are adequately reflected in the CFs of ESSENZ or whether the ESSENZ methodology masks these changes and no significant differences in the CFs can be observed. Further, the updated CFs are provided to be applied in future case studies. To achieve this goal, an approach was developed to analyze original and updated CFs (Section 2). Next, the results and outcomes are presented (Section 3). Further, the shortcomings of the presented approach are discussed (Section 4) and finally, conclusions are drawn (Section 5).

Background—ESSENZ Method

ESSENZ assesses resource efficiency in the context of sustainable development and therefore considers environmental, social, and economic aspects. The focus of this paper is on the short-term supply risk assessment of ESSENZ (economic aspects), which has to be updated more frequently than, e.g., the long-term environmental assessment. Overall, eleven supply risk categories (*company concentration*, *coproduction*, *new material content*, *political stability*, *demand growth*, *mining capacity*, *concentration of production and reserves*, *trade barriers*, *price volatility*, and *feasibility of exploration projects*) are taken into account and potential supply risks are determined for 40 abiotic resources. A short explanation of the individual categories is given in the accompanying sections below.

The following shortly describes how the CFs of ESSENZ are determined. The CF for each resource i in category c is determined based on the ecological scarcity approach [23,24] (see Equation (1)).

$$\mathrm{CF}_{\mathrm{i,c}} = \left(\frac{\text{indicator result}_{\mathrm{i,c}}}{\text{target}_{\mathrm{c}}}\right)^2 \times \frac{1}{\text{normalization factor}} \tag{1}$$

In a first step, the indicator result of a specific resource for the considered category is calculated (as the calculation procedure differs for each category it is explained separately for each category below). In a second step, the indicator result is set in relation with the category specific target value. Each category has its individual target value based on expert judgments and stakeholder surveys (details are explained in [25]). The target value reflects the point when resources are assumed to have potential supply risks. By setting the indicator result in relation to the target value, it can be determined if a potential supply risk occurs. Calculated distance-to-target values above 1 point to potential supply risks, whereas values below 1 indicate no potential supply risks. As only potential supply risks are relevant for the analysis, distance-to-target values below 1 are set to zero to avoid a distortion of the overall results. In a third step, the distance-to-target values are normalized. The normalization factor is the global production amount of the considered resource. The global production amount is chosen for normalization to take into account the effect of the overall amount of the resource currently produced. In the fourth and last step, the CF is determined by scaling all normalized distance to target results to the overall global production amount of the considered resource portfolio $\left(7 \times 10^{13}\right)$. This step is carried out to increase the value of the CFs and enhance their applicability. The normalized distance to target values are very small (usually below 1). When these small values are multiplied with big inventory data (up to several tones), only the inventory data defined the overall results. When the CFs are scaled to higher values, the results are defined based on the CFs as well as the inventory data. When applying the CFs, they are multiplied with the inventory data of the considered product system to determine product system specific results. For each category, the results are determined separately. Aggregation of the results of the eleven categories is not allowed mostly due to the fact that currently no consensus on weighting exists [8]. Thus, every category has to be analyzed separately and trade-offs between the categories face the same challenges as other LCA case studies [26,27].

2. Method

This section describes how the updated results are analyzed to determine if changes in the underlying data are adequately reflected in the CFs. The approach (see Figure 1) starts with clustering the CFs of each category into the following four groups:

- Group 1: Declining potential supply risks: The CFs of the affected resources no longer indicate potential supply risks (after data update), i.e., these resources have an original CF above 1 (potential supply risk occurs), but have a CF of 0 (no potential supply risk) after the update
- Group 2: Emerging potential supply risks: The CFs of the affected resources indicate potential supply risks, i.e., these resources have an original CF of zero (no potential supply risks), but have a CF above one (potential supply risks occur) after the update
- Group 3: Persistent potential supply risks: The CFs of the affected resources display potential supply risks (before and after data update), i.e., these resources have an original and updated CF above 1 (potential supply risks occur);
- Group 4: Non-occurring potential supply risks: The CFs of the affected resources do not display potential supply risks, i.e., these resources have an original and updated CF of 0 (no potential supply risks occur).

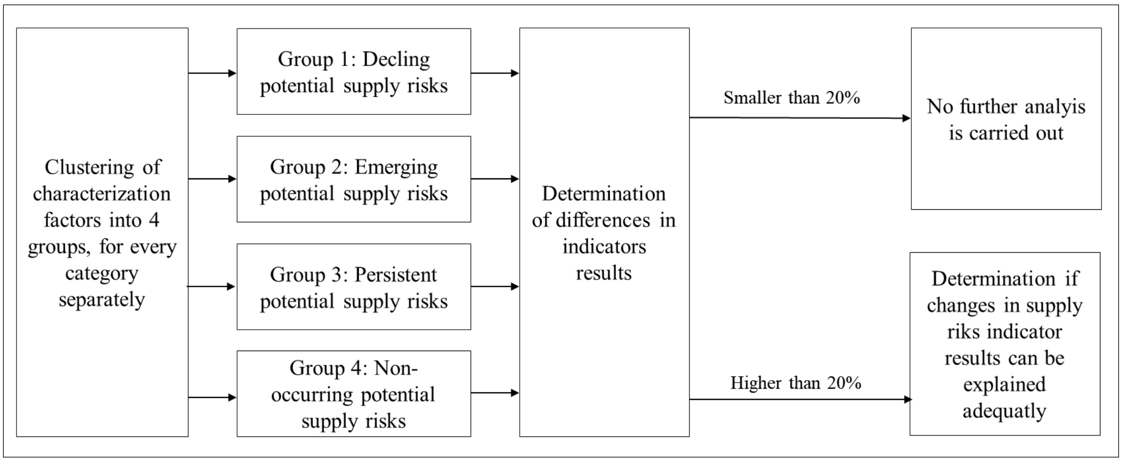


Figure 1. Approach to analyze the original and updated characterization factors (CFs) and derive results regarding their ability to adequately reflect potential supply risk changes.

Next, the four groups are analyzed separately for each category by determining the differences in the indicator results. The indicator results are chosen as the basis of comparison, because they are the first step in determining the CFs. Differences in the indicator results can be:

1. Smaller than 20% and therefore classified as not significant: in this case no further analysis is carried out, because it is assumed that small changes come from small uncertainties in the underlying data.

2. Higher than 20% and therefore classified as significant: in this case it is determined if changes in the indicator results can be explained adequately by analyzing the changes in the underlying data such as production statistics, available reserves, and category indicators (e.g., WGII (worldwide governance index) of the category *political stability*).

After the changes of potential supply risks are thoroughly evaluated within each category, meaning that for all four groups the analysis as shown in Figure 1 has been carried out, overall conclusions are drawn with regard to the ability of the CFs to reflect changes in the underlying data. If possible, reasons why the underlying data and therefore associated potential supply risks have changed are shortly addressed.

3. Results

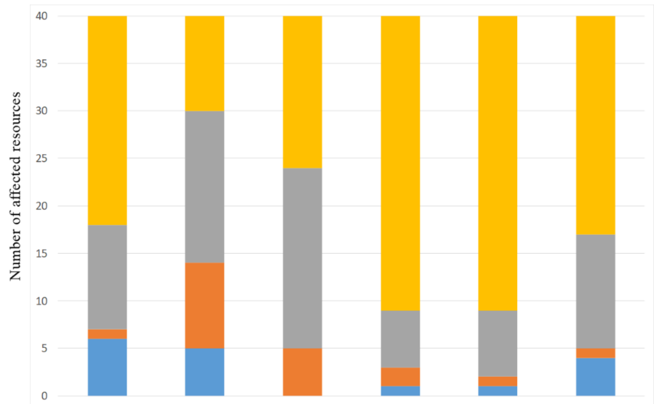
Within this section, the results of the analyses described in Section 2 are presented. Due to the extent of the analyses—considering 40 resources and six categories—only a selection of the results is presented in the paper. Additional details are shown in the Supplementary Materials. First, results of the overall analysis are presented, showing how much resources within each category are clustered in groups 1–4 and how many indicator results show differences above 20%. Then, the results of the considered categories are analyzed individually (see Sections 3.1–3.6).

Only six of the 11 categories of ESSENZ can be analyzed (see Table 1). The categories *occurrence of coproduction* and *primary material use* are not included in the analysis, because there is no updated data available. The category *company concentration* could not be updated, because data is only available in proprietary databases (e.g., SNL metals & mining database [28]). Further, as underlying data for the category *price volatility* could not be accessed, this category is excluded as well. The category *feasibility in mining explorations* can also not be updated, because the underlying indicator—the Policy Potential Index provided by the Fraser Institute [29]—has been changed to the Policy Perception Index, which still uses the same data, but determines the overall score differently [30].

Table 1. Overview of ESSENZ categories considered in the analysis and their explanations.

Categories	Considered in Analysis	Explanations
Political stability	yes	Data of United States Geological Survey (USGS) [31] and World Bank [22] are openly available
Feasibility of exploration projects	no	Underlying indicator was changed by method developers
Demand growth	yes	Data of USGS [31] are openly available
Mining capacity	yes	Data of USGS [31] are openly available
Trade barriers	yes	Data of USGS [31] as well as World Economic Forum and the Global Alliance for Trade Facilitation [32] are openly available
Concentration of reserves	yes	Data of USGS [31] are openly available
Concentration of production	yes	Data of USGS [31] are openly available
Company concentration	no	Updated data is not accessible
Occurrence of coproduction	no	Updated data is not available
Primary material use	no	Updated data is not available
Price volatility	no	Updated data is not accessible

In Figure 2, the results of the four groups for all six categories are shown. It can be seen that most resources within most categories face "persistent potential supply risks" (group 3—yellow). Exceptions are the categories *demand growth* and *mining capacity*. Group 1 "emerging potential supply risks" (blue) is relevant for only a few resources and not dominant in any category. Group 2 "declining potential supply risk" (orange) is also relevant for only a few resources and not dominant for any category. For group 4 "Non-occurring potential supply risk" (grey) results vary between the categories; within some categories, the group influences few resources (e.g., for the categories *concentration of reserves* and *production*), whereas for other categories many resources are influenced (e.g., for *mining capacity*).



	Political stability	Demand growth	Mining capacity	Concentration of reserves	Concentration of production	Trade barriers
Group 1: Newly emerging potential supply risks	6	5	0	1	1	4
Group 2: Newly declining potential supply risks	1	9	5	2	1	1
Group 3: Persistent potential supply risks	22	10	16	31	31	23
Group 4: Non-occurring potential supply risks	11	16	19	6	7	12

Figure 2. Overall results of the four groups for all six categories.

In Figure 3, the results of the four groups for the 40 considered resources are shown, according to their changing potential supply risks. Thus, it is demonstrated in which groups the resources are clustered. It can be seen that overall the implications on the declining (group 1) and emerging (group 2) potential supply risks are rather lower for all resources, whereas the implication for persistent (group 3) and non-occurring (group 4) potential supply risks are higher. This means that in most cases, changes of the potential supply risks due to changes of underlying data did not change the resource's original criticality evaluation.

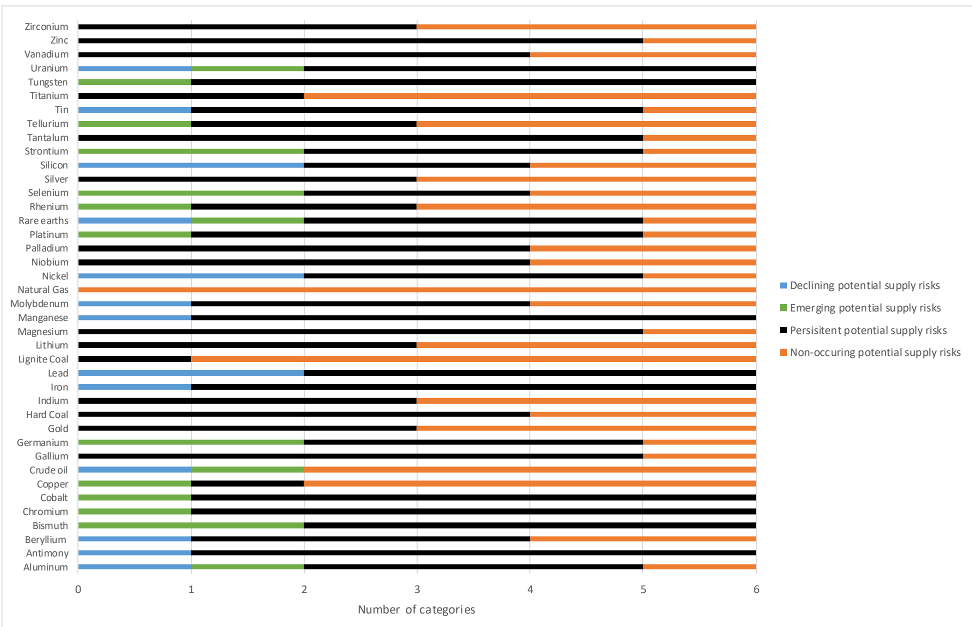


Figure 3. Overall results of the four groups for the 40 considered resources.

3.1. Political Stability

The category *political stability* assesses the governance stability of ore producing countries. To quantify it, the worldwide governance index (WGII) was developed, which is determined by obtaining the average of the six worldwide governance indicators [22,33]. For every resource x the indicator result is calculated by multiplying the country i based WGII with the global production shares and summing them up (see Equation (2)).

$$\text{Indicator result}_x = \sum \text{WGII}_i \times \text{global production shares}_{i,x} \tag{2}$$

Overall, six resources show a "declining potential supply risks" (group 1). These resources do not have a potential supply risk based on the updated CF, but had one based on the original CF. This means they no longer face potential supply risks because the governmental performance (political stability) of the mining countries improved. To determine how significant the differences are the indicator results are compared (see Table S1). As the differences of the original and updated indicator result are smaller than 20% for all affected resources, no further analysis is carried out. However, to better understand why a change from "having a potential supply risk" to "not having a potential supply risk" can even be classified as not significant, the original and updated indicator results of the six affected resources are set in relation to the target value of 1.9 (see Figure 4). It can be seen that the original indicator results are only slightly above the target value, whereas the updated indicator results are slightly below. Even though the change in the indicator results are not that significant, the implication on the result is substantial. Thus, it can be concluded that for this category, changes in underlying data cannot be properly reflected by ESSENZ.

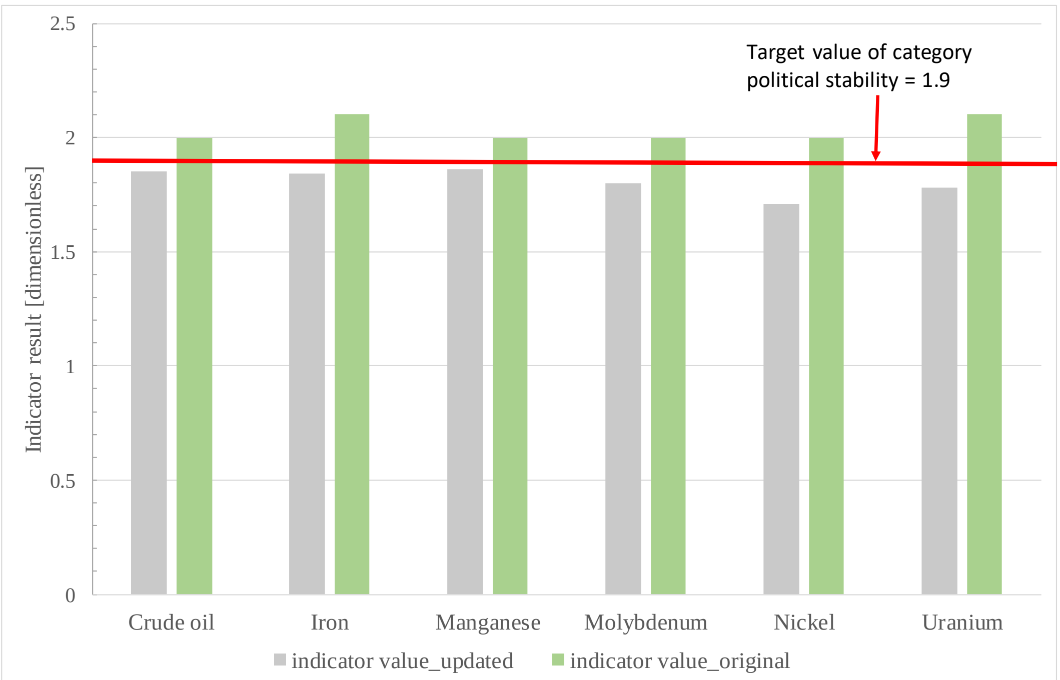


Figure 4. Original and updated indicator results of crude oil, iron, manganese, molybdenum, nickel, and uranium, set in relation to the category-specific target value.

Overall, 22 resources show a "persistent potential supply risk" (group 3). For these resources, both the original and updated indicator results imply a potential supply risk. Thus, the governmental performance of the countries, where these resources are mined, has not been improving to a point, where potential supply risks are no longer expected. The indicator results are compared to determine how significant the differences are (see Table S1). It can be seen that only for strontium the difference is higher than 20%, whereas for all other 21 affected resources the differences are smaller than 20%. Thus, for strontium the underlying data—here: Changes of resource production as well as the WGII for the years 2012/13 vs. 2014/15—are analysed further (see Table 2). It can be seen that the production increased from 0% to 35% in Iran, whereas it decreased by almost 30% in Spain. As the category indicator (WGII) is much higher for Iran than it is for Spain [22] the increase of the indicator result for strontium can be explained.

Table 2. Overview of strontium mining countries and their associated global production shares in 2012/2013 and 2014/2015 based on data by [22,31,34].

Strontium Mining Countries	Global Percentage of Mining Production 2012/2013 in Percentage	Global Percentage of Mining Production 2014/2015 in Percentage	World Governance Index (WGII) Based on Data from 2013 (Dimensionless)	World Governance Index (WGII) Based on Data from 2015 (Dimensionless)
Argentina	1.50	1.85	2.48	2.42
China	36.00	33.36	2.66	2.50
Mexico	12.00	9.05	2.27	2.32
Iran	0.00	35.21	3.24	3.02
Morocco	0.75	0.00	2.46	2.31
Spain	49.55	20.53	1.30	2.16

The results of the other groups are shown in the supplementary material—Section S.1.1.

Overall, approximately half of the resources (23 out of 40) still face potential supply risks and half (24 out of 40) show an increase in potential supply risks, meaning that the political instability of mining countries has increased over the last years. This can be underlined by other studies addressing the current political instability of countries in Latin America (e.g., [35–37]) and Africa (e.g., [38–40]), where many resources are produced.

Considering the analysis of the four groups, it can be stated that changes in the CFs of ESSENZ consider the underlying data. However, by setting the distance-to-target values below one to zero the CFs of ESSENZ are inherently not designed to reflect changes in potential supply risks below the criticality threshold. This analysis has shown that data changes around the threshold react sensitively to data updates, if either the previous or the updated values were just below or above the threshold. In such situations, relatively small changes in the data lead to a significant difference in the CFs.

3.2. Demand Growth

The category *demand growth* assesses the uncertainty (i.e., increase) in demand growth (in ESSENZ an increase of 5% and more is considered critical), which might lead to potential supply risks. When the demand is significantly higher than the actual production, potential supply risks might occur due to mines not being able to increase their production accordingly. The category indicator is determined for resource i by calculating the production increase (or decrease) over the last five years (with n = 2008 for the original CFs; with n = 2010 for the updated CFs) (see Equation (3)).

$$\text{Demand growth}_\text{i} = \frac{\sum_1^5 \left(\frac{\text{global production}_{\text{n}+1}}{\text{global production}_\text{n}} - 1 \right)}{4} \tag{3}$$

Overall, 11 resources show "emerging potential supply risk" (group 2). These resources did not face potential supply risk based on the original CFs, but face potential supply risks based on the updated CFs. For these resources, potential supply risks occur due to an increase in demand growth beyond 5%. As shown in Table S7 the differences of the indicator results are higher than 20% for nine out of 11 resources (exceptions are bismuth and chromium). This can be explained as follows:

- Platinum: increasing demand in the year 2015 by almost 30%, decrease in recent years (e.g., in 2012 by 6%) or constant production (e.g., by 0%—meaning constant production amount—in 2013).
- Tungsten: constant increase of demand over the last years with peaks in 2014 with 7% (which is only considered in the updated calculation)
- Rare earth: strong increase of demand in 2014 by 12%
- Germanium: strong increase in demand in 2013 by 23% and strong decrease in demand by 16% in 2010, which is not included in the calculation of the updated indicator result due to the considered timeframe (original: 2009–2013; updated: 2011–2015)
- Aluminum: increase of 17% in 2015 and only a constant increase of 2–4% in the years before
- Selenium: strong decrease of 19% in 2012, but a constant increase above 5% for the years 2013–2015
- Strontium: strong decrease of demand in 2012 by 39%, but strong increase in 2013 by 46%
- Tellurium: demand increased in 2011 by 23% and in 2013 by 25%

The results of other groups are presented in the supporting materials (see supplementary material—Section S.1.2).

Overall, approximately half of the resources (19 out of 40) still face potential supply risks and almost one third (27 out of 40) show an increase in potential supply risks, meaning that the growth of demand has been above 5% in the last years and therefore, more resources face potential supply risks. This can be underlined by other studies, which confirm strong demand growth; e.g., for germanium [41–43], gallium [44,45], and indium [46–48].

Even though changes in the underlying data are reflected in the CFs, the current calculation approach of ESSENZ does not adequately reflect all relevant aspects of possible supply risks due to demand growth. A sudden demand decrease/increase in one year dominates the CFs even when in the years before small decreases/increases occurred. Further, increase in resource use due to future technologies (e.g., e-mobility) in the coming years is not reflected. For example, a significant demand growth for copper by 2035 [43] is predicted, which is not reflected in the updated CFs, where copper has a CF of zero. For future method development, it should be considered if the amount of currently used resources serves as a better indicator than the production statistics. Further, by setting the distance-to-target values below one to zero the CFs of ESSENZ are not able to adequately reflect changes in potential supply risks. However, compared to the category *political stability*, this aspect is less relevant as only three resources—tungsten, chromium, and germanium (see supplementary material—Section S.1.2)—are affected by it.

3.3. Mining Capacity

The category *mining capacity* quantifies how long a reserve can be mined under current conditions (considering technological and economic feasibility) before existing mines are exhausted and no more reserves can be extracted. It takes approximately 10–15 years to open a new mine or further develop an existing one. Thus, when the capacity of existing mines only lasts for a few additional years and new mines are not under development yet, not enough mines are open to extract the desired amount of reserves. The term "reserves" refers to economically and technically extractable mineral commodities. As stated by USGS [31] the reserve data can change due to increased production, newly discovered mines, exploration of existing deposits, new technology, and improved economic feasibility. The indicator results are determined by setting the amount of a reserve x in relation to the annual production (also called static lifetime; expressed in years) (see Equation (4)).

$$\text{Static lifetime}_x = \frac{\text{Reserves}_x}{\text{Annual production}_x} \quad (4)$$

Overall five resources show "emerging potential supply risks" (group 2). These resources did not face potential supply risks based on the original CFs, but do based on the updated CFs. Potential supply risks might occur, because the time until the developed reserves are exhausted is below 50 years, which is considered as too small to guarantee that future demand can be satisfied. As shown in Table S8 the differences of the indicator results are higher than 20% for bismuth and selenium. When comparing production and reserves of bismuth in the reference years, a large increase of 3.55% in production occurred in 2015 (1030 t) compared to 2013 (290 t), whereas only a small increase of 1.2% in additionally developed reserves can be observed. For selenium the indicator result increased because the production grew by 1.7% in 2015 (3.834 t) compared to 2013 (2.254 t) and only a small increase of 1.16% in additionally developed reserves can be observed [31,34].

The results of other groups are presented in the supporting materials (see supplementary material—Section S.1.3).

Overall, approximately half of the resources (21 out of 40) still face potential supply risks and almost two third (26 out of 40) show an increase in potential supply risks. The mining boom during the years 2003 to 2012 led to an increase of mining and exploration expenditures. These challenges paired with decreasing ore grades and increasing global resource use has led to a decrease in mining explorations since 2012 [49–52].

Considering the analysis of the four groups, changes of the CFs can be explained considering the underlying data. The step of setting the distance-to-target values below one to zero leads to a not adequate reflection of potential supply risks for crude oil, cobalt, and rhenium (see supplementary material—Section S.1.3).

3.4. Concentration of Reserves

The category *concentration of reserves* reflects the distribution of reserves within countries, i.e., the number of countries where the considered reserve can be extracted (increase of countries leads to decrease of concentration) as well as their global shares in these countries (when few countries have most of the reserves, high concentration occurs). High concentrations lead to potential supply risks. The category indicator results are determined by means of the Herfindahl–Hirschmann Index (HHI) [53], using global reserve data.

Overall, 31 resources show "persistent potential supply risks" (group 3). These resources do have a potential supply risks according to the original as well as updated CFs. As shown in Table S10, the difference of the indicator results are below 20% for 25 resources and above 20% for only six resources (antimony, bismuth, chromium, molybdenum, rare earths, and strontium). For antimony, bismuth, rare earths, chromium, and strontium, the reserve concentration decreased, whereas for molybdenum it increased. As shown in Tables S12 and S17, the decrease in the reserve concentration can be explained by the exploration of reserves in additional countries (for antimony: USA, Australia, and Mexico; for bismuth: Vietnam) and therefore a more even distribution of global reserves. In case of rare earths (see Table S14), the reserve concentration decreased due to more countries (12 instead of seven) hosting these resources. The reason for the decrease of reserve concentration for chromium is a more even distribution of reserves (see Table S15). For strontium, no data are provided regarding reserves, nor are information provided if the reserves are abundantly available (as done for e.g., silicon [54]). Thus, it was decided to use strontium production data to determine reserve concentration as a rough approximation. For strontium, a decrease in the production concentration can be explained by the decrease in the production share of Spain from 50% in 2013 to 21% in 2015 (see Table S16). The increase of reserve concentration for molybdenum can be explained by the increase of global production in China from 40% to 56% (see Table S17).

The results of the other groups are presented in the supporting materials (see supplementary material—Section S.1.4).

Overall, most resources (33 out of 40) still face potential supply risks. Compared to the original CFs, only a small change in supply risks can be observed as 31 resources had and still have potential supply restrictions. These resources further show an increase in potential supply risks, meaning that the distribution of reserves diminished. This goes in line with the findings of the category mining capacity as no new deposits were developed for several reserves.

The analysis of the four groups shows that changes in the CFs can be explained considering the underlying data. Thus, the CFs can be determined as adequate to reflect changes in potential supply risks. However, the step of setting the distance-to-target values below one to zero leads to a not adequate reflection of potential supply risks for copper and uranium (see supplementary materials—Section S.1.4).

3.5. Concentration of Production

The category *concentration of production* reflects the distribution of the countries extracting ores and their shares of the global mining activities. High concentrations (meaning that only few countries produce most of the ores) can lead to potential supply risks. The category indicator results are determined by means of the Herfindahl–Hirschmann Index (HHI) [53], applying global production data.

Overall, 31 resources show "persistent potential supply risks" (group 3). These resources do have a potential supply risk based on the original as well as updated CFs. Potential supply risks occur, because the concentration of production is high (above 0.15), i.e., because the resources are mined in only a few countries. As shown in Table S18, for five (aluminum, gallium, bismuth, strontium, and tin) of the 31 resources changes in the indicator results are above 20%.

For aluminum, bismuth, gallium, and strontium, an increase in production concentration from 2013 to 2015 and therefore an increase in potential supply risks can be observed, whereas for tin, the concentration of production increased and therefore potential supply risks decreased. This can be explained as follows:

- Aluminum (see Table S19): In 2013 overall 21 countries mined aluminum, whereas in 2015 only 15 of these countries mined it;
- Bismuth (see Table S21): In 2013 most of the mining was carried out by three countries (China, Japan, and Mexico), whereas in 2015 only two countries (China and Vietnam) mined the majority of the resources;
- Gallium (see Table S20): In 2013 overall eight countries mined gallium, whereas in 2015 only three of these countries mined it;
- Strontium (see Table S22): In 2013 the three countries with the highest production share (Spain, China, and Mexico) contributed to 89% of the overall production, whereas in 2015 the three countries with the highest production share (China, Spain, Iran) contributed to 98% of the overall production
- Tin (see Table S23): In 2013 the three countries with the highest production share (Bolivia, China, and Indonesia) contributed to 77% of the overall production, whereas in 2015 the three countries with the highest production share (China, Indonesia and Myanmar) contributed to only 72% of the overall production

The results of the other groups are presented in the supporting materials (see supplementary material—Section S.1.5).

Overall, most of the resources (32 out of 40) still face potential supply risks. No big change in supply risk can be observed compared to the original CFs because 31 resources had and still have potential supply risks. However, for most of the resources (20 out of 31), the supply risks decreased, meaning that the distribution of production increased (and concentration decreased). As explained before, the production of resources shifts between countries (see Strontium) as it might no longer be economically feasible to extract from a certain mine, which is an important factor for opening and closing mines (e.g., [55–57]).

Considering the analysis of the four groups, changes in CFs can be explained by the underlying data. Thus, the ESSENZ method is adequate to reflect changes in potential supply risks.

3.6. Trade Barriers

The category *trade barriers* quantifies potential supply risks due to existing trade barriers regarding export of resources (e.g., export duty). The indicator results are determined according to the same principle as for the category "political stability" (see Equation (1)): by multiplying the resources share of global production per country with the category indicator—here the Enabling Trade Index (ETI) [32].

Overall, 12 resources show "non-occurring potential supply risk" (group 4). These resources do not have a potential supply risk based on the original as well as updated CFs because their associated trade barriers are not that high so that potential supply risks occur. As shown in Table S26, differences in the indicator results are only higher than 20% for rhenium. The decrease in potential supply risks can be explained by a relocation of global production of rhenium from Russia (3% in 2013) to China (5% in 2015) (see Table 3). Further, also the production in Uzbekistan decreased (from 11% in 2013 to 2% in 2015), whereas an increase in production occurred in Chile, Poland, and the US. Thus, the decrease in potential supply risk can be explained by the production shift as well as the associated trade barriers of these countries.

Table 3. Overview of rhenium mining countries and their associated global production shares in 2012/2013 and 2014/2015 based on data by [31,32,34,58].

Rhenium Mining Countries	Global percentage of Mining Production 2012/2013 in Percentage	Global Percentage of Mining Production 2014/2015 in Percentage	Enabling Trade Index Based on Data from 2013 (Dimensionless)	Enabling Trade Index Based on Data from 2015 (Dimensionless)
Argentina	1.50	1.85	2.48	2.42
China	36.00	33.36	2.66	2.50
Mexico	12.00	9.05	2.27	2.32
Iran	0	35.21	3.24	3.02
Morocco	0.75	0	2.46	2.31
Spain	49.55	20.53	1.30	2.16

The results of the other groups are shown in the supplementary material—Section S.1.6.

Overall, approximately half of the resources (23 out of 40) still face potential supply risks and half (24 out of 40) show an increase in potential supply risks, meaning that the trade barriers increased over the last years. Other existing studies also address the influence of trade barriers, in particular export taxes, on the supply risks of resources, since especially large manufactures use export taxes as an instrument to raise prices and exercise control on other countries [59–61].

Considering the analysis of the four groups, it can be stated that changes in the CFs can be explained considering the underlying data. However, by setting the distance-to-target values below one to zero the CFs of ESSENZ are not able to adequately reflect changes in potential supply risks for aluminium, lead, rare earth, silicon, and strontium.

4. Discussion

The applied approach to analyze if changes in underlying data are adequately reflected in the CFs has some drawbacks, which are discussed in the following.

Due to data limitations only six out of eleven categories can be analyzed. No conclusion can be drawn for the categories not analyzed with regard to the question, if changes in the underlying data are adequately reflected in the CFs of ESSENZ. Further, conclusion can only be drawn for the categories considered and not for the entire ESSENZ method.

By only analyzing differences of the indicator results above 20%, some potentially important information might not be considered, as also changes below 20% could be relevant. For some categories, the analysis includes only few resources as the differences in most indicator results are below 20%. As shown in Figure 5 for some categories like *trade barriers*, the changes in the indicator results are only above 20% for one (out of 40) resources. Thus, only this one resource is further analyzed, whereas potential supply risk changes of the other 39 resources are not further taken into account. Depending on the category, the number of resources not further considered in the analysis can vary from 39 (for trade barriers) to 11 (for demand growth).

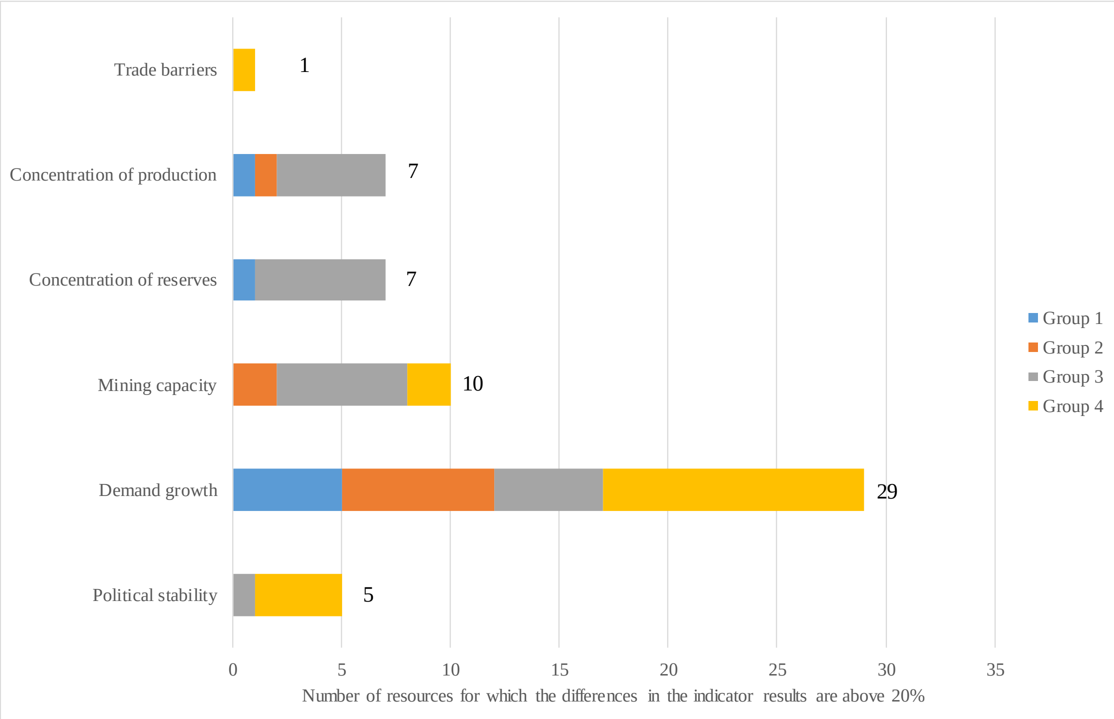


Figure 5. Overview of the considered categories and the number of resources for which the differences in the indicator result are above 20%.

Additionally, even though the analysis determines that changes in underlying data are adequately reflected in the CFs, that does not mean that the chosen indicators are capable to reflect all aspects of potential supply risks. For example, the WGIs are widely used indicators in several methodologies to assess criticality and supply risk aspects of resources (e.g., [9,20]). Thus, its reliability can be seen as high. However, the WGI also faces criticism with regard to its overall meaningfulness for all considered countries [62,63].

Further, the focus of the analysis is on the determination of the category indicators, associated indicator results, and the distance to target calculation. Another step of ESSENZ—the normalization by global production amounts—is not analyzed and effects on the ability to reflect potential supply risk changes are not included in the analysis.

As the underlying data is updated and therefore improved constantly, the results will most likely always change to a certain extent. It is not possible to determine if the change in the data can be associated with an actual change of the considered factor or if the change is only being attributed due to improved data. However, both option support an update of the CFs.

Quality and reliability of the underlying data, e.g., [22,30,31,64], is not determined. Most likely some data uncertainty will occur (this is the reason why the authors determined a change below 20% as not significant). Further, the indicators are based on data from the past years and no prognosis is taken into account. Thus, the data reflect only the current state and cannot predict future events.

5. Conclusions

Differences in potential supply risks over time (2009–2013 compared to 2011–2015) reflected in CFs (of selected categories) are analyzed. Several changes in the determined CFs (for the selected categories) are observed which underlines the necessity to update supply risks data regularly to adequately reflect changing supply risks. Within the paper it is determined that most of the underlying data are adequately reflected in the associated CFs. However, it is also determined that the applied step "set all distance-to-target results below one to zero" can lead to significant changes of the results. Thus, the ESSENZ method should be adapted accordingly to avoid potential misinterpretation. With regard to the category demand growth, the ESSENZ method should be adapted so that small changes in demand over several years are reflected in the overall result. This way, the overall trend can be better reflected. Further, future trends can be taken into account to increase the reliability of the results.

Supplementary Materials: The following are available online at http://www.mdpi.com/2079-9276/8/2/83/s1, Figure S1: Original and updated indicator result of copper and uranium, set in relation to category specific target result, Figure S2: Original and updated indicator result of aluminum, lead, rare earths, and silicon, set in relation to category specific target value based on data by [1,2,7,8], Figure S3: Original and updated indicator result of strontium, set in relation to category specific target value based on data by [1,2,7,8], Table S1: Indicator results (updated and original) of the considered resources and calculated differences comparing the indicator results for the category political stability based on data by [1–5], Table S2: Overview of the six individual worldwide governance indicator results from 2012 and 2015 for USA [3] as well as the differences in percent, Table S3: Overview of beryllium mining countries and their associated global production shares in 2012/2013 and 2014/2015 based on data by [1–3], Table S4: Overview of lithium mining countries and their associated global production shares in 2012/13 and 2014/15 based on data by [1–3], Table S5: Overview of rhenium mining countries and their associated global production shares in 2012/2013 and 2014/2015 based on data by [1–3], Table S6: Overview of tellurium mining countries and their associated global production shares in 2012/13 and 2014/15 based on data by [1–3], Table S7: Indicator results (updated and original) of the considered resources as well as calculated differences comparing the indicator results for the category demand growth based on data by [1,2,4,5], Table S8: Indicator results (updated and original) of the considered resources as well as calculated differences comparing the indicator results for the category mining capacity based on data by [1,2,4,5], Table S9: Overview of production and reserve data (original and updated) as well as differences in percentage for aluminum, gallium, lignite coal, rare earths, and strontium based on [1,2,4,5], Table S10: Indicator results (updated and original) of the considered resources as well as calculated differences comparing the indicator results for the category concentration of reserves based on data by [1,2,4,5], Table S11: Overview of countries with tin reserves and the associated global reserve shares in 2013 and 2015 based on data by [1,2], Table S12: Overview of countries with antimony reserves and the associated global reserve shares in 2013 and 2015 based on [1,2], Table S13: Overview of countries with bismuth reserves and the associated global reserve shares in 2013 and 2015 based on [1,2], Table S14: Overview of countries with rare earths reserves and the associated global reserve shares in 2013 and 2015 based on [1,2], Table S15: Overview of countries with chromium reserves and the associated global reserve shares in 2013 and 2015 based on [1,2], Table S16: Overview of countries with strontium reserves and the associated global reserve shares in 2013 and 2015 based on [1,2], Table S17: Overview of countries with molybdenum reserves and the associated global reserve shares in 2013 and 2015 based on [1,2], Table S18: Indicator results (updated and original) of the considered resources as well as calculated differences comparing the indicator results for the category concentration of production based on data by [1,2,4,5], Table S19: Overview of countries mining aluminum and the associated global production shares in 2013 and 2015 based on [1,2], Table S20: Overview of countries mining gallium and the associated global production shares in 2013 and 2015 based on [1,2], Table S21: Overview of countries mining bismuth and the associated global production shares in 2013 and 2015 based on [1,2], Table S22: Overview of countries mining strontium and the associated global production shares in 2013 and 2015 based on [1,2], Table S23: Overview of countries mining tin and the associated global production shares in 2013 and 2015 based on [1,2], Table S24: Overview of countries mining nickel and the associated global production shares in 2013 and 2015 based on [1,2], Table S25: Overview of countries mining selenium and the associated global production shares in 2013 and 2015 based on [1,2], Table S26: Indicator results (updated and original) of the considered resources as well as calculated differences comparing the indicator results for the category trade barriers based on data by [1,2,4,5,7,8].

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