European Journal of Social Impact and Circular Economy

Criticality assessment of green materials: institutional quality, market concentration and recycling potential

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Received: 29/07/2021
Accepted for publication: 01/11/2021
Published: 12/11/2021

Abstract

The carbon transition and digitalization transformation are tied to a set of critical raw materials (CRM). Energy accumulators, renewable energy modules, and electronic devices all contain a certain amount of these. The versatility and utility of such elements come together with the limited number of countries where their extraction and refining occur. As the demand for these materials is growing globally, concerns arise regarding the security of the production chain. Several works highlighted the risks associated with these materials without presenting clear interaction between such factors. This gap in literature might have overlooked systemic risks underlying green sectors. This article investigates the correlation between three aspects: market concentration, institutional quality, and circularity. The approach will contain the presentation of the main characteristics of recyclability and the institutional status of exporters. A synthetic index is derived and plotted against the potential of recycling per material. In such a manner, we can group minerals according to sourcing vulnerability: one comes from material recovery and the other via imports. An indicator calculated with a Cartesian distance method provides the synthesis of security versus safety. According to our findings, Electrical Vehicles carry the highest vulnerability for their main components in circularity and human rights violations. This implies that the supply chains' instabilities threaten the transition to a low carbon society. Ending remarks highlighted the limitations of our research, where possible interest for future research may lay.

Keywords: Critical raw materials; Responsible Sourcing; Market Concentration; Conflict Minerals; Circularity

1. Introduction

Acquisition of CRMs is topical for the EU strategic Agenda: a stable and clean supply of raw materials is necessary to key industries. It is called criticality, the economic and technical dependency on a particular material, and the probability of supply disruptions for a defined stakeholder group within a specific time frame (Schrijvers et al., 2020). The EU institutions established a three-fold policy direction to aid in this context in 2008 with the raw material initiative (Commission of the European Communities, 2008). It involved three pillars: safe mining within the EU economic area, secondary materials from waste recovery, and sustainable and fair supply from global markets. The first relates to sustainable mining and new explorations (Hàmor, 2004; Vrkljan et al., 2017). Material recovery is also connected to municipal waste as urban mining (Cossu & Williams, 2015). Households are not the primary source of waste within the EU economy. However, it represents one of the

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core issues of EU waste policy (Expósito & Velasco, 2018). Finally, safe trade practices are intended to reduce the vulnerability of imports. Due to industrial dependency, CRM extraction cannot be delinked from nations that cannot foster human rights. This is why some of them are part of the so-called conflict minerals (Koch & Burlyuk, 2020). The policy issue abides by the OECD due diligence practices (OECD, 2016a). While internal EU production increases the safety of the supply line, the other two are face limitations. Material recovery from waste still faces technological uncertainties (Ali et al., 2017), and harmonization of due diligence data is still in evolution (OECD, 2020). Mineral Governance should and policy-making at different levels (Bleischwitz & Bahn-Walkowiak, 2007), possibly anticipating risks and crises (Bleischwitz, 2020). Safe mining represents a strategic source. However, within a circular perspective, extractive practices might be taken as secondary. Therefore, the circular tools for material governance should focus on the limitations of the other pillars in Material Governance. Securing external sources and advancing recycling technologies could impact the resolution of the EU agenda for digitalization and green transition. Material governance is linked to several strategic industries: EEE, EV, Solar panels, and Wind farms (Bobba et al., 2020; Monnet & Ait Abderrahim, 2018).

Safe trades and secondary materials are elements of the umbrella definition of Circular Economy (Homrich et al., 2018). Several authors have commented on the capability of circular economy practices to reduce the criticality of materials (Chiu et al., 2020; Tercero Espinoza et al., 2020). However, it was commented on the potential trade-offs between materials and processes (Schaubroeck, 2020). This might represent a structural limit to EU policies intended to reduce the criticality. Yet, there are few if no articles that address the complementarity between critical aspects. The purpose of this paper is to highlight the potential presence of a trade-off between circular economy pillars of material governance under the framework of internal versus external weakness of European raw material supply chain. The reference literature of criticality assessement for CRM have not investigated the issue so far (Mudd et al., 2018; Santillán-Saldivar et al., 2021a; Song et al., 2019). We will develop an indicator for external safety according to market concentration and national institutional quality. For circularity, we will use the contribution of recycled materials to raw materials demand, known as the end-of-life recycling input rates (EOL-RIR). This is not the only possible indicator of circularity. It is, however, the one adopted by the EU commission and EUROSTAT to classify materials for circularity (Talens Peiró et al., 2018). Since market distribution, institutional quality cannot change is short term, we will consider them complementary in this study. The complementarity of recyclability and safe markets is analyzed using a Cartesian distance indicator, identifying as vulnerable the elements that cannot be accessed with either of the pillar.

It is necessary to consider the changes in definition to recall which CRMs are. A revision of the criticality definition was implemented several times. The first official publication was in 2011 with 14 CRMs. Following editions every three years increased the number of elements: 2014 with 20, 2017 with 27, and 2020 with 30. Such a surge could be interpreted by the attention that the EU commission had towards several evolving topics. Circular economy policy packages were implemented during those years: 2008 and 2014 the Waste Framework Directive, Circular Economy Action Plan in 2015 and 2017 was the waste of the EEE package. The Paris Agreement's signatures accelerated climate Change policy in 2016. Regarding Responsible sourcing, the EU passed the EU's Regulation on Responsible Sourcing of Minerals, also sometimes referred to as the 'Conflict minerals Regulation', in May 2017. According to this legislation, by January 2021, around 95% of CRM imports should follow RS criteria (EU, 2017). The recommendations declined within the Due Diligence Guidelines follow the premise of corruption avoidance, human and environmental rights, conflict avoidance (OECD, 2016b).

The article is structured in such a manner. The literature review presents the major works regarding CRM criticality. The methodology section is used to explain the derivation and use of indicators for our analysis. The Results will deliver a synthetic outcome. In the discussion, we will comment on the relevance of the results according to each sector and how this could affect the development of the EU agenda. Finally, a review of the limitations of our methodology is presented, along with the possible new application.

2. Literature review

The thriving market for consumer and portable electronics and low-carbon technologies (hybrid and electric vehicles, wind turbines, and solar panels) is heavily dependent on the availability of critical raw materials (CRMs): it is possible to find studies on EV (Jones et al., 2020), solar panels and wind farms (Rabe et al., 2017). Their extraction, production, and trade are associated with various risk factors. In 2013, a study conducted by the IISD identified 32 materials as significant for the de-carbonization

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of the European energy system (Church & Crawford, 2018). Some are classified as "critical" and included in the EU critical raw material list, being either scarce or extracted in a limited number of countries (Blagoeva et al., 2016). Commonly, criticality assessments consider the 'supply risk' and 'economic importance' of the raw material. Supply risk reflects the severity of the impact on the disruption of supply chains and is based on significant suppliers' concentration and political stability. Economic importance reflects the sum of the value of end-use sectors that consume the raw material (Song et al., 2019). Other studies also include analyses of the reserves and the number of raw materials. Some have been confirmed and can be economically recovered with current technology, even potentially by EEE waste (Mazzarano, 2020). It is possible to estimate depletion rates for global reserves with a long-time focus. In general sourcing material use from production, chains relate equivalent measures (Pehlken et al., 2017; Ziemann et al., 2018). Such approaches are similar to ecological footprint, applying water and carbon emissions (Misopoulos et al., 2020; Stefanakis, 2019).

Criticality assessment usually involved the development of indexes. One of the most famous has been annually derived from UK geological survey (British Geological Survey, 2015). It uses a composition of several indicators involving geopolitical risk, economic relevance, recycling potential, and ore scarcity. However, several of such indicators have been subjected to criticism in the context of life-cycle assessment (Cimprich et al., 2019), in the sense that they made hands challenging to use in supply chain analysis. The geopolitical risk component is somewhat relevant in CRM studies, but it is significantly mitigated by recycling capacity, becoming a less critical factor (Santillán-Saldivar et al., 2021b). Furthermore, scales and non-continuous indicators are not helpful to capture correlations in the supply risk index used in criticality indicators (Blengini et al., 2017). From the Markowitz portfolio approach, the correlation between indicators is a possible tool to minimize risk. For CRM, there exists no significant correlation between depletion, self-sufficiency, and economic importance indicators (F. F. Martins & Castro, 2020). Economic importance has also been uncorrelated to supply risk (Arendt et al., 2020).

The study of indicators correlation is a recent development, and RS aspects are often not considered a primary study interest. Furthermore, the result in terms of which material is more critical is a redundant exercise. Top positions are usually occupied by the same materials (F. Martins & Castro, 2019). There are comprehensive studies on the supply chain of CRMs such as lithium and cobalt. Macro-economic factors have been addressed in studies regarding European Union imports (Deloitte, 2015). Few studies pay attention to the correlation between the institutional quality of exporters and material circularity. The instability of institutional systems affects the endurance of economic relations. This generates uncertainty and impacts the value chain of products (Ambekar et al., 2019; Silva & Schaltegger, 2019). There is no absolute way to examine stability. According to a normalized scale, available indexes are based on the investigation of experts panel and grade nations (KUNČIČ, 2014). This indicator has been used in several studies of CRM supply risk. We will show in the next section how it is possible to correlate market safety to circularity in next section.

3. Methodology

We employed three indicators to evaluate the criticality of materials under the frame of circularity vs. market safety. For circularity, we adopted the percentage of reuse of discarded materials, the EOL-RIR. Volumes of CRM international transactions could be traced to the exporters using the COMTRADE dataset. We use the reference value of 2018, as it is its latest entry. According to each product, this trading indicator is hereby used to derive the market quota of each exporter. Institutional quality is based on six normalized indicators. The EOL-RIR was the most suitable circularity indicator in criticality analysis: it aligns well with EU targets, including raw materials policy, and the section explains how it can be calculated using Material System Analysis data (Talens Peiró et al., 2018). EOL-RIR refers only to available recycling. It is the percentage of participation of discarded materials in input to production. CRM is defined by both market concentration and a north-south dynamic of human rights. Since institutional quality does not identify directly human rights violations, we assumed that institutional quality is a robust measure of protection. Thus, we do not presume that nations with generally good institutions have no infringement. Human rights could be violated everywhere, but good institutions tend to repair or counter the damage.

Raw materials exporters with stable institutions might host relatively decent work environments. When rights are violated, it is more probable to restore the previous situation than in a nation with weak or unstable institutions. The operational definition of institutional quality is based upon a rating approach. Estimating a general value of quality is non-trivial. According to Regulatory quality, six quality indexes evaluate nations, Government effectiveness, the rule of law, Corruption, Voice, and accountability index. Values of such variables are collected in indicators of Worldwide Governance Indicators. They are

European Journal of Social Impact and Circular Economy - ISSN: 2704-9906
DOI: 10.13135/2704-9906/5988 Published by University of Turin http://www.ojs.unito.it/index.php/ejsice/index

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estimated using the unobserved components model (UCM). The premise underlying this statistical approach is straightforward – each of the individual data sources provides an imperfect signal of some more profound underlying notion of governance that is difficult to observe directly (Kaufmann et al., 2011). The distribution of such indexes is expected and always has a variance of 1 and a mean of 0, with a minimum value of -2.5 and a maximum of 2.5. Since we cannot choose which is more effective in preventing or restoring human rights, we will assume that they are jointly and equally responsible for human rights respect. Since it is needed positive values from a normal distribution, the exponential value will be used in such way:

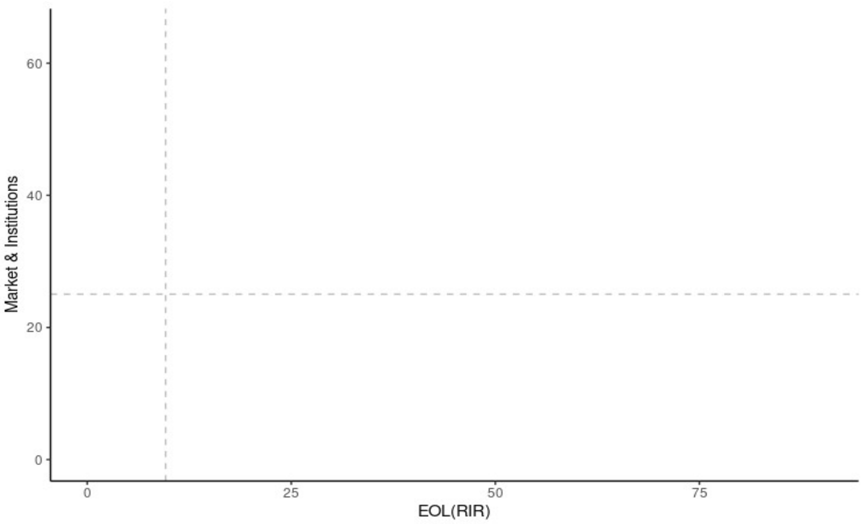
$$I_i = \sum_{\forall m} e^{-xm} \qquad (1)$$

The generalized index "I" for a country "i" is the inverted average between the value of the six indexes. Each index 'm' could be given any weight 'x' according to the institutional quality the criticality assessment requires. However, as previously stated, it might be better to have no discrimination on such occasions. All weights are equal to 1/6. This methodology is helpful as it does not substantially change the value of the variance of distributions, avoiding other biases to our analysis. Since we had to refer the value to a material, we matched the generalized index with the market participation.

$$M_k = \frac{1}{n}\sum_{\forall i} p_i I_i \qquad (2)$$

In such a way, the index of market institutional quality "M" for material "k" is an average of the institutional quality of nations. The value can vary from 0 to 100. The meaning of the index is a positive interaction between a market distribution and the quality of partners. The maximum index level can only be achieved when the market is split between fair exporters: the lower the level, the more concentrated the market around unfair partners. Since market distribution is not necessarily normally distributed, we cannot expect the "M" index to appreciate the same properties as the institutional one.

Figure 1. Classification Areas



Source: Author's elaboration

According to circularity and market source vulnerability, the classification of materials will be plotted on a reference of two axes. The x-axis will represent the first while the y-axis the latter. Splitting the area into four, it is possible to discern between zones of no policies (both high values), overall criticality (low and low), high market vulnerability, and low circularity. Speaking of mere distribution, it is possible to see the objectives according to frequencies. The areas will be split according to the median value. As reported in figure 1, half of all materials have either very low EOL-RIR (˜8) or low market vulnerability (˜22). Each commodity is constituted by a cloud of points spread between four areas. According to where these dots are located, it is possible to see where each sector should focus its policy.

European Journal of Social Impact and Circular Economy - ISSN: 2704-9906
DOI: 10.13135/2704-9906/5988 Published by University of Turin http://www.ojs.unito.it/index.php/ejsice/index

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Unfortunately for CRM in international trade datasets, Heavy and Light Rare Earth Elements (HREE and LREE) are used. The former comprehends Yttrium (Y), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb), Lutetium (Lu). The latter comprehends Scandium (Sc), Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu). Furthermore, Group 5 elements have to be considered as a whole. This collects Vanadium (V), Niobium (Nb), Tantalum (Ta), and Dubnium (Db). Criticality assessment considers, therefore, twenty-eight materials and groups.

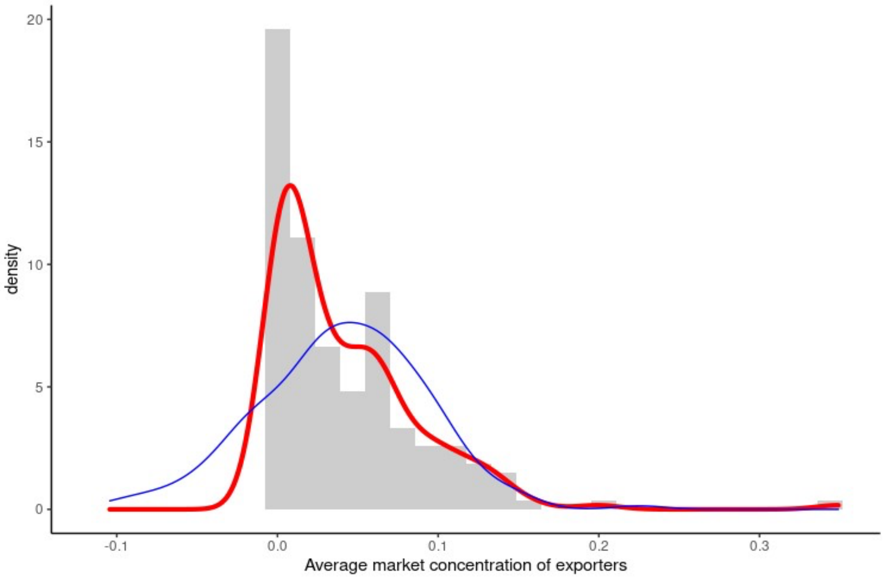
Market concentration could be considered on two levels. One could be captured by index M, as the proportion of trade that each nation control for a particular CRM. The second appears when nations participate and possibly control several markets. To summarize market concentration, Shannon index of attention is

applied. Its derivation originates from communication theory but has prolific application in social sciences (Tabner, 2007). The lowest value of 0 indicates the monopoly of markets of one country on every market. The number of exporting counties is collected in i = 1,..., N, and commodities in k = 1,..., K

$$S_i = \frac{1}{K}\sum_{\forall k}\sum_{\forall i} p_i \, ln(p_i) \qquad (3)$$

We suggested in figure 2 that the number of dominators is few in CRM markets. While these nations have unstable institutions and deal with low circular materials, it is rather challenging to address diversification. For our purpose, the M index is penalized by high concentration for commodities exchanged in this condition, even by very stable countries. It is possible to compare concentration from this panel to a" normal one" using a standard distribution fitting (blue). In figure 2, a comparison of concentration is highlighted. Dominant exporters do most transactions of CRM. The normal distribution in blue is centered around S_i mean and standard deviation.

Figure 2. Market concentration per exporters, S_i



Source: Author's elaboration

European Journal of Social Impact and Circular Economy - ISSN: 2704-9906
DOI: 10.13135/2704-9906/5988 Published by University of Turin http://www.ojs.unito.it/index.php/ejsice/index

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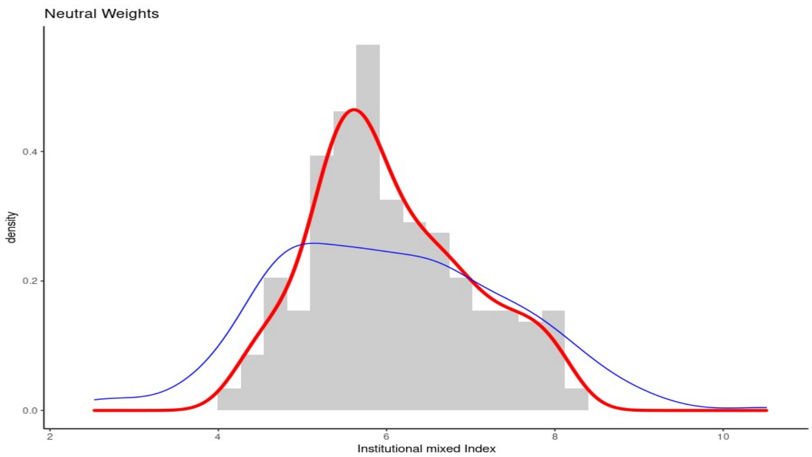
The M index multiplies market concentration to the I index of institutional quality. This index has low tails, and most firms are distributed around its mean of 6. Nations with an index around 1 have the most inferior instability to report, with all indexes near -2.5. The characteristics of such distribution are helpful to penalize extreme events and allow higher points on middle-tier countries. The interaction between such data is reported in the result section. To have a comparable criticality index, we needed to synthesize the correlation between the indicators and the distance to the most unsafe of trades for RS-circularity objective: those low on both M and EOL-RIR (c in equation 4).

Figure 3. I index with normal density fitting



Source: Author's elaboration

Since we intend to address the usefulness of the trade-off, we place no preference between the two indicators. Cartesian distance between each element to (0,0) functions as a Pareto-efficient indicator: elements are given a higher value if any form of hedging strategy exists between circularity or safe markets.

$$D_k = \sqrt{M_k^2 + c_k^2}$$

According to EU standards, the analysis we provided allows for interpreting results for market safety according to possible RS considerations and circularity. We reported hereby the outcome of our study.

4. Results

We reported a summary of the preliminary analysis in table 1. Among essential categories of CRM, it is possible to find LREE, HREE, and G5. Their market is respectively controlled by Japan (15.44%), the Popular Republic of China (11.6%), and Brasil (24%). Cobalt, LREE, and Silicates are the lowest circularity in EV, EEE wind, and solar farms. For market and institutional fragility, Molybdenum and Cobalt are the lowest. The latter is particularly vulnerable for both factors. China represents the most relevant source of market concentration and instability. While it is ranked low on all institutional quality indicators, it is the dominant player in several markets. Among these, we find Bismuth, HREE, Molybdenum, and Nickel. Cerium and LREE are dominated by Japan, which generally accounts for stable institutions.

In responsible sourcing, "top-down" approaches based on institutional indicators for critical analysis have generally similar results, despite different focuses. In our case, we developed a system based on three major indicators: market safety, circularity, and Cartesian distance index. Institutional quality has been weighted to market participation. In case most any market is composed mainly of overall fragile states, we called the market tainted. The comparison element to draw vulnerability is the

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circular limits of the EOL-RIR. The exposure is based on the possibility to acquire a material according to fair market or circular source, as recycled materials.

Table 1. Table's example

HS92	M index	EOL(RIR)	Cartesian D	Chemical Name	Application	Main Trader
2613	5.68	30.00	30.532	Mo	Wind	CHN (31.036%)
250410	36.57	3.00	36.693	C	EV	CHN (10.46%)
251910	29.18	9.50	30.686	Mg		IND (23.039%)
252010	32.57	1.10	32.589	Ca		ESP (5.29%)
260111	20.31	24.00	31.439	Fe	Solar, Wind, EV, EEE	BRA (11.134%)
260200	25.34	12.00	28.040	Mn	Wind, EV	GAB (17.484%)
260300	24.69	55.00	60.289	Cu	Solar, Wind, EV, EEE	BGR (8.882%)
260400	10.24	33.90	35.412	Ni	EV, EEE	CHN (40.858%)
260500	4.73	0.00	4.729	Co	Wind, EV, EEE	AUT (28.584%)
260600	31.03	12.40	33.413	Al	Solar, Wind, EV, EEE	GIN (17.477%)
260700	19.49	75.00	77.490	Pb	Solar, Wind, EV	BLX (7.352%)
260800	30.26	22.90	37.945	Zn	Solar, Wind, EEE	BLX (7.772%)
260900	9.44	32.00	33.364	Sn	EEE	MYS (31.452%)
261400	21.00	19.10	28.383	Ti	EV, EEE	BLX (9.73%)
261590	11.22	15.43	19.079	G5	Solar, Wind, EV, EEE	BRA (23.849%)
261610	15.53	55.00	57.152	Ag	Solar, EEE	BOL (8.522%)
280450	19.09	1.00	19.115	Te		CHN (15.148%)
280490	33.78	1.00	33.798	Se	Solar, EEE	DEU (6.511%)
280530	19.87	8.45	21.589	HREE	Solar, EEE	CHN (11.598%)
282560	29.99	1.70	30.040	Ge		JPN (6.044%)
283691	30.65	0.00	30.648	Li	EV, EEE	CHL (11.023%)
284610	32.64	1.00	32.651	Ce	EEE	JPN (20.777%)
284690	30.81	0.50	30,815	LREE	EEE	JPN (15.431%)
391000	55.63	0.00	55.628	Si	Solar, EV	BLX (5.368%)
711019	26.68	11.50	29.054	Pt		ZAF (23.751%)
711029	24.72	9.70	26.555	Pd	EEE	RUS (34.217%)
810600	27.57	1.00	27.590	Bi	EEE	CHN (19.52%)
811219	13.55	0.00	13.549	Be	EEE	USA (20.995%)

Source: Author's elaboration

European Journal of Social Impact and Circular Economy - ISSN: 2704-9906
DOI: 10.13135/2704-9906/5988 Published by University of Turin http://www.ojs.unito.it/index.php/ejsice/index

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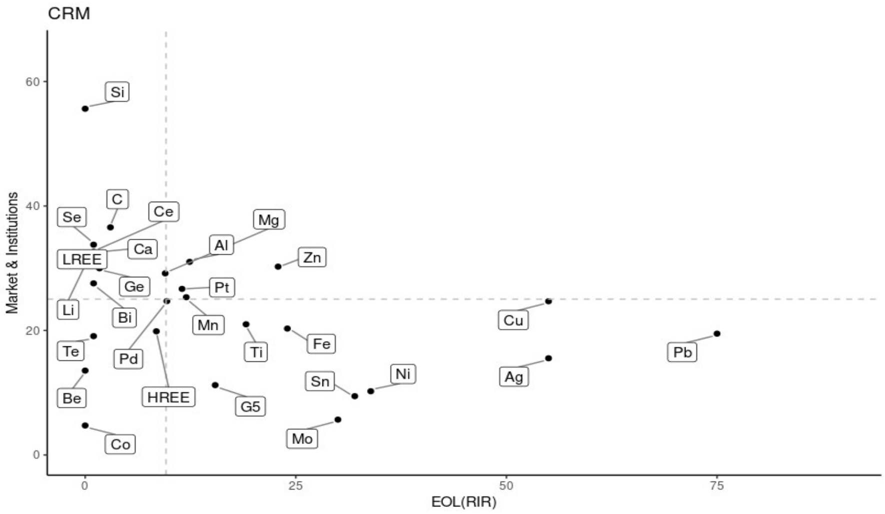
Figure 4. Scatter plot areas's indication



Source: Author's elaboration

Critical materials for the sector intending to secure the production chain could look at circularity and/or market safety. Again, institutional quality is just a 'preventive' measure. It does not state an absolute and unequivocal measure of violations. In this application, we see that most green materials are outside the comfort zone of fair and recyclable materials; a synthetic graph of the analysis is portrayed in figure 4, along with the distinction areas we previously mentioned.

With a wider perspective on all examples, we could outline a trade-off between circularity and institutional quality. The correlation for EEE is -26.5%, for solar panels is -37.2%, for EV -22.9% and finally Wind farms is 24.0%. Its relevance in this paper is to prove the existence of the inverse relation between Index M and EOL-RIR in CRM. The calculation has been made on all CRM according to the report of the EU commission. We collected the relevant information in table 1. The total panel of materials is referred to the category of Electronic and Electrical Equipment (EEE). They design all commodities that are designed to function via electricity. We used EEE as a yardstick configuration as they contain almost all CRM. Its waste designation is named waste EEE (WEEE) according to EU packages of 2008 and 2014. A recent report highlighted that these commodities are normally not designed to be fully recycled (Raudaskoski et al., 2019). They are relevant for the strategy of circularity, and usually, the other three products are considered related to them for sustainable electricity generation and components (accumulators). Therefore, we split materials according to the uses in three sectors of the Green Transition. These are Solar panels, electric vehicles (EV), and wind farms. The highlighted trade-off is present in both Solar farms and EVs. The difference between sector vulnerability is represented in figure 5.

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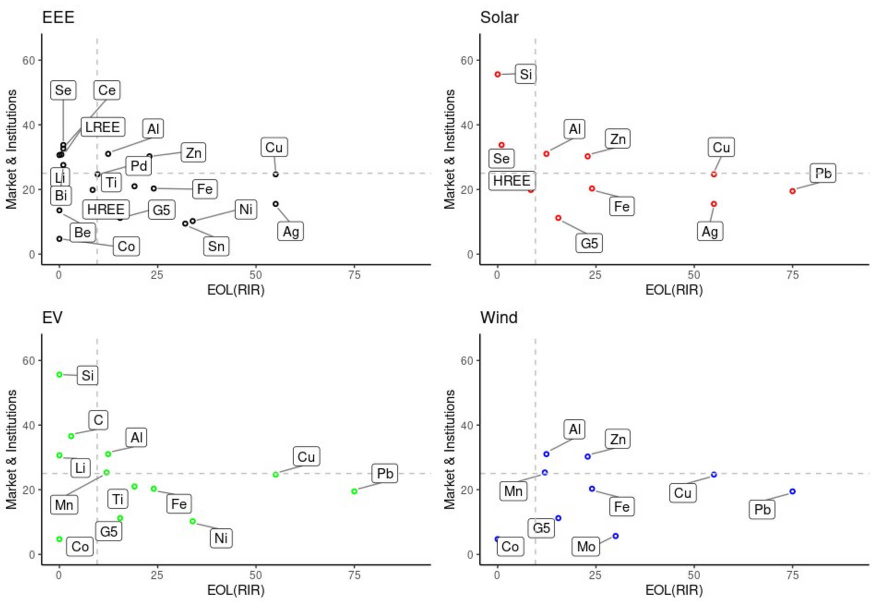
Figure 5. Sector allocation of CRM



Source: Author's elaboration

Wind farms are based on materials characterized by a heterogeneous set according to circularity and generally tainted markets. Solar farms register some materials in the comfort zone, such as Copper and Zinc. Outside HREE and G5 materials, it is overall a safe sector. Some materials could be recovered by discarded (Iron, Silver, and Lead). Others by acquired on fair markets (Silicon, Aluminum, and Selenium). Wind farms rely mostly on tainted markets, whereas most of these are easy to recover from European scrap metals (Copper and Lead). Unfortunately, Cobalt and G5 are necessary for components, greatly endangering this sector's circularity and production chain fairness.

Finally, EV CRM is characterized by both trade-offs and deep criticalities. Due to the level of technological complexity, this should not sound surprising. Nonetheless, it is relevant to point out that both Lithium and Cobalt, the lowest in EOL-RIR, are required. According to our result, lithium is significantly safer than most other recyclable materials but not within the trade-off. These two are, according to our criticality, the most difficult to control for a sustainability transition. The European production chain for transition commodities such as these is incredibly vulnerable in the following decades without institutional quality and recycling technology improvements. In this section, we briefly classified materials according to an index "M" and EOL-RIR. The first evaluated together market concentration and institutional quality. It greatly penalizes materials that are concentrated in fragile states. EOL-RIR refers to the recycling potential of the referred material. A brief discussion over the results will classify the focus of policies.

5. Discussion

Circularity and RS collect strategies are intended to reduce the adverse effects of external dependency. Since the EU is abiding by OECD Due Diligence practices, imports must conform to international standards. However, indicators for human rights violations are sparse, and data clearance is one of the main pillars of Due Diligence. Efforts to create a consensus have been made (OECD, 2020). Using national-level indicators for institutional quality allows having a homogenous measure comparable between suppliers and between sectors. Using such indicator along with market concentration is possible to identify the nodes of monopoly and political instability. Reducing dependencies from fragile nations (or fostering their development) represents a strategy for external risk mitigation. Investing in recycling technologies and enforce circularity policies reduce internal vulnerability: the lack of relevant raw materials' deposits.

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Demand for green transition commodities still is dominated by the European market. EU represents the destination of most of those raw materials, nevertheless their risk. The focus on GDP use in criticality analysis is redundant in these terms. The main vulnerability to recall is to EU welfare. The impossibility of applying carbon-neutral policies and allocate enough EEE affects contemporary and future standards of living. Thus, when considering RS, firms increase the welfare value of their chain more than the economic value. In such a sense, GDP is not a measure of welfare (Stiglitz et al., 2018). It is a common feature to use as an economical substitute when using economic value over the total GDP (or sector) (Ferro & Bonollo, 2019). In this sense, focusing on critical indicators of circularity and institutional quality allows identifying alternative strategies. For instance, sectors that are characterized by negative correlation could focus on circularity or RS efforts according to their cost function. Such approach could be done with three indicators at time, and could be repeated for as many indicators are necessary. However, literature has demonstrated that the relevance of geopolitical and economic relevance indicators could be redundant.

The Cartesian distance approach has an inherent limitation: it is an indifference indicator. Since our interest was to give no particular preference to the indicators at any level, it does not penalize our results. The higher the value, the safest in the supply line. The Cartesian distance indicator grows logistically with its argumenta values. In case one of the two variables is near zero, the other hand explains its importance. Therefore, a long distance with one of the two arguments as near-zero indicates specialization possibility. If the application (for instance, solar panel) involves Lead, circular policies could mitigate risks on the supply line. Lead is relatively cheaper to recycle, but the sources are often not institutionally stable. As long as sectors can allocate their inputs according to the correlation, they can maximize their results in circularity and RS. Applications of Cobalt are, in terms of RS, the most unsafe. The nearest element in terms of low value is Beryllium, with 13.549 points of Cartesian distance. In our study, its applications are mainly concentrated in EEE, in particular for circuits. While its circularity is nearly null, its primary source consists of USA mines. This means that RS strategies might yield better results.

Circularity policies are topical for CRM. Secondary materials substitute virgin materials, reducing dependency on fragile countries. As reported in results and figures 4 and 5, most materials low in the M index have decent EOL-RIR (in many cases debatable but helpful). Similarly, one LREE, Cerium, is low in circularity but proper in the M index. Sectors that rely on such material could focus on circularity improvements to success in SDG. Overall, commodities related to wind farms and solar panels employ CRM characterized by a decent level of circularity: most of them are above the median demarcation line. Complex commodities Such as EEE and EV are unfortunately challenging to manage. EEE is a comprehensive group. However, CRM applications are characterized by stable trade partners such as Japan. Our analysis may affect, for the most significant part, only some of the commodities within EEE. For instance, ICT-related commodities are composed of a complex set of CRM (Kasulaitis et al., 2015) compared to heavy household appliances.

Green transition dependency to CRM does not represent a bottleneck for its policies. Some commodities critical for it could benefit from concentrated efforts on only one of these: RS or circularity. Solar farms, for instance, use HREE, but most of their materials generally have decent circularity levels. Therefore, improving RS factors by blending the product chain with secondary materials is possible. A similar approach could be made for Wind farms. Energy policies involving such instruments are fascinating nexus for mineral securities and RS. Considering their relatively low-risk sources, they are useful for carbon transition, considering conflict minerals legislation. On the other hand, EVs are a strong driver of carbon-free mobility. Unfortunately, their production relies on several CRM affected by possible conflicts and low circularity.

6. Conclusion

Although used in low concentrations, the growing electronics and transition commodities market has increased the global demand for critical materials. This has generated concerns about CRM international reserves and supply since they are either scarce or extracted in a limited number of countries. The main strategies for mitigating material criticality are recycling and responsible sourcing (Lapko et al., 2019; Young, 2018). Recycling is likely to reduce input from primary raw materials, although it may not meet the growing market demand for certain materials (Mayyas et al., 2019). RS leverages stewardship and certification programs that support sustainable development and practices in mining countries, steering cooperation among countries and industrial sectors, arguably securing the supply of raw materials (Gandenberger et al., 2012). Both strategies present organizational and operational constraints, besides major technological issues (for recycling). Commonly described as immaterial, digital technology is, on the contrary, high energy and material intensive (see the work of EcoInfo in France. See also Maxwell (2014) and Lepawsky (2018)).

European Journal of Social Impact and Circular Economy - ISSN: 2704-9906
DOI: 10.13135/2704-9906/5988 Published by University of Turin http://www.ojs.unito.it/index.php/ejsice/index

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There is now vast literature documenting the materials, infrastructure, labor conditions, and energy requirements underpinning digital technology production, maintenance, and disposal. There is still no consensus, however, on which indicators are necessary for disclosure. NGOs and national laws in the US and EU have recently focused on supplying "conflict minerals" tin, tantalum, tungsten, and gold. The first two, in particular, are used to produce components of circuit boards and electronic devices). Mining and trade are entangled in conflict and severe social conditions in the Democratic Republic of the Congo (DRC). Demanding enterprises to verify purchased goods as "conflict-free" means that they are not extracted in a conflict zone and used to finance war as in certain provinces of the DRC.

Our paper has presented a critical study on CRM. To classify the vulnerability of the EU in terms of total supply, we considered two aspects: responsible sourcing and circularity. In this sense, the general objective should be to access materials on markets safe from human rights violations and secondary materials. We identified as a proxy variable for human rights safety an index of institutional quality. EOL-RIR is the reference for circularity. It is generally employed in criticality assessment for CRM, and it is a proxy for secondary material recovery. The former relates to the market concentration jointly with the institutional quality of exporters. We elaborated a synthetic index for these two aspects: market/Institution fragility versus circularity, hence internal versus external vulnerability. Using a classification based on trivial index generation, we presented evidence of a trade-off between circularity and market concentration/institutional quality. According to our results, energy commodities of wind and solar farms represent a safe instrument for transition policies when we consider internal and external vulnerability. The article presents a novel investigation of the systemic limits of outsourcing green commodities. Considering that European Union has put the transition to a low carbon society, the production of such artifacts should at least abide by principles of fair labor and democracy. It addresses the emergent correlation between the two aspects of circularity and safe trades using external and internal weakness as the key of interpretation.

The study presents several limitations anyway. First, it was mainly an exploratory study over the limits of criticality studies in the context of CRM. The indicators employed were the most used in the literature. However, there is a lack of comprehensive indicators of welfare regarding raw materials and their extraction. The methodology tried to overcome the issue by generating more indicators from available data. The implied complementarity of the two weaknesses is highly debatable from an economic standpoint, especially if looking at a dynamic one. Thus, the paper presents a conservative perspective over the potential of electrification of the automotive sector.

Transition commodities such as EV, solar panels, and wind farms present decent average circularity and safe external sources when the former lacks. The EV sector represents both methodologies, the most critical sector for circularity, market vulnerability, and human rights violation. In terms of liability risk, it means, according to these results, the industry with the most significant liability risk for responsible sourcing and material circularity. The exponential growth of markets for electric vehicles is likely to put under pressure in the short and medium-term. The results show that Beryllium and Cobalt traded in Europe are critical from the institutional quality and circularity perspective. The methodology applied is not necessarily bound to application in CRM. Energy commodities such as gas and oil are affected by similar performance. Instead of circularity, climate impact could be a possible substitute. Overall, the paper presented results on non-energetic elements using two main aspects. This limitation could hinder the completeness of our results. However, indicators of RS could greatly vary between commodities and nations. Circularity is based upon industrial definitions. Thus fewer indicators could be considered alternatives to EOL-RIR. Finally, RS and circularity represent a gap in the literature. While our study is not intended to give a complete toolkit for supply strategy, it identified an advantage. Future studies might consider the problem of destabilized supply chains. A trade war affecting green products could impede carbon reduction for short periods. The effect on welfare would therefore be significant, especially in the long term. Several studies have presented the potential for business accounting (Piontek et al., 2021; Scarpellini, 2021). Further data in the field could improve the understanding of listed companies' financial risks with unstable supply chains.

Better knowledge of the complex supply networks of CRMs for Europe can provide several insights for European policy-makers. Consensus over RS indicators is vital for this purpose and represents a relevant gap in the literature. It should be further explored to support the development of cooperation programs and actions (e.g., the Clean Cobalt Initiative). The challenges for a sustainable transition consist of discovering more innovative technologies and rethinking commodity design to improve their durability and reparability. Improved interaction with local communities might strengthen supply security even when national indicators say otherwise. Local realities often constitute particularities.

European Journal of Social Impact and Circular Economy - ISSN: 2704-9906
DOI: 10.13135/2704-9906/5988 Published by University of Turin http://www.ojs.unito.it/index.php/ejsice/index

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