Adapting the ESSENZ Method to assess company specific criticality aspects
Supplementary Material

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Content

1. Background on ESSENZ, SCARCE and CS-ESSENZ

In this regard the integrated method to assess resource efficiency (further referred to as ESSENZ) and later the approach to enhance the assessment of critical resource use on country level (further referred to as SCARCE) were developed at Technische Universität Berlin [1–4]. Thus, the deviation to the target is measured. If a materials indicator is lower than the target set for it, no concerns regarding the availability or criticality occur and be therefore set to zero. If an indicator is higher than the target value, its availability could be limited. In order to emphasize high deviations from the target - indicating lower availability and higher criticality - the ratio is squared, resulting in the distance to target value (DtT-value) [5,6] (for more details see supplementary material – Section 1.1.).

The indicators of the societal acceptance are split in two, measuring the compliance with social standards and compliance with environmental standards. These are not put in relation to a target value but squared to emphasize high values. If a negative impact is recorded, an improvement is desirable. Characterization factors (CF) for each category of the dimension availability (criticality) and societal acceptance are currently provided for 40 metals and four fossil raw materials.[1]

Determination of CFs in ESSENZ and SCARCE

The determination of CFs in ESSENZ and SCARCE can be described in five steps:

1. Determination of the indicator values as described in section **Error! Reference source not found.** and **Error! Reference source not found.** for the raw materials in the BoM.
2. For each category targets are determined (see supplementary material). These are mainly based on ESSENZ and can be adjusted by the company. The indicator values are set into

[1] https://www.see.tu-berlin.de/menue/forschung/daten_tools/essenz/parameter/en/

relation to these targets and squared (see **Error! Reference source not found.**), resulting in the Distance-to-Traget (DtT) value. As described above, a DtT-value lower than 1 stands for a target met and can therefore be set to zero. A DtT-value of 1 or greater indicates a possible constrain to availability or increased vulnerability. The higher the DtT-value the greater the impact. The choice of the target values is decisive for the final results of the assessment. Thus, target values should not be set too high or too low in order to avoid an under- or overestimation [1].

3. The DtT-values are normalized, resulting in the normalized DtT-value (nDtT-value). The global amount of annual production of the individual elements represent the normalization factors. Although this method is taking a company specific perspective, global values were chosen. Firstly, to keep consistency with ESSENZ and secondly to account for the impact of the global production on the criticality. The nDtT-value of a material produced in high amounts will be lowered greatly by such a normalization, while the nDtT-value of a material produced in smaller amounts will be decreased less. This way, the absolute global annual availability can be integrated into the characterization factors. A material produced in high amounts sets less of a supply risk than a material produced in little amounts.
4. In the final step, the nDtT-values are scaled. For reasons of consistency it was chosen to scale to same values as in ESSENZ. Here all nDtT-values are scaled to $1.7\ x\ 10^{13}$ [1]. The highest result is set to $1.7\ x\ 10^{13}$ the others CF's are scaled in accordance.

1.1. Choice of sub-categories CS-ESSENZ

The physical availability of a material does not change due to the level of assessment. It is a global value and will therefore be represented by the same characterization factors as in

ESSENZ. As no variation or changes are taken in this category it is only applied in the first step of CS-ESSENZ, when ESSENZ is applied to the BoM of the considered product system. The economic dimension is covered by the dimension criticality, which consists of supply risk, physical availability, and vulnerability. The societal dimension of the assessment includes compliance with social and environmental standards.

The SCARCE categories share of global production, utilization in future technologies and domestic required demand were excluded. Share of global production and domestic required demand are only relevant on the national level as the share of raw material imported is already reflected by dependence on imports. Utilization in future technologies is implicitly covered by demand growth and economic importance. On one hand the mass of increasing usage in future technologies is reflected in the predicted demand growth. Additionally, the indicator of economic importance is based on importance for future technologies (see section 3.2), which together with the demand growth provides information on how important a material will be in the future and how much of it is predicted to be used. This makes the category usage in future technologies redundant.

For the societal dimension only *human right abuse* and *small-scale mining* were chosen (compare **Error! Reference source not found.** to 1). The categories *conflict zone* and *geopolitical risk,* which are part of ESSENZ/SCARCE [1,2], are excluded in order not to discriminate production taking place in conflict areas. In ESSENZ and SCARCE these categories are included as profits from mining in conflict areas is often serving violent conflicts. However, especially in conflict areas stable employment status and income are generating a positive impact on the society [7–10] and should therefore not be discriminated by this method for being potentially serving violent conflicts. *Forced labor* as well as *child labor* are abuses of human rights and therefore implicitly covered by the category *human rights abuse*. At the same time, the integration of the category *human rights abuse* enables to cover a broader perspective and to include aspects like torture, violation of indigenous rights, women's rights, and other predicaments.

The indicator *human right violation* is based on data from [11]. CIRI provides human rights scores for each country and scales them from 1 to zero. For each raw material, the scores of the country of origin were weighted with the share supplied by that country. The values are not squared or modified in any other way to keep their origin as clear as possible.

The term *small-scale and artisanal mining* is not explicitly defined and will be used in this paper like in 12)[2]. *Small-scale and artisanal mining* (ASM) comes along with a variety of negative side effects for the surrounding community. Several paper address problems like child labor, crime, prostitution, conflicts and lack of security, high fatality rate, rapid spread of diseases, unsafe working tools, lack of protective clothing, lack of collateral security and further more [12–16,16–18]. The indicator for ASM is calculated as the share of a material *i* extracted in ASM based on company data. In cases of lacking information on the specific supply chain global values are applied.

For compliance with environmental standards two of the SCARCE categories: *sensitivity of local biodiversity* and *water scarcity.* These two categories were chosen as they reflect the impacts on people's daily. For the environmental impacts life cycle inventory assessment (LCIA) methods are applied.

[2] "The author defines ASM as the exploitation of marginal ore deposits, which are not profitable to mine on a large scale, through both informal and formal channels using rudimentary tools" ([12])

1.2. Additional information on some characterization factors of CS-ESSENZ

In the following listing additional information, formulas, rationales, etc. concerning some of the characterization factors of CS-ESSENZ can be found.

Sub-dimension: Supply risk

- Concentration (reserves, production, and company): A high concentration of reserves or production in specific countries as well as a high company concentration among the suppliers leads to high dependence on the suppliers. More suppliers cause more transaction costs and at the same time increase the security of supply (Melzer-Ridinger 2009). It results in a trade-off between costs and security. In some cases, the structure of the market, the geographic distribution of reserves or production is highly concentrated.
- Mining capacity: The indicator for the mining capacity is calculated using the static lifetime, regarding only the supplying countries.

$$Static\ lifetime\ suppliers_i = \sum \frac{Reserves_i}{Annual\ production_i}$$

Equation 1

- Feasibility of exploration projects: The existence of technologically accessible reserves as itself does not guarantee that raw materials can or will be extracted in practice. Political circumstances, judication, the enforcement of existing regulations, etc. can lower the interest of potential investors or make it economically impossible to mine metal *i* in country *x* [19,20].
- Occurrence of coproduction: Most metals are either mined as a main product or as a companion metal, only few metals are the main product of one mine and a co-product in another [21]. Once the main resource is exploited or is not assessable in an economic way the mine is closed. As the co-products are not the main business

of the mine, the occurrence as a companion metal raises the supply risk [21]. In ESSENZ the indicator for the occurrence as a co-product is based on qualitative data from 22) which was transferred onto a discrete scale between zero and 1.

- Trade barriers: Limitations on exports by a producing country affect companies in several ways; market prices can change due to limited access or increased taxes, companies might have to change their supplier, etc. [23,24]. Common platforms like 25 and organizations like 26) portray protectionist policy as a negative act by rating such policy with low scores in their assessments. With regard to trade promotion this might be the right evaluation, while in regard to economic stability a protectionist policy might be better for emerging and developing countries [23,24]. Within ESSENZ the Enabling Trade Index (ETI) by 26) is used to determine supply risks. The ETI consists of four pillars Market Access, Border Administration, Infrastructure and Operating Environment. The assessment result of each country in each pillar is reflected in a score. The overall ETI score of a country is the average of the scores of the four pillars.
- Demand growth: Increasing/decreasing need for a material is reflected in demand growth. Increasing global demand without simultaneously increasing production leads to rising prices and supply shortages. In most cases the production cannot react as quickly as demand changes. Due to technical, political and economic reasons new exploration projects cannot be realized on short notice. The indicator for demand growth ($DG_{i\ ESSENZ}$) in ESSENZ implies that the market for all materials is cleared, because the demand growth is calculated based on the production growth over 5 years based on data from 27) (see Equation 2) [1].

$$DG_{i,ESSENZ} = \sum_{1}^{5} \left(\frac{global\ production\ of\ year\ n+1}{global\ production\ of\ year\ n} - 1 \right) / 4$$

Equation 2

- Primary material use: The amount of primary material used in a production process can vary. It largely depends on the price of recycling and quality of recycled material. The less primary material of substance *i* is used, the lower the demand for *i* becomes. In ESSENZ, the primary material use of a metal (PMU_i) is determined by subtracting the percentage of recycled content from 100%, while the recycled content is based on 28) representing global averages.
- Price variation: The indicator result is calculated analogously to ESSENZ. Rising prices impact companies directly. They usually result from increasing demand, decreasing production, speculation, stockpiling, etc. leading to limited economic availability. Prices in metal trading contracts are usually composed of a base reference price, reflecting the market price and a negotiated premium or discount [29]. This means that long-term contracts as well as short-term contracts are affected by changes in the market price. The indicator for the impact category price variation is therefore independent from the type of contract given. Like in ESSENZ it is based on the volatility approach and data supplied by 30).

Sub dimension: Vulnerability

The vulnerability of a company regarding a specific raw material reflects its sensitivity to the supply of and dependence on the material. Over the last years vulnerability has become a topic of growing interest in the evaluation of raw material supply risk [31].

- Dependency on imports: Imported raw materials constitute a higher supply risk than domestic raw materials. Exports of raw materials can be limited due to national, political or economic interests [32]. The dependency is, therefore, an important factor for the vulnerability assessment [31]. A high share of materials imported increases the vulnerability of the regarded company.

- Purchasing strategy: In addition to negotiations and contracts between companies, the procurement of raw materials can be secured by bi- or multilateral contracts among nations. Trade among countries with close raw material diplomacy is politically more secured and can therefore be regarded as more stable.
- Substitutability: A raw material that can be substituted by another raw material can be replaced in cases of shortage or increasing prices. Thus, substitutability can reduce the vulnerability of a company [33]. Next to the technological ability to replace a material, substitutability is only given when the substitute is economically, geologically, and politically accessible. A technologically clean substitution of material a with material b, were b is very expensive, or hardly accessible does not represent a practicable substitution.

1.3. Target values CS-ESSENZ

For all criticality categories target values were defined (see Table S1). The choice of the individual target values will be shortly discussed in the following:

- <u>Occurrence of coproduction, mining capacity, political stability, feasibility of exploration projects, price variation</u>: in analogy to ESSENZ
- <u>Primary material use</u>: The indicator result is the ratio between the share of secondary material used in the production of the company and the average global secondary material usage of the material. Therefore, the target value expresses, how well the company should perform in comparison to the world average. A target of 1 = company should perform at

least as well as the world average, a target of 0,5 = the company should use no more than half of the worlds average; etc.

- Concentration: All three concentration indictors represent ratios between the HHI within the supply chain and the global HHI. A target value of 1 = the concentration of reserves/production/companies among the suppliers should be max. as high as the corresponding global concentration; a target of 0.5 = the concentration of reserves/production/companies among the suppliers should be max. as high as half of the corresponding global concentration; etc.
- Demand growth: The demand growth indicator result is the ratio of the demand trend of the company to the global production trend of the last years. A target of 1 = the demand trend of the company should not exceed the global production trend; a target of 0.5= the demand trend of the company should not exceed half the global production trend; a target of 2= the demand trend of the company should not exceed twice the global production trend; etc.
- Trade barriers: In analogy to ESSENZ but adjusted to the different scale of the indicators used

All target values can be adjusted to the priorities of the company undertaking the evaluation. They should also be revised with changing technology (e.g. new recycling technology).

Table S1: CS-ESSENZ target values criticality

Targets	Value
Occurrence of coproduction	0.25
Mining capacity	50 years
Primary material use	1
Concentrations	1
Demand growth	1
Trade barriers	2
Political stability	1.9

Feasibility of exploration projects	55
Price variation	20
Economic importance	0.25
Dependency on imports	0.50
Purchasing strategy	1.00
Substitutability	0.10

Setting up a target value for the societal acceptance (compliance with social and environmental standards) is ethically questionable. A target value reflects a state where further improvement is not necessary. It is hardly possible to set up a value for e.g. *child labor* or *climate change* from which on improvement is not needed anymore.

2. Case Study

In Table S2. background data on the case study is listed.

Table S2: Overview case study including BoM, supplying countries, share of supply by country, demand growth of importing country, recycling content in production, criticality for the functionality of the phone[3]

Material	Smart phones [kg]/unit	Supplying country 1	share in %	Supplying country 2	share in %	Supplying country 3	share in %	Supplying country 4	share in %	Supplying country 5	share in %	Own demand growth in %	Recycling content 0 to 100	Criticality for phone functionality from 0 to 1
Aluminum	0.0029	Australia	30	Brazil	40	China	30					3.00%	0	0.5
Antimony	0.000084	Australia	30	Bolivia	50	China	20					1.00%	0	0.75
Beryllium	0.000003	USA	100									1.00%	0	0.75
Cobalt	0.0063	CONGO, DEM. REP.	40	China	35	Canada	25					2.00%	0	0.75
Copper	0.014	Chile	70	Australia	30							2.00%	34	1
Glass	0.0106											1.00%	0	
Gold	0.000038	Australia	60	China	10	USA	20	Canada	10			1.00%	0	0.25
Lead	0.0006	Mexico	30	China	30	Peru	30	Australia	10			0.10%	0	0
Neodymium (REE)	0.00005	China	30	USA	20	India	25	Malaysia	25			1.00%	0	0.75
Nickel	0.0015	Canada	50	Indonesia	50							1.50%	0	0.75
Palladium	0.000015	Zimbabwe	50	Canada	50							1.00%	0	0.25
Crude oil	0.06	China	50	Canada	30	Kuwait	10	Saudi Arabia	10			1.00%	50	0.5
Platinum	0.000004	South Africa	100									1.00%	0	0.75
Praseodymium (REE)	0.00001	China	30	USA	20	India	25	Malaysia	25			1.00%	0	0.75
Silver	0.000244	China	100									1.00%	0	0.25
Steel/Iron	0.008	Brazil	90	China	10							2.00%	0	0.25
Tin	0.001	Bolivia	30	Peru	25	Indonesia	30	China	15			1.00%	100	0.25
Zinc	0.001	Australia	30	India	10	China	20	Bolivia	10	Ireland	30	1.50%	0	0.25

In 2011 Materion Corp. was the only beryllium producer in the USA and accounted for 91% of the world production [40] which accounts for a HHI of 8281.

[3] Based on Apple 2017, 2018; [34],[35],[36],[37],[38],[39],[22].

3. Results ESSENZ

Table S3 shows the results for the case study applying ESSENZ.

Table S3: Results ESSENZ

Category/ Element	*Crude oil*	*Aluminum*	*Antimony*	*Beryllium*	*Lead*	*Cobalt*	*Iron*	*Gold*	*Copper*	*Nickel*	*Palladium*	*Platinum*	*REE*	*Silver*	*Zinc*	*Tin*
Political stability	0.00E+00	8.34E+04	1.72E+06	0.00E+00	2.09E+05	1.52E+08	0.00E+00	2.43E+07	0.00E+00	0.00E+00	3.29E+07	3.81E+07	1.07E+06	1.74E+07	1.34E+05	8.77E+06
Demand growth	0.00E+00	3.54E+04	0.00E+00	0.00E+00	0.00E+00	4.23E+07	2.33E+03	0.00E+00	0.00E+00	1.35E+06	0.00E+00	9.42E+06	2.96E+05	0.00E+00	0.00E+00	0.00E+00
Mining capacity	6.63E+01	0.00E+00	6.27E+04	5.10E+07	4.54E+03	2.28E+05	4.68E+01	4.26E+05	6.13E+03	6.10E+03	0.00E+00	0.00E+00	0.00E+00	2.44E+05	3.23E+03	1.86E+05
Concentration of reserves	0.00E+00	4.78E+03	1.36E+05	2.97E+07	2.31E+04	1.35E+07	2.44E+02	0.00E+00	8.44E+04	0.00E+00	5.95E+07	6.80E+07	9.57E+04	0.00E+00	8.30E+03	0.00E+00
Concentration of production	0.00E+00	2.30E+04	1.03E+06	3.96E+07	3.80E+04	2.28E+07	7.15E+02	0.00E+00	0.00E+00	0.00E+00	7.10E+06	3.17E+07	9.59E+05	0.00E+00	1.03E+04	7.23E+05
Trade barriers	0.00E+00	0.00E+00	1.81E+06	0.00E+00	0.00E+00	2.09E+08	7.22E+03	3.81E+07	0.00E+00	2.36E+06	5.61E+07	6.80E+07	0.00E+00	2.60E+07	2.16E+05	1.07E+07
Feasibility of exploration projects	1.51E+05	4.23E+05	0.00E+00	0.00E+00	0.00E+00	3.20E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Price volatility	4.69E+04	0.00E+00	4.04E+05	1.47E+07	7.67E+04	0.00E+00	3.79E+03	0.00E+00	0.00E+00	4.44E+05	2.38E+07	0.00E+00	1.09E+06	0.00E+00	4.64E+04	0.00E+00
Occurrence of coproduction	0.00E+00	0.00E+00	5.41E+04	1.19E+06	1.11E+04	1.60E+07	0.00E+00	0.00E+00	6.67E+04	6.56E+04	6.98E+06	1.94E+06	1.74E+05	3.34E+06	6.93E+03	0.00E+00
Primary material use	1.70E+04	0.00E+00	5.27E+05	1.10E+07	0.00E+00	2.43E+07	0.00E+00	7.39E+06	4.54E+05	0.00E+00	0.00E+00	0.00E+00	5.68E+05	5.83E+06	5.61E+04	2.20E+06
Company concentration	5.24E+02	0.00E+00	3.93E+05	1.16E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.13E+06	8.18E+05	3.68E+05	0.00E+00	0.00E+00	0.00E+00

In Figure S1 the second format of the results for the supply risk is shown: here the overall results of each material are set to 100%. This way it can be pointed out, which category influences the overall supply risk of each resource the most. A low feasibility of exploration projects is the main restrictions to crude oil and aluminum supply. The low feasibility of exploration projects is a result of the political situation in the mining regions. Antimony's supply is nearly equally affected by trade barriers and by political stability, followed by concentration of production. Beryllium is the only element in the product, that is significantly impacted by low mining capacity, followed by concentration of production and concentration of reserves. Low political stability has the biggest impact on the supply risk of lead, while the cobalt supply is mainly affected by the feasibility of exploration projects and trade barriers. More than 70% of the impact on copper results from primary material use. Palladium and platinum are both mainly impacted by concentration of reserves and trade barriers. The supply risk of rare earth elements is driven by political stability, price variation and concentration of production. The supply risk of iron, gold, nickel, silver, zinc, and tin is most likely to be affected by trade barriers. Overall trade barriers, low political stability and high price variation are each restricting the supply risk of 10 elements in the case study, while feasibility of exploration projects, concentration of reserves or mining capacity are only relevant to 2-3 materials each. The results for (non) compliance with social and environmental standards are presented in Figure S3. Cobalt, crude oil and iron perform worst, followed by aluminum and copper. All metals are mainly mined in countries with a low political stability and a high rate of human right abuses.

The results for *(non) compliance with environmental standards* are presented in Figure S4. Cobalt, crude oil and iron perform worst, followed by aluminum and copper. These metals are mainly mined in countries with a low political stability and a high rate of human right abuses (Brazil, China, Democratic Republic of Congo, Saudi Arabia, and others). Figure S3 displays the ESSENZ results of *(non) compliance with social standards*. Due to the situation in the countries of origin crude oil has the lowest compliance followed by cobalt, copper, iron, and aluminum.

Figure S2 displays the results for the *physical availability* of the resources in the case in form of the Abiotic Depletion Potential (ADP) indicator, showing that gold and crude oil have a much higher risk of restricted geological availability than any other included commodities. In comparison to the ADP of gold and crude oil, the other metals' results are minor.

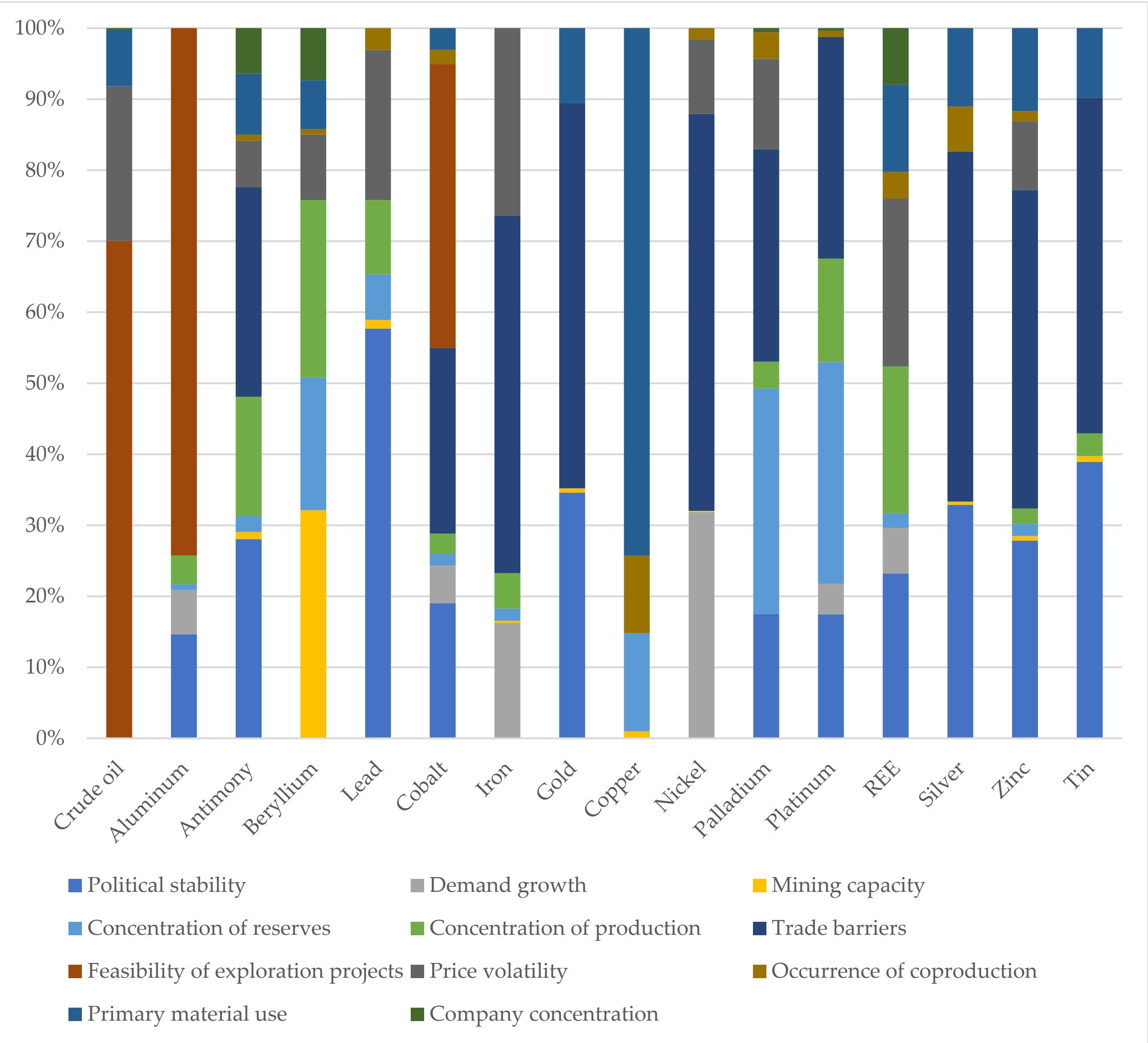

Figure S1: ESSENZ results – supply risk by element

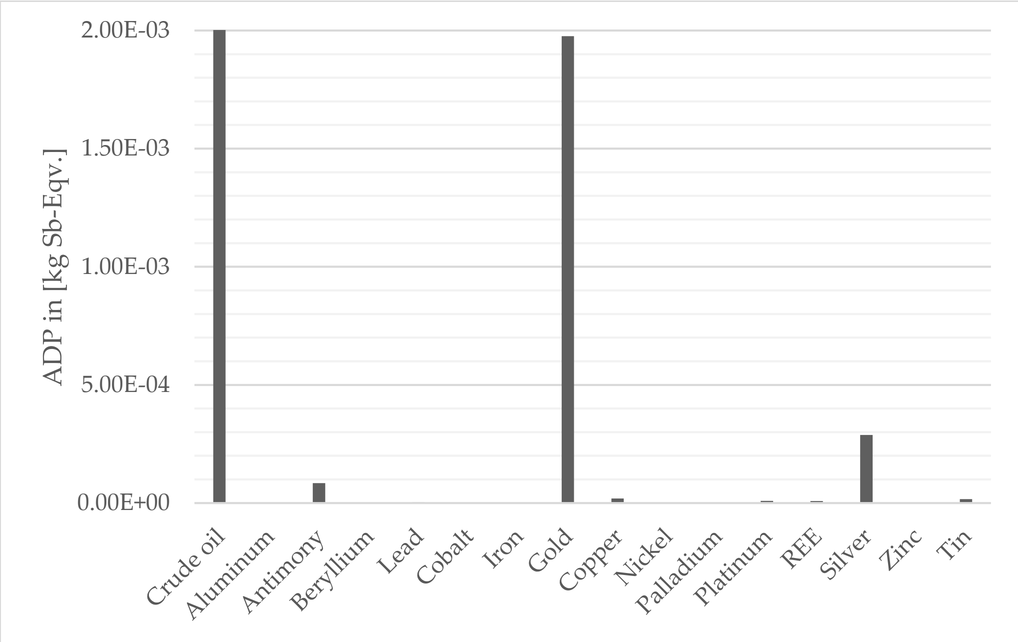

Figure S2: ESSENZ results - Physical availability

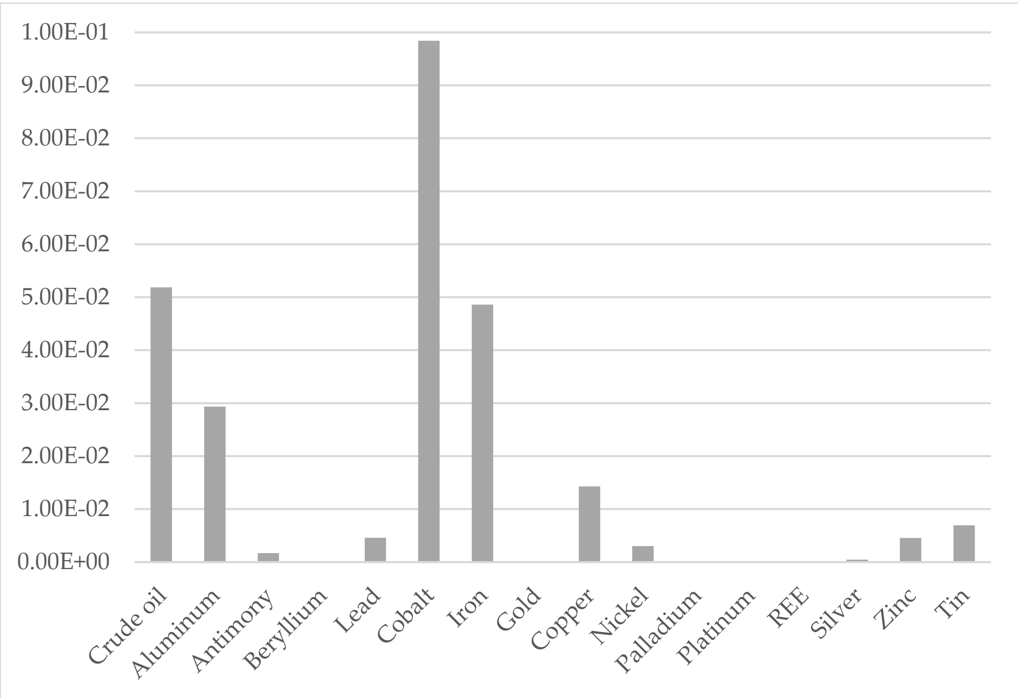

Figure S3: ESSENZ results - (Non) compliance with social standards

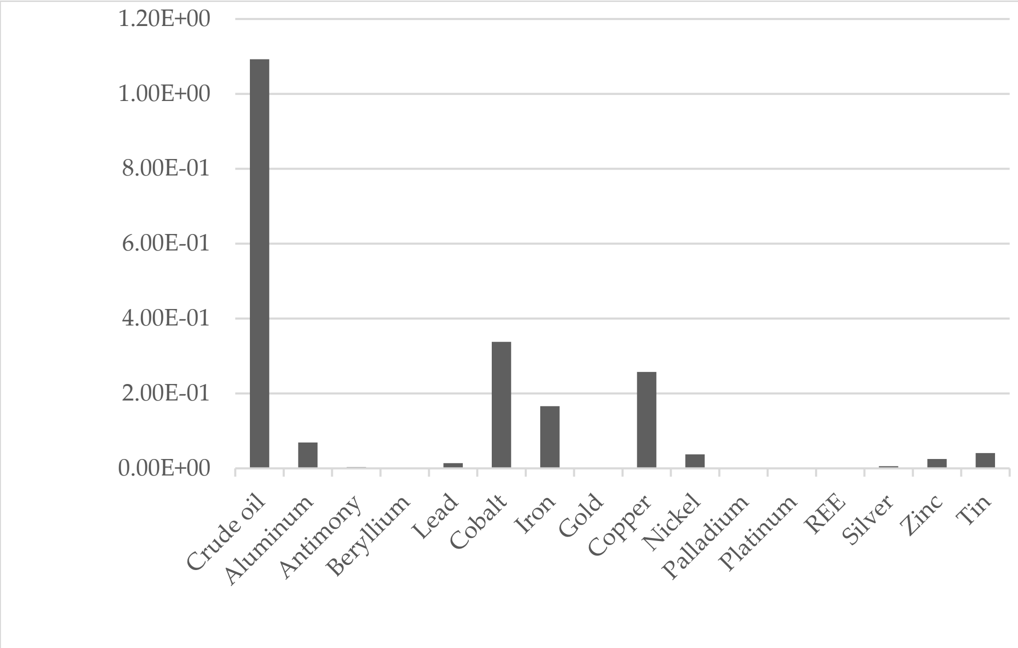

Figure S4: ESSENZ results - (Non) compliance with environmental standards

4. Characterization factors for CS-ESSENZ

Table S4 shows the characterization factors calculated for the case study.

Table S4: CS-ESSENZ characterization factors for case study

Category	*Crude oil*	*Aluminum*	*Antimony*	*Beryllium*	*Lead*	*Cobalt*	*Iron*	*Gold*	*Copper*	*Nickel*	*Palladium*	*Platinum*	*REE*	*Silver*	*Zinc*	*Tin*
Political stability	0.00E+00	4.92E+07	2.52E+07	0.00E+00	8.81E+08	5.63E+10	1.42E+06	0.00E+00	0.00E+00	0.00E+00	1.39E+13	1.68E+13	2.46E+10	2.13E+11	0.00E+00	1.66E+10
Demand growth	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.68E+13	0.00E+00	0.00E+00	4.06E+08	0.00E+00
Mining capacity	0.00E+00	0.00E+00	4.85E+05	1.16E+13	1.06E+07	2.62E+07	3.66E+03	1.16E+10	0.00E+00	2.46E+06	1.87E+10	1.68E+13	0.00E+00	2.50E+09	2.82E+06	3.24E+08
Concentration of reserves	5.13E-03	2.56E-01	2.98E-02	1.15E+04	9.55E-01	8.76E+01	5.00E-03	4.45E+03	9.13E-01	1.38E+01	0.00E+00	1.68E+13	1.17E+02	3.01E+03	6.89E-01	2.90E+01
Concentration of production	2.19E+09	1.24E+08	1.71E+10	6.26E+12	1.74E+09	6.45E+10	3.68E+06	7.76E+12	1.32E+09	2.78E+10	1.68E+13	4.53E+12	1.50E+10	3.00E+12	4.46E+08	1.05E+10
Trade barriers	0.00E+00	0.00E+00	3.83E+06	0.00E+00	0.00E+00	2.45E+10	2.23E+05	1.54E+12	3.08E+08	1.68E+09	1.30E+13	1.68E+13	2.84E+10	1.30E+11	2.89E+08	7.34E+09
Feasibility of exploration projects	0.00E+00	4.00E+12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.68E+13	1.17E+13	0.00E+00	0.00E+00	0.00E+00	6.37E+09
Price variation	2.21E+06	0.00E+00	1.36E+07	1.38E+13	3.61E+08	0.00E+00	1.34E+06	0.00E+00	0.00E+00	8.36E+08	1.68E+13	0.00E+00	5.15E+10	0.00E+00	1.31E+08	0.00E+00
Occurrence of coproduction	0.00E+00	0.00E+00	2.02E+07	0.00E+00	0.00E+00	1.94E+10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.68E+13	0.00E+00	2.80E+10	8.00E+10	0.00E+00	0.00E+00
Primary material use	0.00E+00	3.27E+07	7.75E+06	5.08E+12	6.97E+08	1.16E+10	6.64E+05	5.22E+11	3.58E+07	1.61E+12	1.47E+13	1.68E+13	6.13E+09	5.43E+10	3.62E+11	0.00E+00
Company concentration	4.58E+06	0.00E+00	0.00E+00	6.82E+12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.68E+13	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Economic importance	0.00E+00	2.46E+07	2.24E+07	1.38E+13	0.00E+00	2.15E+10	0.00E+00	0.00E+00	2.95E+08	1.52E+09	0.00E+00	1.68E+13	2.45E+10	0.00E+00	0.00E+00	0.00E+00
Dependency on imports	7.32E+05	5.53E+07	2.24E+07	1.38E+13	6.42E+08	2.15E+10	9.56E+05	1.02E+12	1.66E+08	1.52E+09	1.47E+13	1.68E+13	2.45E+10	1.16E+11	1.18E+08	9.34E+09
Availability of purchasing strategy	1.97E+08	0.00E+00	1.54E+10	0.00E+00	0.00E+00	1.03E+13	0.00E+00	0.00E+00	0.00E+00	1.05E+12	0.00E+00	0.00E+00	1.68E+13	0.00E+00	6.48E+10	7.93E+12
Substitution index	0.00E+00	4.43E+07	2.01E+07	1.53E+13	7.12E+08	2.38E+10	9.56E+05	1.13E+12	1.84E+08	1.52E+09	1.47E+13	1.68E+13	2.20E+10	1.28E+11	2.16E+08	8.38E+09
ASM	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.00E-01	0.00E+00	0.00E+00	6.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human rights violation	6.63E-01	6.38E-01	0.00E+00	0.00E+00	0.00E+00	7.81E-01	7.75E-01	0.00E+00	3.00E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

5. Results CS-ESSENZ

Table S5 displays the results for the case study applying CS-ESSENZ CFs. The first section represents the absolute results. The second and third section are scaled by element and category.

Table S5: Results CS-ESSENZ

	Crude oil	Aluminum	Antimony	Beryllium	Lead	Cobalt	Iron	Gold	Copper	Nickel	Palladium	Platinum	REE	Silver	Zinc	Tin
Political stability	0.00E+00	1.43E+05	2.12E+03	0.00E+00	5.28E+05	3.55E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.57E+07	6.73E+07	1.47E+06	5.19E+07	0.00E+00	1.66E+07
Demand growth	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.73E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mining capacity	0.00E+00	0.00E+00	0.00E+00	3.48E+07	0.00E+00	0.00E+00	0.00E+00	4.43E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Concentration of reserves	0.00E+00	0.00E+00	0.00E+00	3.44E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.28E-02	0.00E+00	0.00E+00	6.73E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Concentration of production	0.00E+00	0.00E+00	1.43E+06	1.88E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.81E+07	9.01E+05	0.00E+00	0.00E+00	0.00E+00
Trade barriers	0.00E+00	0.00E+00	3.21E+02	0.00E+00	0.00E+00	1.54E+08	1.79E+03	5.87E+07	0.00E+00	2.52E+06	5.21E+07	6.73E+07	0.00E+00	3.18E+07	2.89E+05	7.34E+06
Feasibility of exploration projects	0.00E+00	1.16E+10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Price volatility	1.32E+05	0.00E+00	0.00E+00	4.15E+07	2.17E+05	0.00E+00	1.07E+04	0.00E+00	0.00E+00	1.25E+06	6.73E+07	0.00E+00	3.09E+06	0.00E+00	0.00E+00	0.00E+00
Occurrence of coproducts	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.22E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.73E+07	0.00E+00	0.00E+00	1.95E+07	0.00E+00	0.00E+00

Primary material use	0.00E+00	0.00E+00	0.00E+00	1.52E+07	0.00E+00	7.32E+07	0.00E+00	1.98E+07	5.01E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.32E+07	0.00E+00	0.00E+00
Company concentration	2.75E+05	0.00E+00	0.00E+00	2.05E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Economic importance	0.00E+00	7.13E+04	1.88E+03	4.15E+07	0.00E+00	1.35E+08	0.00E+00	0.00E+00	4.12E+06	2.28E+06	0.00E+00	6.73E+07	1.47E+06	0.00E+00	0.00E+00	0.00E+00
Dependency on imports	4.39E+04	1.60E+05	1.88E+03	4.15E+07	3.85E+05	1.35E+08	7.65E+03	3.89E+07	2.32E+06	2.28E+06	5.89E+07	6.73E+07	1.47E+06	2.82E+07	1.18E+05	9.34E+06
Availability of purchasing strategy	1.18E+07	0.00E+00	1.29E+06	0.00E+00	0.00E+00	6.47E+10	0.00E+00	0.00E+00	0.00E+00	1.57E+09	0.00E+00	0.00E+00	1.01E+09	0.00E+00	6.48E+07	7.93E+09
Substitution index	0.00E+00	1.28E+05	1.69E+03	4.60E+07	4.27E+05	1.50E+08	7.65E+03	4.31E+07	2.57E+06	2.28E+06	5.89E+07	6.73E+07	1.32E+06	3.13E+07	2.16E+05	8.38E+06
ASM																
Human rights violation	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.26E-03	0.00E+00	0.00E+00	8.40E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3.98E-02	1.85E-03	0.00E+00	0.00E+00	0.00E+00	4.92E-03	0.00E+00	0.00E+00	4.20E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table S6 shows the CS-ESSENZ results for element category combinations which were not identified as hotspots with ESSENZ in dark blue.

Table S6: Comparison of some CS-ESSENZ supply risk categories applying CS-ESSNEZ to all elements

	Crude oil	**Aluminum**	**Antimony**	**Beryllium**	**Lead**	**Cobalt**	**Iron**	**Gold**	**Copper**	**Nickel**	**Palladium**	**Platinum**	**REE**	**Silver**	**Zinc**	**Tin**
Political stability	0.00E+00	1.43E+05	2.12E+03	0.00E+00	5.28E+05	3.55E+08	1.14E+04	0.00E+00	0.00E+00	0.00E+00	5.57E+07	6.73E+07	1.47E+06	5.19E+07	0.00E+00	1.66E+07
Demand growth	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.73E+07	0.00E+00	0.00E+00	4.06E+05	0.00E+00
Mining capacity	0.00E+00	0.00E+00	4.08E+01	3.48E+07	6.33E+03	1.65E+05	2.93E+01	4.43E+05	0.00E+00	3.69E+03	7.48E+04	6.73E+07	0.00E+00	6.11E+05	2.82E+03	3.24E+05
Concentration of reserves	3.08E-04	7.42E-04	2.50E-06	3.44E-02	5.73E-04	5.52E-01	4.00E-05	1.69E-01	1.28E-02	2.08E-02	0.00E+00	6.73E+07	7.02E-03	7.35E-01	6.89E-04	2.90E-02
Concentration of production	1.31E+08	3.58E+05	1.43E+06	1.88E+07	1.04E+06	4.06E+08	2.94E+04	2.95E+08	1.85E+07	4.17E+07	6.73E+07	1.81E+07	9.01E+05	7.32E+08	4.46E+05	1.05E+07
Trade barriers	0.00E+00	0.00E+00	3.21E+02	0.00E+00	0.00E+00	1.54E+08	1.79E+03	5.87E+07	0.00E+00	2.52E+06	5.21E+07	6.73E+07	1.70E+06	3.18E+07	2.89E+05	7.34E+06
Feasibility of exploration projects	0.00E+00	1.16E+10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.73E+07	4.67E+07	0.00E+00	0.00E+00	0.00E+00	6.37E+06
Price variation	1.32E+05	0.00E+00	1.14E+03	4.15E+07	2.17E+05	0.00E+00	1.07E+04	0.00E+00	0.00E+00	1.25E+06	6.73E+07	0.00E+00	3.09E+06	0.00E+00	1.31E+05	0.00E+00

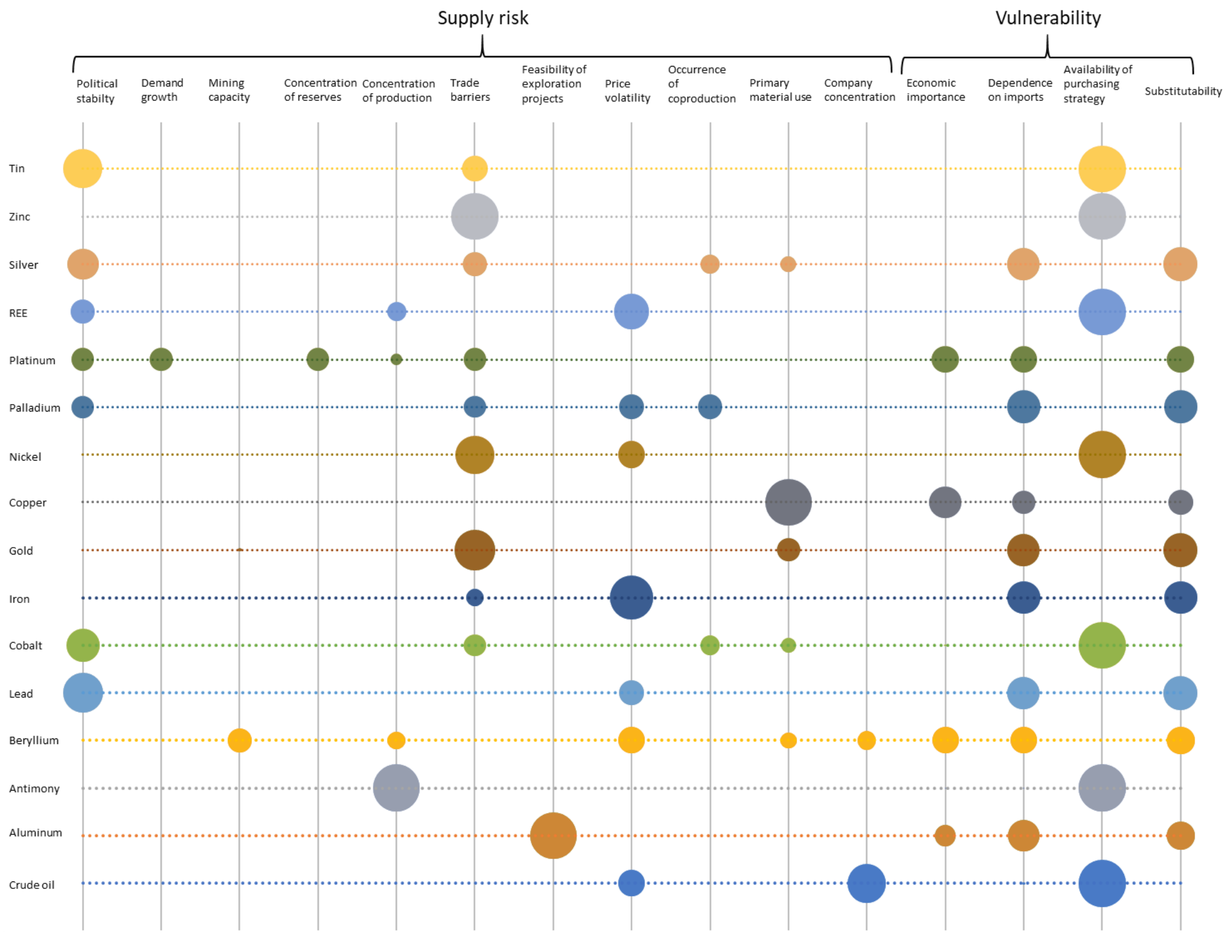

Figure S5: Results for the economic dimension of CS-ESSENZ scaled by element

The societal categories were evaluated for crude oil, aluminum, cobalt, iron, and copper. Cobalt (20%) and copper (6%) are partially supplied by ASM. As more copper than cobalt is used in the production of the smartphone, the difference between the results for both in *artisanal and small-scale mining* is respectively small (see Figure S6). The results for *human rights violation* (see Figure S7) show that crude oil performs worst in this category, mainly due to 50% of it originating from China and 10% from Saudi Arabia. Also, in the exploitation of the supplied iron, cobalt and copper *human rights violations* are likely to occur. The iron in the case study originates from Brazil and China. The cobalt is mainly imported from China the Dem. Rep. Congo. All these countries perform badly concerning human rights. For copper, the case is slightly different. The CF of copper for human rights violations is less than a half of the CFs of iron or cobalt, but as the mass of copper in the phone is much higher than the mass of the other two metals, its overall result concerning *human rights violations* is the third worse. The *local biodiversity* is gravely by copper (see Figure S8) as the majority of the mining and production of the it takes place in high density biodiversity zones (e.g. most parts of Chile). The effect of crude oil is less than half as high, followed by iron and cobalt. The *water scarcity* is highest for crude oil, followed by iron and copper (see Figure S9) due to the high water scarcity in some of the mining countries.

Error! Reference source not found. shows a comparison of the results of ESSENZ and CS-ESSENZ for the categories of the sub-dimension supply risk. The first letter in each cell represents the ESSENZ result and the second the CS-ESSENZ result (H = high, M = medium, S = small).

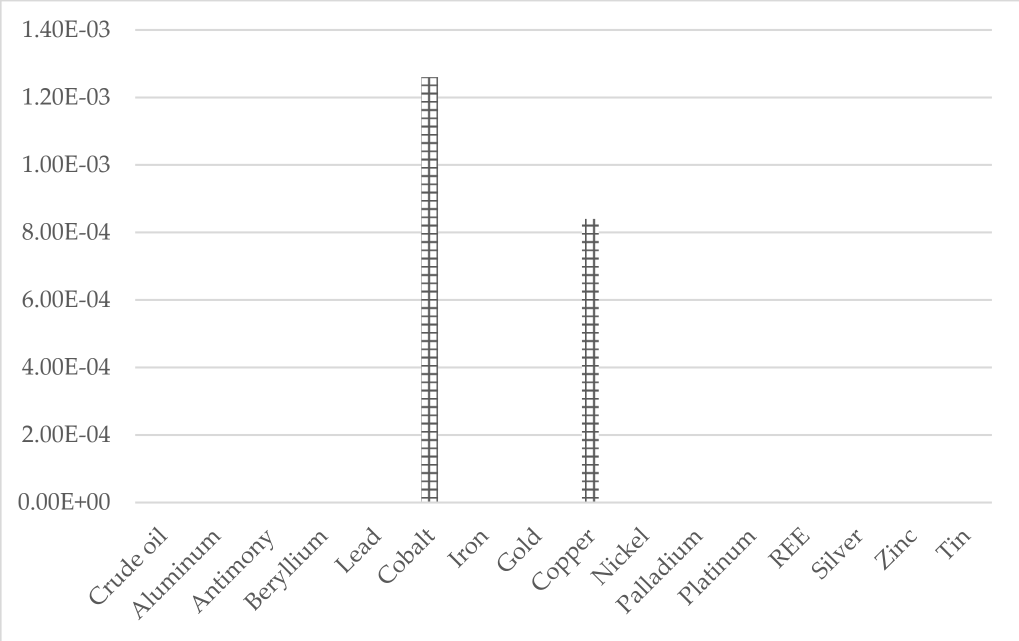

Figure S6: CS-ESSENZ results for artisanal and small-scale mining

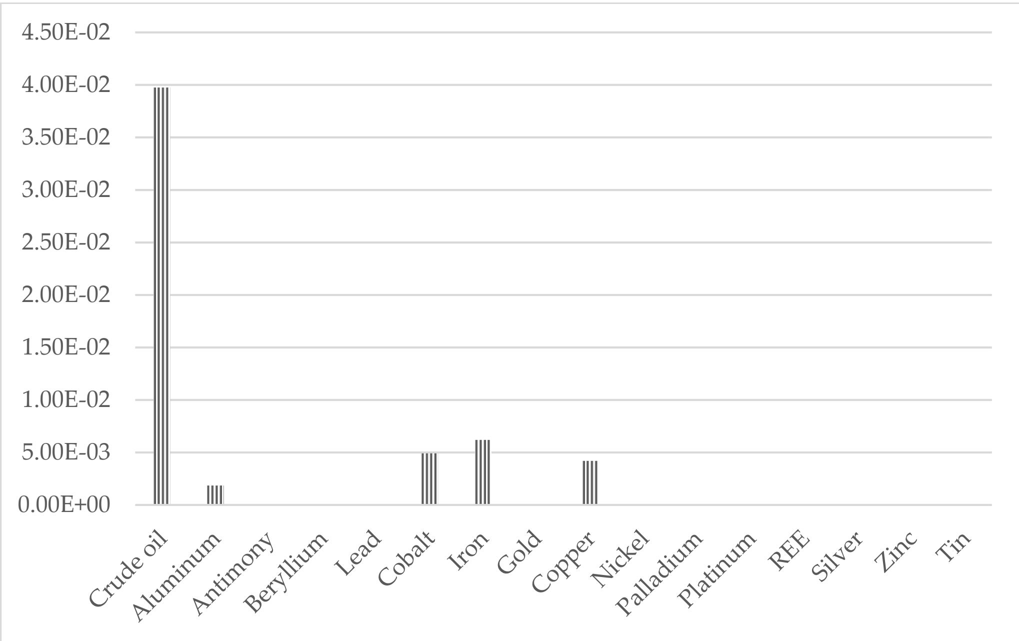

Figure S7: CS-ESSENZ results for human rights violation

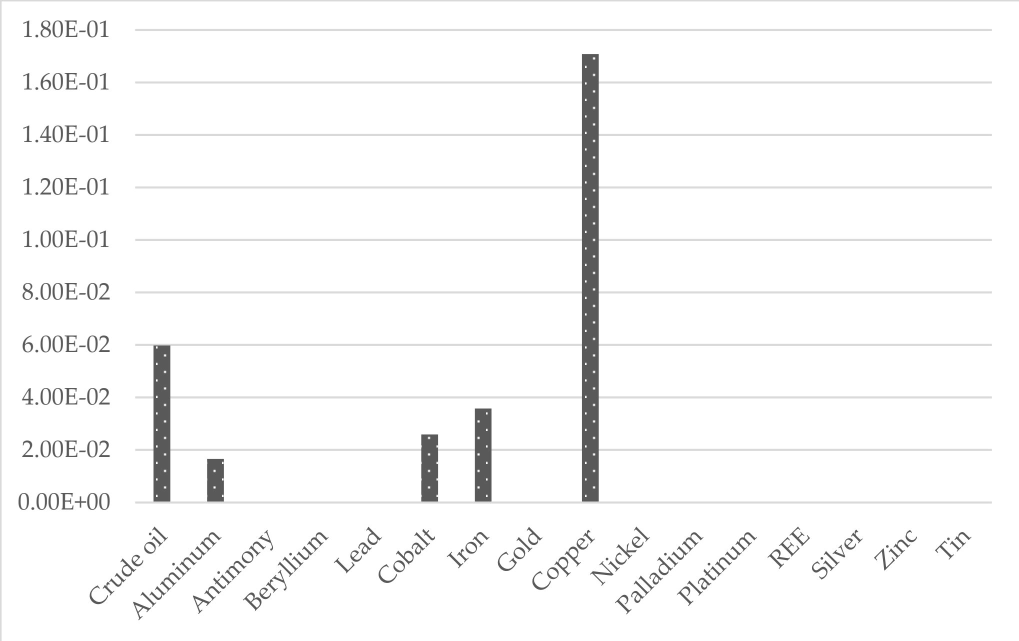

Figure S8: CS-ESSENZ results for sensitivity of local biodiversity

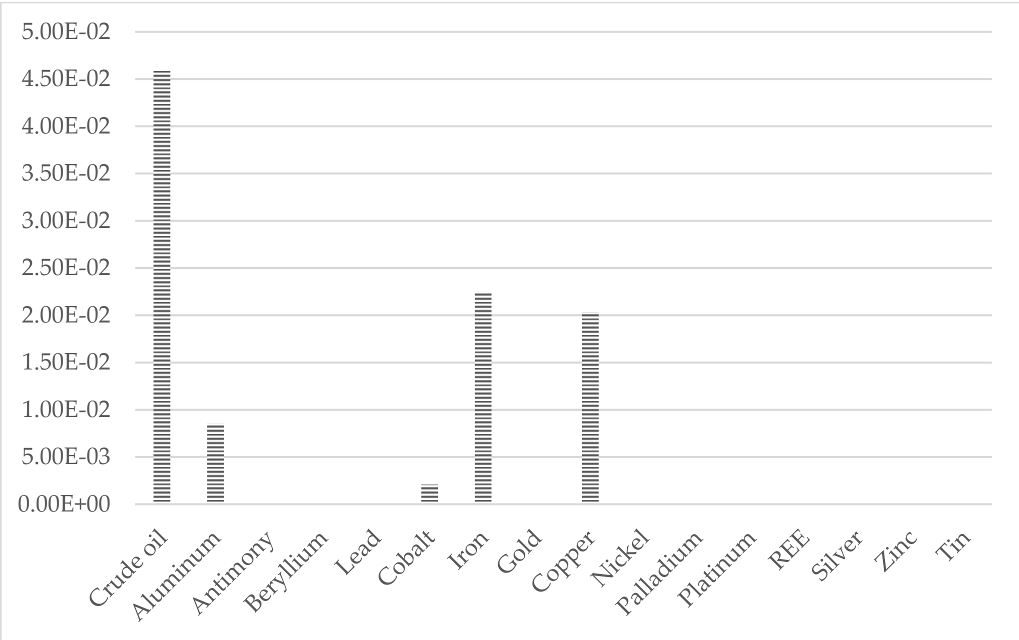

Figure S9: CS-ESSENZ results for water scarcity

6. Further points of discussion

Before scaling the CF's, the individual categories and elements are normalized by the global yearly production of the element. A high yearly production of material i sets down the CFs of i and vice versa. A small production of an element can increase its supply risk. The opposite effect of the normalization that was used in this paper can be desirable too. For example, materials with high production rates are most likely consumed at high rates as well. Therefore, their impact categories should rather be increased to emphasize the large demand for them. Primarily for reasons of consistency with ESSENZ, it was decided to keep this normalization. An alternative solution to the one presented in this paper could be to divide all supply risk results by the yearly production and to multiply the vulnerability results. This would meet both the increased supply risk by smaller production and increased vulnerability of commonly used materials.

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