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Global Resource Indicator for life cycle impact assessment: Applied in wind turbine case study

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ABSTRACT

Different methodological approaches under Life Cycle Assessment framework are used so far to address the impact of resource depletion. However, they provide partial visions, based on limited available data, and do not reflect resource related aspects. The aim of this article is to go beyond the current Life Cycle Impact Assessment methodologies to complete the existing indicators, by adding important parameters (e.g. recycling), not yet covered by Life Cycle Assessment resource impact assessment indicators.

New Characterization Factors are developed, considering different criteria which affect the availability of resources through different life cycles. Global Resource Indicator integrates resource assessment aspects to better characterize the Resource. Both recyclability and criticality of resources are part of the multi-criteria indicator complementing scarcity.

Results illustrate that the importance of different resources are influenced by introduction of recyclability and criticality. The new indicator assesses all types of resources including renewables and non-renewables using regeneration rates. The sensitivity of the Characterization Factors with regard to different input parameters is tested and discussed. The results are compared with Abiotic Depletion Potentials indicator and assessment is made on the differences.

The newly developed factors provide a more exhaustive vision of the availability of resources and may be used in Life Cycle Assessment or circular economy approaches. Characterization Factors, derived from the new method are tested in a wind turbine case study and their applicability is validated.

1. Introduction

Increase in resource demand raises concerns over their availability. In the recent years, national and international institutions have targeted sustainable resource supply and circular economy as a core goal of their short- and long-term strategies (European Commission, 2015a, 2015b, 2011; UNEP, 2010). Efficient resource consumption and production patterns are promoted by local, regional and global actors in developed and developing countries.

The environmental impacts, associated with the use of resources, minerals, metals, etc., are addressed in LCA, using different approaches, categorized initially by Stewart and Weidema (2005) followed by Klinglmair et al. (2014). More recent works evaluates the current LCIA methods with regard to mineral resource depletion potential (J. A. Drielsma et al., 2016). The four following groups of indicators as presented in Fig. 1 could be identified in the context of LCA resource assessment:

Group 1 Inherent resource characteristic: indicators such as entropy production or exergy consumption (Dewulf et al., 2007) which are dealing with inherent characteristics of resources.

Group 2 Scarcity: ratio of extraction to a measure of resources or reserves available is the core of the methods of this group, e.g. EDIP (Environmental Design of Industrial Products) (Wenzel and Hauschild, 1997) and CML (Centrum voor Milieukunde Leiden - Center of Environmental Science of Leiden University) (Guinée and Heijungs, 1995; Oers et al., 2002). Few indicators of this group cover the renewable rates for biotic resources. More recent works include the anthropogenic stocks for metals (Schneider et al., 2015, 2013, 2011).

Group 3 Availability: availability of resources as a more wider

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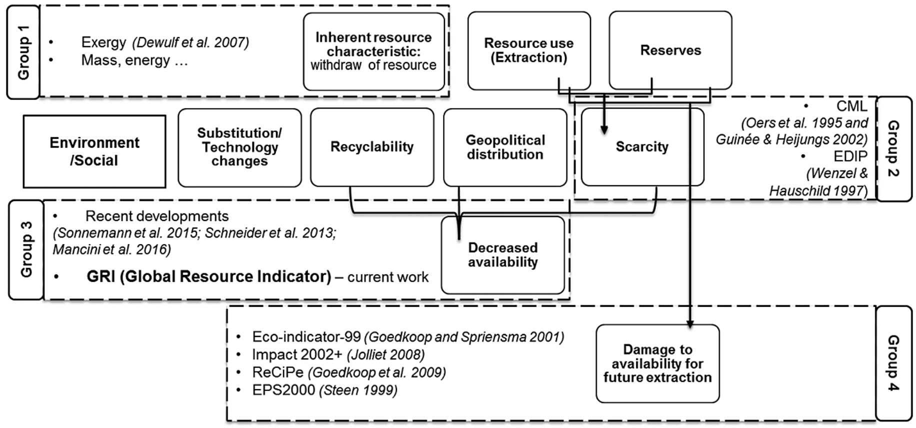

Fig. 1. Resource assessment cause and effect chain, including groups of indicators in LCA, and overall methodology for development of Global Resource Indicator (GRI) current work.

term is proposed within LCA framework (J. A. Drielsma et al., 2016) also the so called ESSENZ method (Henβler et al., 2016) where socio-economic availability is introduced as a new dimension in resource assessment beyond physical availability of resources. Although LCA focuses mostly on the geophysical availability of the resources, the criticality of resources is also introduced and discussed recently within the framework of LCA (Sonnemann et al., 2015).

Group 4 Damage to availability for future extraction: indicators are based on environmental impacts of the future extractions: these indicators are based on additional energy and cost of extraction for future extractions. The scarcity of metals extracted include surplus ore produced, surplus energy required, and surplus costs in the mining and the milling stage. Methods are available today within the LCA framework, e.g. EcoIndicator 99 (Mark and Renilde, 2001), ReCiPe (Goedkoop et al., 2009) and Surplus Cost Potential (Vieira et al., 2016).

Different approaches under the Life Cycle Assessment (LCA) framework are provided and used so far to address the resource consumption and production. However, they provide partial vision, based on limited available data, and do not reflect all the aspects related to different resources. Indicators confuse in some cases resource depletion with impacts on resource availability (J. Drielsma et al., 2016). Therefore, it is crucial to go beyond the current Life Cycle Impact Assessment (LCIA) methodologies in order to incorporate other important factors (e.g. recycling), not yet covered by the LCA resource assessment indicators and to assess resource availability as a more meaningful and comprehensive concept (J. Drielsma et al., 2016).

1.1. Critical review of resource assessment in LCA

Group 1 indicators focus on inherent properties of the materials. They cover relatively robust and certain characterization factors. Nevertheless, the resource problem is not limited to the inherent properties of materials. Impact pathway does not describe the availability of a resource, and therefore the environmental relevance of these indicators is low. The scarcity of the resources is not part of these indicators.

In the group 2, the resource problem is only linked to the depletion from the earth crust (Guinée and Heijungs, 1995; Oers et al., 2002; Wenzel and Hauschild, 1997). Their environmental relevance is higher than the indicators of the group 1. These indicators reflect the problem of scarcity of the resources as production is going on. But, exploratory activities and development of extraction technologies have increased reserve availability during the past years (USGS, 2014). Also, the elements, extracted from the ecosphere are not vanished after their use (J. Drielsma et al., 2016; J. A. Drielsma et al., 2016; Sonnemann et al., 2015). They are just transformed, alloyed, dispersed or coming back to the ecosphere directly, e.g. metallic compartment landfilled, or after a series of changes, e.g. energy resources.

Beyond the extraction from the earth' crust, the indicators of group two do not include recycling in the current LCIA models, leading to underestimation of total available substances within techno-sphere (Jolliet et al., 2003). It is considered here that recycling and anthropogenic stock (Schneider et al., 2015, 2013, 2011), is a promising initiation for evolution of the LCIA methods. The ratio of recycling rate to the anthropogenic stock plays the same role as the ratio of extraction rate to the extractable deposits. Within the context of the LCA, further development in modelling is necessary to incorporate recycling in both levels of inventory and impact assessment. In LCA, it is needed to go beyond geological or anthropogenic availability of the resources, also to include the difficulty of obtaining the resources which are available within either the techno-sphere or eco-sphere. The increasing attention on the expansion of circular economy proves the importance of recycling and accessible resources, besides depletion.

With regard to group 3, the Criticality was assessed in the European context by the Ad-hoc Working Group on defining critical raw materials (European Commission, 2010). Although LCA has focused mostly on geophysical availability of the resources, recently the criticality of resources is introduced and discussed within the framework of LCA.

In 2013, the Economic Resource Scarcity potential (ESP) was proposed based on assessment of resource provision capability from an economic angle, complementing existing LCA models (Schneider et al., 2013). The review of existing critically literature and the importance to integrate criticality in LCA was assessed by Sonnemann et al. (2015). Later in 2016 The ESSENZ method was proposed, assessing a product's resource efficiency considering the pollution of the environment as well as the physical and socio-economic availability of resources (Henβler et al., 2016). Mancini et al., in 2016 focus on the economic dimension of the resource criticality and propose the integration of this aspect in LCA through the use of characterization factors (CFs) based on the supply risk factors for Europe (Mancini et al., 2016). The concept of was applied to several industrial minerals and metals in LCA (Henβler et al., 2016; Mancini et al., 2016). These indicators provide a new supply risk vision to the LCA. Nevertheless, the fact that they are highly correlated with socio-economic aspects makes the prevision in future uncertain and generate high fluctuation in the results due to different interpretations. In addition, the socio-economic parameters are numerous and complex to establish and update. Further work is needed to establish an applicable LCA indicator based on availability of resource and the current work is also an attempt in this direction (Fig. 1).

The indicators of the group 4 analyze the resource problem from the viewpoint of prediction of future extraction efforts. The main difficulty is the uncertainty of the future prediction. Also, the complexity of parameters and indicators restrain those to a very limited number of Characterization Factors (CFs). These indicators cover only the resources available in the ecosphere as part of their scope of application.

The conceptual problems in the existing indicators limits the coverage of the resource type significantly. Vast coverage of an LCIA indicator is a requirement for a comprehensive resource assessment. None of reliable LCIA methodologies provide full coverage over various resource types. Few indicators cover the renewable rates for biotic resources. Some others, do not cover the energy resources. No distinction is made between fossil resources, being burnt in energy consumption or used for the non-energy purposes, e.g. plastics. In most cases, even when CFs are available, they are not comparable with different resource types, e.g. renewables versus non-renewable resources.

One of the major issues, related to the resource assessment, is that the resources availability is influential, and may even halt the development of sustainable products and services. Therefore, this article aims at assessing the availability of the resources based on the new indicator called Global Resource Indicator (GRI), including the recyclability and geopolitical availability (criticality). Several valuable works have been already conducted in the context of LCA to include different aspects of resource problems. The new indicator proposed in this article is based on several aspects of the material circulation during its life cycles: Recyclability, criticality and geopolitical availability of resources are part of the indicator (Fig. 2). The new approach enlarges and include the extent possible different resource assessment related criteria in a comprehensive and coherent framework.

The article also aims at adjusting the aspects and parameters when they are not in line with the proposed core resource consumption and production concept (e.g. adjust indicators to cover renewables and non-renewable resources). Also, it seeks simple and updatable input parameters so the largest number of Characterization Factors may be produced in the future.

2. Methods

Newly proposed Global Resource Indicator (GRI) integrates different resource assessment aspects to improve the characterization of the resources. Different aspects, related to the availability including both recyclability and geopolitical availability of resources are part of the multi-criteria indicator complementing scarcity, Fig. 2. Including recyclability and criticality enables to go beyond the resource depletion potential (geological availability). The GRI has positive correlation with the scarcity and negative correlation with both geological availability and recyclability.

The Scarcity is the first parameter to reflect the available resources in the earth crust. In this work, this factor is derived from CML characterization factors (F_{CML}) in LCA. They are used in group 2 of LCIA indicators.

One of the major new considerations in the proposed GRI is the “recyclability”. Although none of existing LCIA methods consider recyclability and recycling, these parameters influence resources availability. Recycling the resources decreases the depletion of virgin resources, so providing new sources to supply raw materials. The regeneration of renewable resources plays a similar role.

Geopolitical availability is another major point. The Geopolitical availability is defined as the inverse of the criticality for a given resource. The homogeneity of distribution of natural reserves is a resource criticality criterion. If a given resource is accessible in 10 countries, and is distributed evenly, long-term availability of the resource could be guaranteed. The worst case is a situation that a resource is available only in a few counties, especially with high relative concentration within one or two countries. In this case, even if the overall amount of the resource within the crust is considerable, the long-term availability is not assured. From the short-term viewpoint, the geopolitical stability of the territories where the resource is available becomes important.

Criticality and therefore geopolitical availability is not a major issue for recycling related to the anthropogenic stock as the resources are assumed to be recycled where they are used. The recycling happens most of the time near the materials consumption. The virgin resources in the China will become available in Europe by exporting the products, containing raw or processed minerals. Therefore, the more progressed the recycling, the more accessible the materials.

2.1. Global Resource Indicator (GRI)

The GRI has positive correlation with the scarcity and negative correlation with both geopolitical availability (inverse of the criticality) and recyclability (equation (1)). The formula to calculate the GRI CFs of resources is:

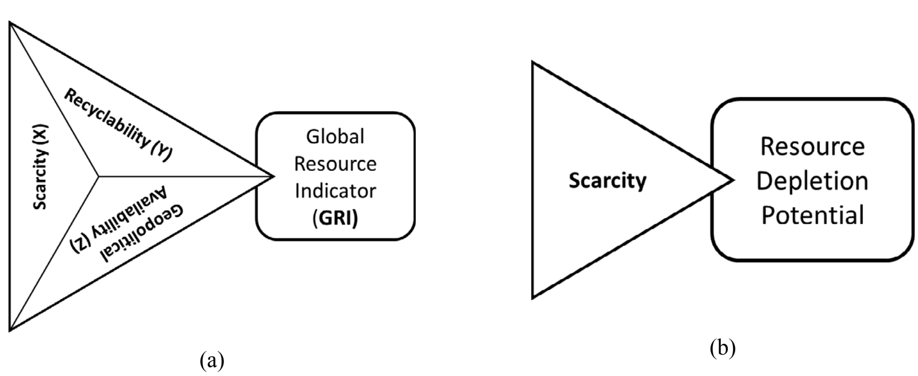

Fig. 2. Diagram of different aspects of Global Resource Indicator (GRI) (a), compared to the second group, i.e. scarcity resource indicators in LCA (b).

$$GRI = \frac{X}{Y \times Z}$$

$$GRI_{Fe-eq} = \frac{F^{normalized}_{CML-Fe-eq}}{\left(1 - F_{dispersion}\right) \times 10 \times F_{recycling} \times \sqrt[3]{F_{WGI} \times F_{deviation} \times F_{countries}}} \times \frac{F^{Fe}_{recycling} \times \left(1 - F^{Fe}_{dispersion}\right) \times 10 \times \sqrt[3]{F^{Fe}_{WGI} \times F^{Fe}_{deviation} \times F^{Fe}_{countries}}}{1} \quad (1)$$

where, X, Scarcity, is based on CML characterization factors (F_{CML}) adapted in case of renewable resources. Y is Recyclability or quality factor that depends on the dispersion and recycling rates ($F_{dispersion}$ and $F_{recycling}$). And Z is geopolitical availability. It depends on WGI index, number of countries and standard deviation (F_{WGI}, $F_{countries}$ and $F_{deviation}$).

Nine resources are studied here, some of them are very critical and are used in diverse sectors, including Rare Earth Elements (REEs): Cobalt–Platinum–Iron–Aluminum–Copper–Silver–Wood–Sand and gravels - REEs (Dysprosium–Europium–Neodymium).

2.2. Scarcity "X" adapted from CML

CML method is an LCIA method, developed by the Institute of Environmental Sciences (CML) of Leiden University (Guinée and Heijungs, 1995; Oers et al., 2002). This method covers several impact categories, including resource depletion. CML resource depletion indicator is recommended by International Reference Life Cycle Data System (ILCD) (JRC European commission, 2011), and is also used in Product Environmental Footprint (PEF) method (European Union, 2013) to assess the resources depletion potential. In CML, dimensionless Abiotic Depletion Potential (ADP) (equation (2)) is the annual extraction rates of a given element, divided by the squared reserve of the same element. Iron is considered as the reference substance; therefore, the formula is normalized by Fe. Fe is selected as reliable input parameters are accessible for Iron and the fact that it is more comprehensible compared to Sb for applicants. So, the CFs of each resource are proportional to Iron.

$$ADP_i = \frac{Ext_i}{Res_i^2} \times \frac{Res\_Fe_i^2}{Ext\_Fe_i} \quad (2)$$

where, ADP is expressed in kg Fe-eq (Iron Equivalent) and *Ext* and *Res* are expressed in unit of mass.

2.2.1. REEs CML characterization factors

The Scarcity indicators are derived from the CML 2002 CFs. The CFs of REEs used in this article are developed by Adibi in 2016 (Adibi, 2016; Adibi et al., 2014). The CML resource indicator is chosen to reflect the depletion from the point of view of geological reserves.

2.2.2. CML characterization factors adaptation for renewable resources

For renewable resources CML is adapted including the regeneration rate. Regeneration is associated with the duration of renovation of a resource; i.e. the rates of current annual replenishment of species. These factors are especially taken into account for biotic resources. Although the limitations of ecosystems and their renewability may impact human needs and life more than availability, this issue needs to be addressed within other LCA impact categories dealing with ecosystem; e.g. land use.

Principally, if the assumption is to assess the availability of a resource, the role of regeneration is very similar to recycling. In order to adapt CML with corresponding regeneration rate, equation (3) is proposed. The regeneration rate is applied to adjust reproduction as renewable (renewable share of the resource). As an example the regeneration rate is not applied to the forest surface loses for agriculture but to the plantations. For biotic resources, regeneration time ranges from one to several hundred years. Regeneration rate is obtained based on regeneration time as provided in equation (4).

$$ADP_{i(renewable)} = \frac{Extraction\ as\ loses_i}{(Res_i + (Reproduction\ as\ renewable_i \times Regeneration\ rate))^2} \times \frac{Res\_Sb_i^2}{Ext\_Sb_i} \quad (3)$$

$$Regeneration\ rate = \frac{1}{Required\ time\ to\ be\ regenerated} \quad (4)$$

where ADP is expressed in kg Fe-eq (Iron Equivalent). *Ext* and *Res* are expressed in unit of mass and *Regeneration rate* is expressed in (1/year).

Example of wood resources: In average wood requires about 100 years to be regenerated in the forest, so the regeneration rate is 0.01 (=1/100).

Metals, including nuclear fuel as stock resources, are nonrenewable resources (regeneration time is infinite, except for the astronomical processes). For flow resources such as wind and solar power, renewability is instantaneous. For the fossil fuels, the regeneration requires large geological timescales, so they are considered nonrenewable in LCA studies.

2.2.3. Sand and gravel CML characterization factor

With regard to Sand and gravel, resources of the world are plentiful. However, because of environmental restrictions, geographic distribution, and quality requirements for some uses, sand and gravel extraction is not authorized in many locations. CF of Sand and gravel in this study is taken from the French norm XP P01-064/CN ("XP P01-064/CN Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction - National addition to NF EN 15804 + A1," 2014) supposing that CF of gravel is equal to Silicium. The authors suggest more assessment in case of Sand and gravel in the future.

2.3. Recyclability "Y"

The first part of the indicator is calculating the Recyclability (reproduction for renewable resources), variable Y. In the formula, the recyclability is between 0 and 100%. It is multiplied by 1-dispersion rate. Then the result is multiplied by ten to provide a value within the range of one to ten.

$$\text{Let } Y = [\textit{Recycling rate} \times (1 - \textit{Dispersion rate}) \times 10] \qquad (5)$$

where Y is dimensionless and *Recycling* and *Dispersion rates* are expressed in %.

Recyclability (Y) shows the availability of the used resource. In another word, none-dispersed part of used material when it is recycled or regenerated. As an extreme case, metals recycling may reach 100%, i.e. ideal recycling without any loss of quality and dissipation in the far future. Metals can be reused many times without losing their functionality, but cannot be regenerated in the ore deposits. In the reality, the ideal recyclability might not be reached due to losses during extraction, transformation, transportation, etc.

2.3.1. Recycling rate

The recycling rate is the percentage of an element in discard that is recycled (United Nations Environment Programme, 2011). The end-of-life functional recycling rates (EoL-RR) from UNEP (United Nations Environment Programme, 2011) could be used to substitute the European recycling data in a global resource prospective. The recycling rate for some of these resources differs from a sector to the other, e.g. in the building sector, these values are quite higher. REEs have small recycling rates because they are used in small quantities, and much dispersed within the products. Quality degradation during recycling is not part of this indicator, therefore future improvement to cover this aspect is recommended.

2.3.2. Dispersion rate

Dissipative losses are defined as the losses of materials into the environment, into other material flows, or when reaching permanent waste. The dissipation makes the of materials recovery unfeasible technically or economically (Zimmermann and Gößling-Reisemann, 2013). Dispersion may happen due to 3 major issues: 1- Intimate mixes between materials inside products: One major reason is that several resources are used in very limited quantities with structural changes in the products. 2- Dissipative application: When small quantities of resources are used inside products. 3- Technology related dissipation: When the state of material change to non-recoverable state, e.g. to gas or liquid state, e.g. use of metals in paint.

Cobalt has a dissipation rate of 30%–40% (Zimmermann and Gößling-Reisemann, 2013). REEs have higher dissipation rates (over 90%), depending on the use of particular REEs. For Platinum group metals, dissipative loses of Pt and Pd from catalysts is between 25% and 30% (Zimmermann and Gößling-Reisemann, 2013). An estimation of 20% of silver from extracted ore is returned to the lithosphere as tailings (Eckelman and Graedel, 2007). Copper can be recovered at the rate of 82% from the slag of 3.7% of Cu. So its dissipation rate can be assumed as 18%. Iron and steel industry have mineral processing technology to recover 90% of Fe in steel scrap, so the dissipation is considered about 10% (Shen and Forssberg, 2003). Considering the high share of recycling in Fe and Al, dispersion rate of aluminum is considered to be 10%. It is mostly because aluminum is used purely and in big quantities in the products, hence easy to recover.

Wood, sand and gravels are considered ignoring the dispersion rate (given their very low dissipation), so the values are not used in the calculations. The estimated dispersion rates of resources, studied in this project are summarized in Table 1.

Table 1
Dispersion rate of the studied resources.

Materials	Dispersion rate
Iron	10%
Aluminum	10%
Cobalt	35%
Platinum	30%
Silver	20%
Copper	18%
Rare Earth Elements	90%

2.4. Geopolitical availability "Z" of extractable resources

Geopolitical availability (defined as the inverse of the criticality) parameters related to the extractable resources are based on three aspects:

1. Geopolitical Stability of the countries, where resources are available:

Resource supply has less fluctuations when the resources are in the stable countries. As an example, the cobalt deposits are located in the countries where there are major governmental problems. In many cases the problem is not originated only from the politics but the social, cultural, environmental or security instability.

2. Number of countries where a given resource is available:

Even in a well-distributed situation (e.g. two countries with 50% of availability for each, i.e. completely heterogeneous) the resource issue is not yet solved completely, as the two stable countries, might become unstable one day. So, the last input in the indicator is the number of countries where the resource is available.

3. Homogeneity of distribution of a given resource in different countries:

When a resource is expanded over several countries but the major supplier is located in a single country (even if the country is geopolitically stable), we might at any time face supply issues. The geopolitical issue is much less probable when the resource is distributed more homogeneously in different countries.

2.4.1. Geopolitical stability

To develop **Geopolitical stability** factors, the World Governance Indicators (WGI) ("WGI, 2015 Interactive > Home," n.d.) are used, which benefits of a research database in the background, summarizing the views of the quality and stability of countries governance, provided by large number of enterprises, citizens and expert survey respondents within industrial and developing countries. The WGI project aggregates individual governance indicators from 215 economies over the period 1996–2013, for six dimensions of governance:

Table 2
Geopolitical stability index of main iron producing countries, considering iron (2013) price.

Iron production 2013 USGS	Mt	Di	*V*	*P*	*G*	*RQ*	*RL*	*C*	x_i
USA	31	2,65	1,08	0,61	1,50	1,26	1,54	1,28	0,20
Brazil	26	2,22	0,37	−0,28	−0,08	0,07	−0,12	−0,12	0,11
China	720	61,54	−1,58	−0,55	−0,03	−0,31	−0,46	−0,35	2,41
Germany	27	2,31	1,41	0,93	1,52	1,55	1,62	1,78	0,18
India	50	4,27	0,41	−1,19	−0,19	−0,47	−0,10	−0,56	0,18
Japan	84	7,18	1,10	0,98	1,59	1,10	1,41	1,65	0,55
Korea	39	3,33	0,69	0,24	1,12	0,98	0,94	0,55	0,22
Russia	50	4,27	−1,01	−0,75	−0,36	−0,37	−0,78	−0,99	0,15
Taiwan	14	1,20	0,88	0,86	1,19	1,14	1,04	0,68	0,08
Turkey	9	0,77	−0,26	−1,19	0,37	0,42	0,08	0,11	0,04
Ukraine	29	2,48	−0,33	−0,76	−0,65	−0,64	−0,83	−1,09	0,09
Other	91	7,78	0,00	0,00	0,00	0,00	0,00	0,00	0,39
TOTAL	1170	100							4,59

1. Voice and accountability (V)
2. Political stability and the absence of violence (P)
3. Government influence (G)
4. Regulatory quality (RQ)
5. Rule of law (RL)
6. Control of corruption (C)

For the aim of this project, we took the estimation of each governance performance that ranges between −2.5 (the weakest) and +2.5 (the strongest) in 2013. As example, the governance performance of China in 2013 is composed of Voice and accountability (−1.58), Political stability and absence of violence (−0.55), Government effectiveness (−0.03), Regulatory quality (−0.31), Rule of law (−0.46) and Control of corruption (−0.35).

For each resource, we used the USGS 2013 dataset that shows distribution in different countries. The geopolitical stability index is calculated by equation (6). In this equation, geopolitical stability index is calculated by averaging over all the mentioned WGIs. The results are added by 5 after being multiplied by 2 in order to scale the outputs from the interval of [-2.5, +2.5] to the new interval of [0, 10]. The lower (upper) boundary corresponds to the weakest (strongest) case. For iron, as an example, the x factor is calculated for essential producing countries (Table 2). Higher the x less critical is the resource.

$$F_{WGI} = \sum_{i=1}^{n}\left(5 + 2 \times \frac{\mathrm{V+P+G+RQ+RL+C}}{6}\right) \times \frac{\mathrm{D}_i}{100} \tag{6}$$

where F_{WGI} is the geopolitical stability index, which varies between 0 (the worst case) and 10 (the ideal case). Di is the percentage of distribution of resources in each country. i is the index of each country and n is the total number of producing countries.

2.4.2. *The homogeneity of distribution of a given resource*

The homogeneity of distribution is calculated by the ratio of standard deviation (SD) to the height (i.e. 30).

$$F_{deviation} = \left(1 - \frac{SD}{30}\right) \times 10 \tag{7}$$

The worst case is SD > 30%. It means that resources are not evenly distributed and there is a high risk of monopoly. The maximum SD = 30% is then chosen since the highest obtained SD is 27.92%, corresponding to platinum. Values of “y” vary between 0 (the idol case) and 10 (the worst case: SD = 30%).

$$\text{For iron}: F_{deviation} = \left(1 - \frac{17.715}{30}\right) \times 10 = 4.094$$

2.4.3. *Number of countries where a resource is available*

This parameter, z, is calculated by the ratio of the number of countries where a resource is available to the highest number among all resources, i.e. 20 (equation (8)).

$$F_{countries} = \begin{cases} \dfrac{n}{20} \times 10 = \dfrac{n}{2}; & 0 < n < 20 \\ 1; & 20 \le n \end{cases} \tag{8}$$

The main assumption here is that when a resource is extractable in more than 20 countries, there is no risk of monopoly, excluding other countries as defined here. In calculating “z”, all the countries with the production rate of less than 10% of the world total production (USGS tables of production) are grouped into “other countries”. The “z” value is again between 0 (the worst case) and 10 (the best case).

For Iron: n = 11 + 1 = 12 so $F_{countries} = 6$.

2.4.4. *Geopolitical availability (GA)*

Three averaging operators are used for combining these three geopolitical factors, x, y and z, and to calculate the geopolitical availability.

1 Simple Arithmetic Averaging $= \frac{F_{WGI} + F_{deviation} + F_{countries}}{3}$

Table 3
Calculation of the geopolitical availability, using the three integral operators.

	1- simple arithmetic	2- weighted arithmetic	3- geometric
iron	4,82	4,90	4,96
aluminum	6,63	6,22	6,47
copper	6,92	6,64	6,87
sand and gravel	8,04	7,72	7,93
platinum	3,11	3,62	2,32
cobalt	4,90	4,58	4,81
silver	6,19	5,92	6,07
wood	8,42	8,02	8,32
Dy	5,15	5,82	4,79
Eu	5,53	5,48	5,45
Nd	5,27	5,27	5,23
La	5,04	5,03	5,02
Ce	4,90	4,89	4,89
Pr	5,16	5,15	5,13
Sm	5,71	5,80	5,64
Gd	5,58	5,90	5,50
Tb	5,19	5,60	5,06
Ho	4,07	5,01	3,32
Er	4,47	5,35	3,88
Tm	3,83	4,89	2,64
Yb	4,77	5,41	4,48
Lu	4,75	5,34	4,50
Y	5,10	5,85	4,62

2 Weighted Arithmetic Averaging $= 0.5\ F_{WGI} + 0.25\ (F_{deviation} + F_{countries})$
3 Geometric Averaging $= \sqrt[3]{F_{WGI} . F_{deviation} . F_{countries}}$

The distribution percentage of the REEs are taken from the tables, provided by Adibi (2016). The results of these three averaging strategies for different resources are presented in Table 3.

The third integration operator seems to be the best, since the geometric averaging is more sensitive to the extreme values. For example: imagine a resource with $F_{WGI} = 1$, $F_{deviation} = 9$ and $F_{countries} = 9$, this resource is well distributed (due to $F_{deviation}$ and $F_{countries}$) but the producing countries have serious political problems ($F_{WGI} = 1$) and the situation is not stable at all.

1st operator → GA = 6.33
2nd operator → GA = 5
3rd operator → GA = 4.32

2.5. Sensitivity analysis on the GRI parameters

Any change in the indicators of GRI (equation (1)) influences the results significantly. We made a sensitivity analysis on the indicators and provided a graphical illustration of changes in the GRI CFs. Fig. 3 shows sensitivity of the CFs to each sub-indicator. The sensitivity curve is exponential for all the factors. Only dispersion rate has a positive correlation with the impact. Dispersion rates vary from 10 to 90% for the studied resources. The geopolitical availability indicators vary from 2.32 (lowest) to 8.32 (highest). Recycling varies for short term indicator from 1 to 68%, while long term recycling given the technology improvements is assumed to be 90%.

3. Results and discussion

The CFs of $\frac{X}{Y.Z}$ accounts all the indicators (extraction rate, recyclability, regeneration rate, dispersion rate, etc.). In this CF, all the indicators (X, Y and Z) are considered with the equal importance. Z and X are respectively geopolitical availability and CFs of CML, normalized by Fe. Y and Z have different tendencies, compared to X. Higher values of Y and Z, and lower values of X show more availability of the resource. That is why Y and Z were introduced in the denominator. The obtained results are shown in Fig. 4 to reveal how

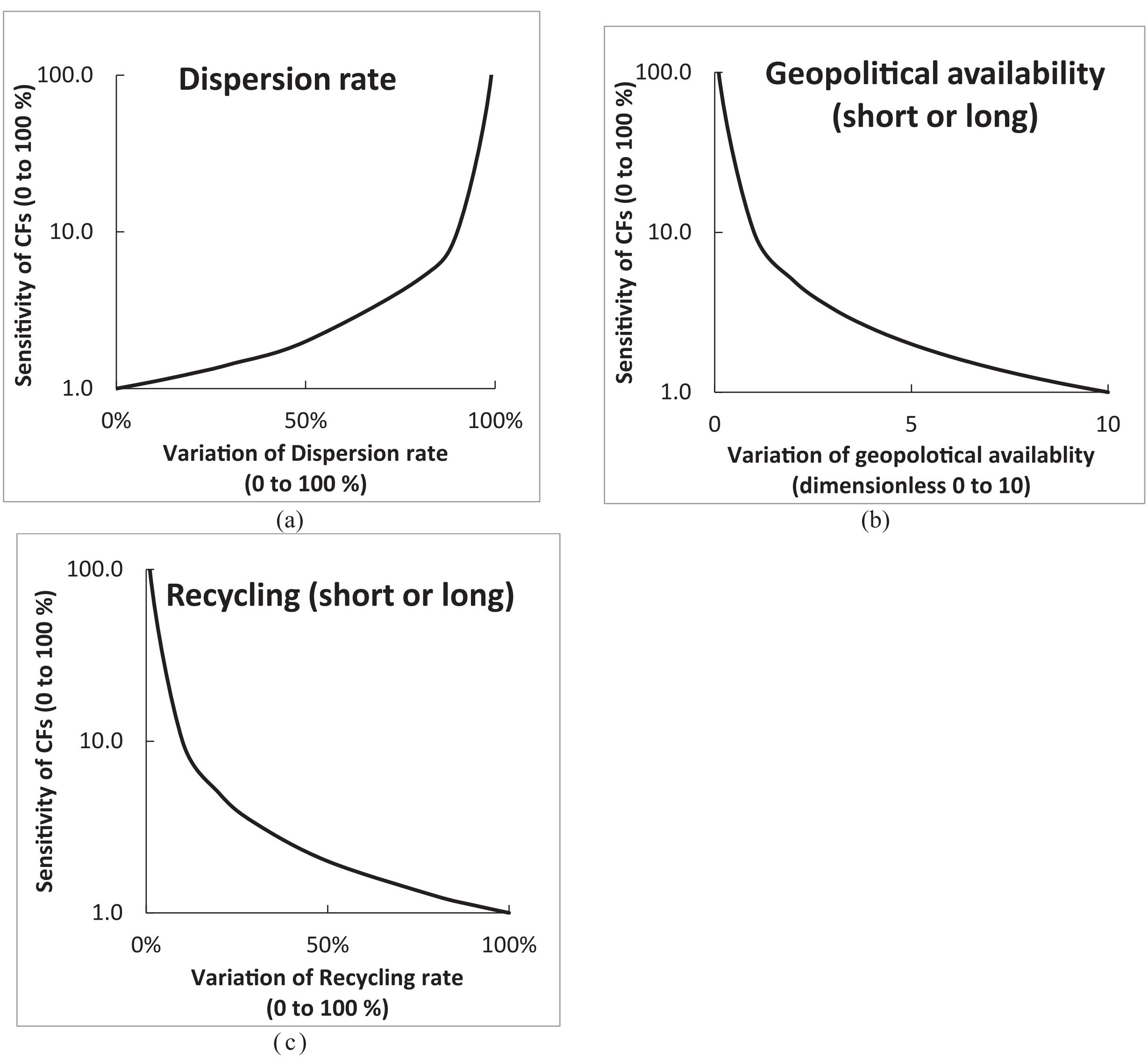

Fig. 3. Sensitivity of the CFs with regard to subcategories. a) Dispersion rate b) Geopolitical availability (short or long) c) Recycling (short and long).

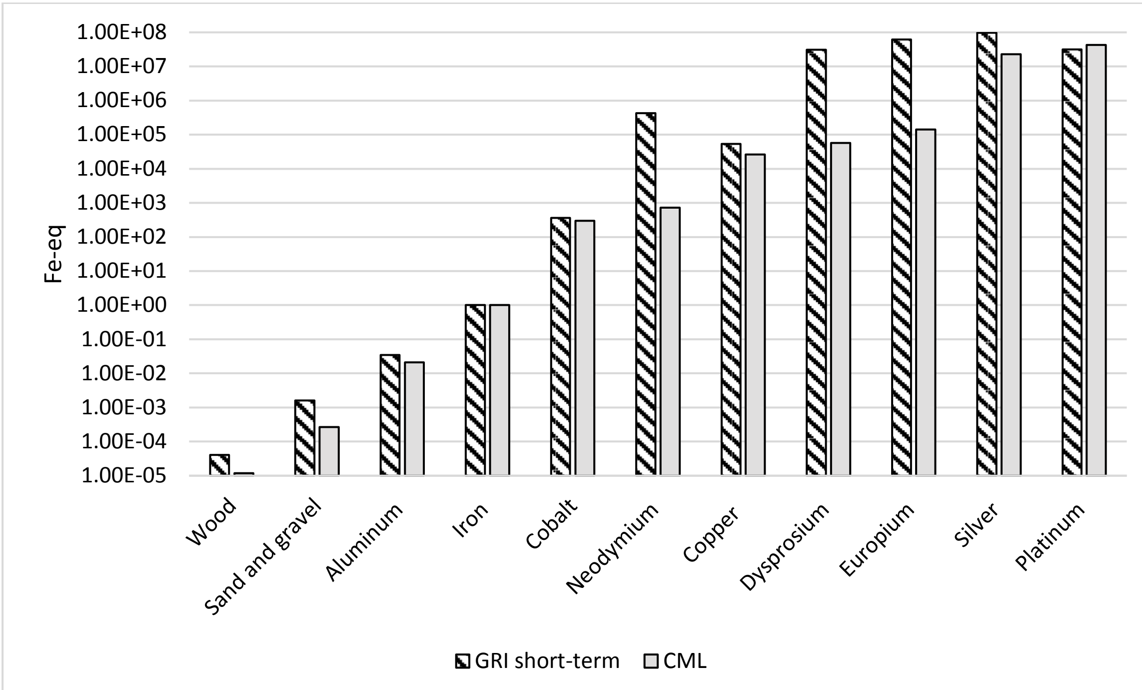

Fig. 4. CFs variation in GRI compared to CML.

the CF varies, using different indicators.

Comparing the results with CML factors, all resources show higher impacts (CF increases for short-term). Comparing to CML, it is found that most of resources are highly influenced by introduction of the other indicators, except "aluminum and copper".

Due to very uneven distribution of REEs in the counties, also the instability of the corresponding counties, the factors of REEs are changed the most. This variation could be understood, comparing factors with the CML CFs. Actually, REEs have a recycling rate of 1% in the Europe, which is very low.

3.1. Short versus long term vison

The LCA-based approaches in assessing environmental impacts are based on long-term prospective (more than 50–100 years). Short-term concerns are mostly related to the resources that are under the risk of geopolitical constraints, geostrategic considerations, social concerns or environmental legislations. The main environmental consequence of the short-term concerns is the supply risk of the resources, used in sustainable products. As an example, shortage in the rare earth supply, affects the development and the use of green technologies (wind turbines, photovoltaic panels, etc.). Nevertheless, interpretation of these indicators needs to be done jointly with long-term resource indicators to provide valid results. Today, these two visions are most of the time making overlaps and even mixed in most recent developments. It is crucial to differentiate the short- and long-term issues in LCA.

In this indicator both short-term and long-term CFs are distinguished. Two indicators affect the short and long term changes:

1 Recycling rate:

Recyclability values are assessed in this study, based on the recycling rates in the Europe, and are used to obtain short-term indicators. For long-term indicators, it is assumed that recyclability is expected to reach 90% due to technological development of recycling in the far future except for wood where 50% wood for energy is considered.

2 Geopolitical availability

The geopolitical stability is not applied to the long-term Geopolitical availability, since the geopolitical stability is considered as a short-term indicator. In this case, Geopolitical availability, Z, is calculated following equation (9).

$$GA_{short-term} = \sqrt{F_{deviation} \times F_{countries}} \tag{9}$$

where, $F_{deviation}$ is the homogeneity of distribution of a given resource, and $F_{countries}$ is the abundance of countries where a given resource is available. Considering both long term recycling rate and geopolitical availability (GA), Table 4 provides the CFs for both short-term and long-term assessment of each resource.

In case of long-term, it is assumed that the recycling of the resources reaches 90%, therefore their impact is reduce significantly compared to the short-term factors except cobalt where the geopolitical availability is increased when the geopolitical stability is not considered. The factors of REEs are changed the most comparing short and long term factors. This variation is due to the high geopolitical instability of the countries at short term. Additionally, the actual REEs recycling rate is 1% in Europe. However, we assumed that in the future, the recycling rate will reach 90%, so the factors are improved.

3.2. Technology changes and substitution

If we assume that technology changes improve the resource assessment parameters: dispersion rate, recycling rate, quality degradation, etc. then the GRI needs to consider these improvements through the time. Substitution is another major issue. The technology has played an important role in finding substitutions for various elements or materials. As an example, the supply shortage

Table 4
Calculation of Characterization Factors for short- and long-term resource assessments. **All values, from the CML are converted to Fe-eq. *Wood is renewable, CF is obtained based on adapted renewable CML.

Resource	Y short-term	Y long-term	Z short-term	Z long-term	X adapted CML CFs (Fe-eq **)	CFs short-term	CFs long-term
Iron	1.000	1.000	1.00	1.00	1.00E+00	1.00E+00	1.00E+00
Aluminum	0.790	1.000	1.30	1.43	2.09E-02	3.44E-02	2.99E-02
Copper	0.676	0.911	1.39	1.45	2.60E+04	5.35E+04	4.14E+04
Platinum	0.627	0.778	0.47	0.30	4.23E+07	3.17E+07	1.63E+07
Cobalt	0.792	0.722	0.97	1.07	2.99E+02	3.66E+02	4.43E+02
Silver	0.287	0.889	1.22	1.28	2.26E+07	9.61E+07	3.25E+07
Dysprosium	0.002	0.111	0.97	0.73	5.68E+04	2.75E+07	3.74E+05
Europium	0.002	0.111	0.78	1.07	1.41E+05	5.50E+07	1.36E+06
Neodymium	0.002	0.111	1.05	1.01	7.21E+02	3.79E+05	6.56E+03
Wood	0.358	0.617	1.68	1.78	8.68E-06*	4.07E-05	2.50E-05
Sand/gravel	0.269	1.111	1.60	1.66	2.67E-04	1.59E-03	3.99E-04

Table 5
Scenarios of different wind turbines studied.

Scenario 1: DFIG Iron	Double Fed Induction Generator, towers made of Iron
Scenario 2: DDPMG Iron	Direct-Drive Permanent Magnet Generator, towers made of Iron
Scenario 3: DFIG Concrete	Double Fed Induction Generator, towers made of Concrete
Scenario 4: DDPMG Concrete	Direct-Drive Permanent Magnet Generator, towers made of Concrete

due to geopolitical concerns, e.g. on REEs, was partially solved by industrial development through finding some extend substitutions e.g. substitution of REEs by other metals and technologies in car industry. Another famous example is banned elements due to safety problems, e.g. the asbestos and many other materials were phased out of buildings. For sure, the substitution and technology adaptions are most of the time unpredictable, occasional, complex and resulted from focused research investments. The substitution is not part of in this work. The authors suggest further research regarding the substitution and its effects in the future.

4. Application of GFs in the wind turbines and assessment of the results

Several LCA studies investigated the environmental impacts of wind turbines. Studies focus on assessment of impacts (Wang and Teah, 2017) and highlight the potential improvements (Demir and Taşkın, 2013). In some cases comparisons are made between available technologies and their performance in different geographical zones (Uddin and Kumar, 2014). This section describes results of resource evaluation based on GRI indicators. They highlight the influence of the new indicator on resource assessment of wind turbines.

Datasets of two different types of 3 MW wind turbine were obtained from Crawford et al. (Crawford, 2009), and complemented using the permanent magnet LCI (Adibi, 2016). The wind turbine towers can be made of iron, concrete or hybrid. For each type, either wind turbines contain REEs (DDPMG) or not (DFIG) generator. Different wind turbines scenarios are provided in Table 5 and their respective composition is provided in Table 6. The main components of the wind turbines include the rotor (hub and blades), nacelle (generator, gearbox, brakes, electronic controller, transformer, and control system), tower and base. The four wind turbines chosen for this study were horizontal axis, 3 blade systems derived from Crawford (2009).

These quantities are multiplied by the proposed characterization factors, and results are obtained and presented in Table 7.

Fig. 5 illustrates the GRI results per resource for the four wind turbines technologies. The impact is attributed less than 40% to copper and more than 60% to Dysprosium and Neodymium. Dysprosium with a 4 kg mass (0.00021%) represents 25% of total impacts. Although a significant mass of copper (around 4 t) is used

Table 6
Composition of different types of wind turbines Crawford et al. (Crawford, 2009). *The copper is used as winding wires (recyclable).

Material		Part	DFIG Concrete	DDPMG Concrete	DFIG Iron	DDPMG Iron
Steel	kg	Rotor	730	730	730	730
Iron Cast	kg	Rotor	19200	19200	19200	19200
Glass fibers (~sand)	kg	Rotor	12040	12040	12040	12040
Epoxy resin	kg	Rotor	8030	8030	8030	8030
Steel	kg	Tower	77122	158760	158760	158760
Paint	kg	Tower		1240	1240	1240
Concrete	kg	Tower	590000			
Steel	kg	Foundation	36000	36000	36000	36000
Concrete	kg	Foundation	1140000	1140000	1140000	1140000
Copper	kg	Nacelle	2561	2561	2561	2561
Aluminum	kg	Nacelle	2311	2311	2311	2311
Steel	kg	Nacelle	55290	55290	55290	55290
Plastics	kg	Nacelle	700	700	700	700
Copper	kg	Generator	1430	14	1430	14
Steel	kg	Generator	5710	1268	5710	1268
Neodymium	kg	Generator		415		415
Dysprosium	kg	Generator		4		4

Table 7
Application of GFs on different wind turbine types.

Wind turbine (Different types)	CML-Fe eq	GRI kg-Fe eq short-term	GRI kg-Fe eq long-term
DFIG Concrete	1.04E+08	2.14E+08	1.65E+08
DDPMG Concrete	6.77E+07	4.05E+08	1.11E+08
DFIG Iron	1.04E+08	2.14E+08	1.66E+08
DDPMG Iron	6.77E+07	4.05E+08	1.11E+08

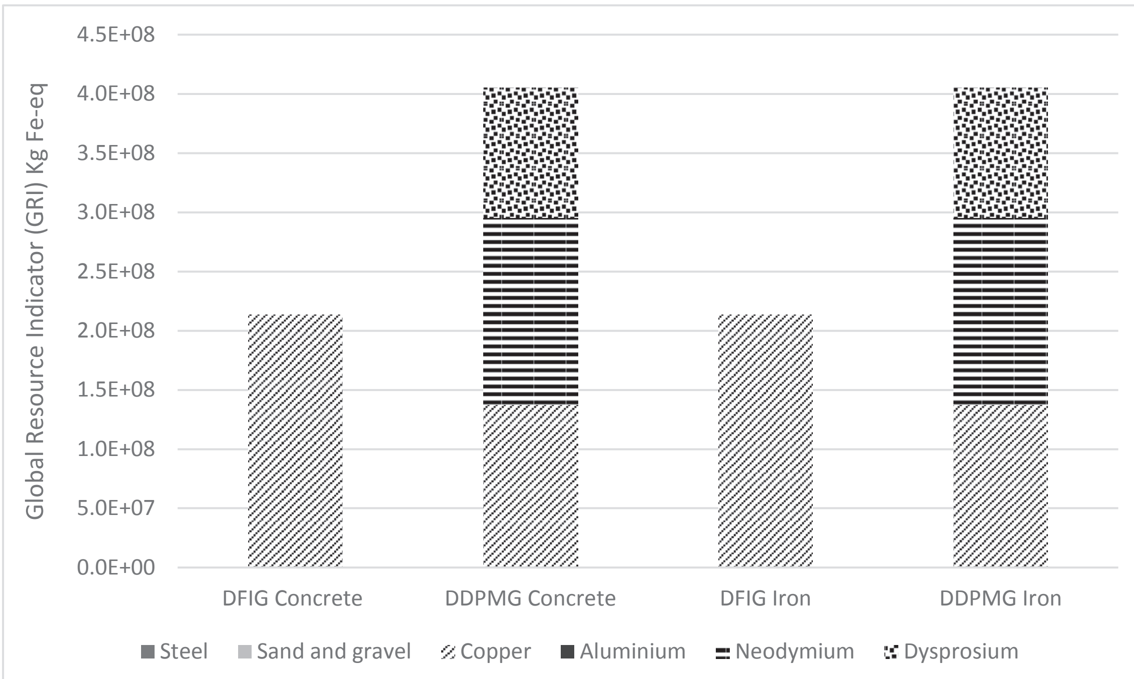

Fig. 5. GRI results for the 4 wind turbines technologies at short term.

in the product, applying the new indicator highlight the importance of the rare earth elements in DDPMG (both iron and concrete). The use of REEs in these application is identified as hotspot applying the indicator.

Due to Fig. 6, wind turbines with REEs (DDPMG) have the highest impact at short-term. The problem with these elements is that they are very dispersed within the products, so recyclability rate is about 1%. Technological enhancement for increasing

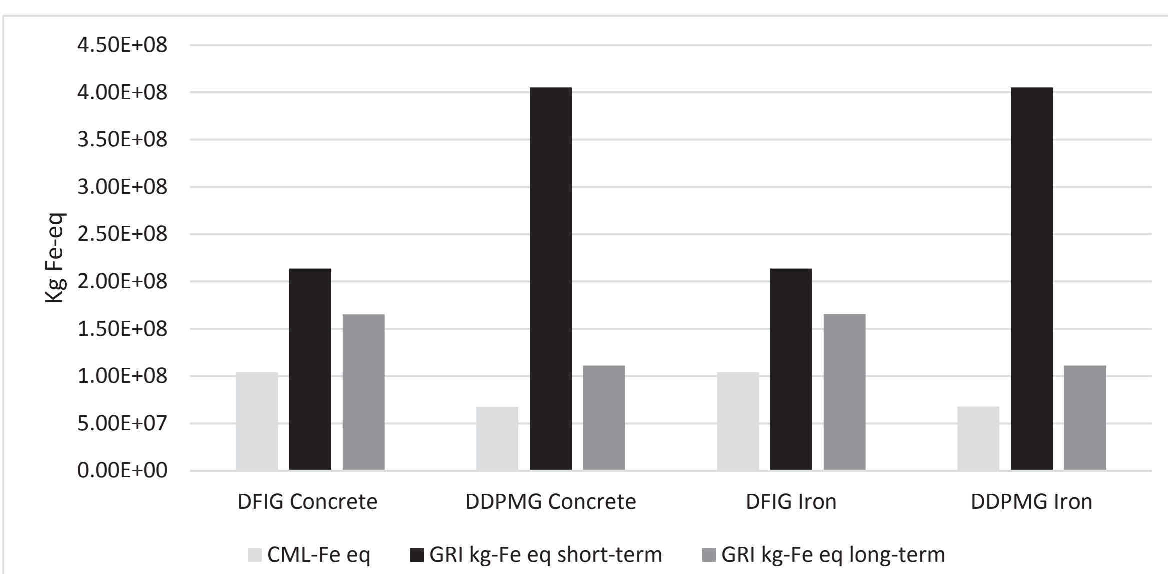

Fig. 6. Comparison between four different types of wind turbines (i) CML baseline (ii) short term GRI and (iii) long term GRI in Fe-eq.

recyclability of REEs may help the security of the resources. The CML impacts are almost 100% resulting from the copper. The limit of this case study is a very dominant quantity of copper. The strength of the indicator may be better highlighted in case of application in a product with a more homogenous diverse composition of materials.

5. Conclusion

Resource assessment and circular economy are defined as topics of growing interest at business, governmental and research contexts. In this work, we propose a new multi-criteria indicator to develop, new characterization factors taking into account different criteria, affecting resources life cycles. In place of a simple depletion potential, Global Resource Indicator is proposed. Both recyclability and Geopolitical availability of resources are part of the method complementing scarcity.

Most of resources are influenced by introduction of the additional indicators. The results also showed that the order of importance of resources are influenced when additional indicators, including recycling is taken into consideration. This is also the case comparing the results with CML characterization factor. The results also show that if short and long term aspects are tackled correctly, they influence significantly the resource classification.

The Global Resource Indicator, may cover all types of resources (renewables and non-renewables). Data needed to develop the missing additional characterization factors are relatively simple to provide. Therefor gaps may be filled compared to existing LCA resource assessment indicators.

From the resource prospective, Circular Economy focuses on the design for reuse and remanufacturing, therefore "making a closed loop" of product life-cycles through recycling, reuse, etc. In some cases, making a closed loop requires more energy. Waste, losses and quality degradation of resources are never equal to zero, therefore additional resources and materials are required to close the loops. All these additional efforts need to be assessed and compared with benefits of the closed-loop resources economy.

Part of these benefits and impacts are covered by life cycle inventory assessment. Aspects that are not covered by life cycle inventory may be covered by life cycle impact assessment methods. This work includes recyclability and dispersion rate as resource impacts and geopolitical availability of virgin resources compared to recycled ones as benefits. Quality degradation is not addressed in this article and need further assessment. Quality degradation and other relevant aspects of circular economy are discussed and assessed by Adibi in 2016 (Adibi, 2016).

Finally, the CFs derived from the new method are tested in a case wind turbine and the applicability is validated. In addition, the below aspects are the point to improve within the next resource related works based on the results and limits of the current work:

- Accessibility is not addressed in this article as there is a need to link the accessibility to the extraction, use and anthropogenic, separately.
- Dynamic models seem crucial, the methodology needs to consider a big picture of the material circulation during its life cycles, and the quantities of each stock (extraction, use and anthropogenic) to be predicted over the time.
- The substitution is not part of the proposed indicator and needs to be elaborated in the resource assessment.

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