Abiotic depletion due to resource consumption in a steelwork assessed by five different methods

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Abstract

This paper assesses the relative contribution of the individual resources to abiotic depletion in the production of steel by ArcelorMittal Gent, a major Belgian Steelwork. The contribution of both energetic (natural gas, coke gas, fuel, cokes, anthracite, coal, powdered coal and electricity) and non-energetic resources (iron-ore, iron scrap and lime(stone)) to the total abiotic depletion is calculated by the CML-, CExD-, EPS-, Eco-indicator 99- and mass and energy-methods. The results obtained by the five methods are compared. In addition the methods are evaluated taking into account three ISO-14042 based criteria. Some reflections on the applicability are dealt with for the specific case of steel production. According to the applied assessment method, ArcelorMittal should, in order to reduce abiotic depletion, either mainly focus on further improving energy efficiency (CML), further improve material efficiency (EPS) or focus on both energy and material efficiency improvement (Eco-indicator 99, CExD). For the EPS- and Eco-indicator 99- method the conclusion is based on events in the (far) future without consideration of technological improvements and therefore does not seem realistic for the actual steel production process.

Keywords: Abiotic depletion; Impact assessment; Steelwork: Industry

1. Introduction

Companies usually evaluate the environmental performance of industrial sites or production processes by the amount of pollutants emitted and resources consumed.

Emissions can however be converted in environmental impacts in the categories climate change, acidification, eutrophication, human and eco-toxicity, photo-oxidant creation and ozone depletion; resource consumption can be converted in an impact in the category abiotic depletion (Block et al, 2007). In this way it is made clear which pollutant or resource has the highest environmental impact in each category and more effective measures for total impact reduction can be taken.

The environmental impact of a pollutant or resource within a certain impact category can be quantified by multiplying the emission or consumption (mass) by an appropriate characterisation factor. The total impact within an impact category then equals the sum of all individual impacts. For several impact categories, such as climate change and photo-oxidant creation, generally accepted characterisation factors (Global Warming Potential, Photochemical Ozone Creation Potential) are available (Solomon et al., 2007; Jenkin and Hayman, 1999). The problem of abiotic depletion, however, can be interpreted in several ways, which led to the development of different characterisation factors. Examples are the ADP (abiotic depletion factor), developed by the Institute of Environmental Sciences of Leiden University (Guinée et al., 1995; Guinée et al., 2002); the exergy, as used in the Cumulative Exergy Demand method (Bösch et al., 2007); the WTP (willingness to pay), developed within the framework of Environmental Priority

Strategies (Steen, 1999) and the surplus energy developed within Eco-indicator 99 (Goedkoop and Spriensma, 2001).

The main aim of this paper is to assess the influence of the different problem definitions of these methods on the relative contribution of the individual resources to abiotic depletion, in the production of steel by Arcelormittal Gent, a major Belgian steelwork. The contribution of both energetic (natural gas, coke gas, fuel, cokes, anthracite, coal, powdered coal and electricity) and non-energetic (iron-ore, iron scrap and limestone) resources to the total abiotic depletion is calculated by the CML-, CExD-, EPS-, Eco-indicator 99- and mass and energy-method. The results obtained by the five methods are compared and discussed. Recommendations for reduction of abiotic depletion by ArcelorMittal Gent are made for each method, based on the relative contribution of the considered resources.

2. Methods

2.1 Steel slab production process; involved resources

ArcelorMittal Gent is located on the right bank of the canal Ghent-Terneuzen, about 20 km from the centre of the city of Ghent in Flanders, Belgium. With a production capacity of ca. $5 \cdot 10^6$ ton of steel per year, it is one of the major production sites of the ArcelorMittal Group, the largest steel producer in the world.

Figure 1 gives a schematic overview of the production process at ArcelorMittal Gent and the resource flows considered in this study. The resource flows indicated by black arrows and quantified in table 1, are the major energetic and non-energetic flows

entering the considered plant boundary (indicated by a dotted black line); their impact to abiotic depletion (for the year 2005) is evaluated by means of the five methods. The resource flows indicated in grey are given to complete the production scheme; they are either internal flows (dotted grey arrows) or external flows not entering the considered system boundary (e.g. coke coal). Some smaller resource flows are not indicated because their relative contribution to the total abiotic depletion is insignificant and thus does not influence the conclusions drawn in sections 3.1 and 3.2. The output flow (steel products) is indicated by a dotted black arrow. As it is not the aim to evaluate the abiotic depletion during the complete life-cycle of steel, resources consumed during mining, refining or transport are not considered.

The production process starts with the unloading of raw materials, mainly coal and iron ore, in the plant's own harbour. In the coking plant, a blend of different coking coal is heated to 1250 °C in the absence of oxygen (dry distillation), resulting in a solid residue, coke, and the valuable by-product coke oven gas. In the sinter plant, a mixture of iron ore fines, limestone, coke and anthracite are heated and converted into sinter. Coke and sinter are then loaded into the blast furnace where hot blast (air heated to 1,250°C) is injected, converting the coke into the gasses for reducing the iron ores and generating the necessary heat for melting the reduced ores. In the steel shop, hot metal flowing out of the blast furnace is converted into liquid steel by removing impurities. The liquid steel is then continuously poured into a mould. After leaving the mould, the steel is supported by a series of rolls through which the slab is guided. Large quantities of cooling water are then sprayed upon the slab between the rolls in order to solidify it.

The slabs leaving the casting machine are cut to length. They then undergo a series of further treatments such as pickling, hot and cold rolling, hot dip galvanisation, organic coating and so on. ArcelorMittal Gent produces merely carbon steel and derived products, no alloys. A more complete description of the steelwork is given in Van Caneghem et al. (2010).

2.2 Impact assessment methods

The total abiotic depletion due to the consumption of resources, in this case in the process of steel making shown in figure 1, can be expressed as the sum of the products of the resource masses consumed with the respective characterisation factor for abiotic depletion:

$$Abiotic\ Depletion = \sum_i CF_i \times m_i \quad (1)$$

where

CF_i : characterisation factor for abiotic depletion of resource i

m_i : mass of resource i consumed in the process.

The five different methods for the assessment of abiotic depletion considered in this study each start from a different problem definition to derive the characterisation factor mentioned in equation (1). A brief description of the methods is given in sections 2.2.1 to 2.2.5.

2.2.1 Method based on mass and energy

The method based on consumed mass and energy is only used for reference and does not apply characterisation factors: CF_i in equation (1) is equal to 1. The abiotic depletion equals the sum of the masses of the consumed resources. For energetic

resources, the energetic equivalent obtained by multiplication of the consumed mass with the heating values is usually preferred.

2.2.2 CML-method

Guinée and Heijungs (1994) and Guinée et al. (2002) developed the Abiotic Depletion Potential (ADP), a characterisation factor based on global reserves and extraction rates. They define abiotic depletion as the consumption of resources that are not renewed in nature and eventually will be depleted completely.

$$CF_i = ADP_i = \frac{DR_i}{(R_i)^2} \times \frac{(R_{ref})^2}{DR_{ref}} \quad (2)$$

where

ADP_i: Abiotic Depletion Potential of resource i (kg Sb-equivalents/kg resource i)

DR_i: the extraction rate of resource i (kg/year)

R_i: the ultimate reserve of resource i (kg)

R_{ref}: the ultimate reserve of the reference resource antimony (kg)

DR_{ref}: the extraction rate of the reference resource antimony (kg/year)

The ultimate reserve is the ultimately available quantity of a resource and can be estimated by multiplying the average natural concentration of the resource in the earth's crust with the mass of the earth's crust. Guinée and Heijungs (1995) recognise that in terms of depletion the ultimately extractable reserve is the only relevant reserve parameter. However, reliable data on the ultimate extractable reserve are not available and not exactly known, because they depend on future developments of technology. By applying the ultimate reserve, Guinée and Heijungs (1995) implicitly assume that the

ratio between the ultimately extractable reserve and the ultimate reserve is equal for all resources. The use of the reference substance (antimony) has the advantage that the ADPs are closer to unity and thus easier to understand. Guinée et al. (2002) assume that all fossil fuels are full substitutes for each other and propose an overall fossil energy ADP, based on data of the World Resource institute, equal to 4.81×10^{-4} kg Sb-equivalents/MJ of fossil energy. The ADPs for a specific fossil fuel can be calculated by multiplying this overall fossil energy ADP with the heating value (MJ/kg) of the considered fossil fuel.

2.2.3 Cumulative exergy demand (CExD) method

Bösch et al. (2007) propose characterisation factors based on the exergy content of the considered resource. Exergy can be regarded as a measure of useful energy. The exergy of a resource accounts for the minimal work necessary to form the resource. Contrary to Guinée and Heijungs (1995), Bösch et al. (2007) approach the problem of abiotic depletion by considering the decrease of this useful energy instead of considering the decrease of global reserves.

For energetic resources the characterisation factor is given by:

$$CF_i = HV_i \times r_{ex/e,i} \quad (3)$$

where:

HV_i : heating value of resource i (MJ/kg)

$r_{ex/e,i}$: the exergy-energy (heating value) ratio of resource i (MJ/MJ)

For non-energetic resources the characterisation factor is set equal to the chemical exergy of the resource, expressed in MJ/kg:

$$CF_i = Ex_{ch,i} \quad (4)$$

where:

$Ex_{ch,i}$: chemical exergy of resource i (MJ/kg)

The chemical exergy of a resource can be calculated on the basis of the chemical formation reaction utilizing the Gibb's free energy of formation and the exergy of the chemical elements in the resource (Finnveden and Östlund, 1997; Bösch et al., 2007).

2.2.4 Environmental priority strategies (EPS) method

In the EPS-method (Environmental Priority Strategies) developed by Steen (1999), the aggregation of different resources is done in the weighing phase and not in the assessment phase, as is the case for the other methods. The abiotic depletion is given by the following equation:

$$Abiotic\ Depletion = \sum_i WTP \times m_i \quad (5)$$

where WTP is the willingness to pay to restore impacts to the 'safe guard subject', in this case abiotic stock resources, expressed in environmental load units (ELU, €). Since mainly future generations are concerned by resource depletion, the WTP cannot be determined in the usual way, e.g. by means of group interviews. Therefore, the WTP for resources is set equal to the cost of the sustainable alternative of the resource. For fossil oil e.g., production of rapeseed oil is taken as the sustainable alternative. For most metal (Cu, Fe, etc) ores, the production of concentrates from the average earth's crust by a mining-crushing-grinding-leaching-precipitation process is considered as the sustainable alternative for today's mining practices. According to Steen (1999), the main problem is

not the future availability of a resource, but the higher production cost of the sustainable alternative resource.

2.2.5 Eco-indicator 99-method

In the Eco-indicator 99-method, the increasing energy needed for the extraction of lower grade resources in the future is seen as the main problem for abiotic depletion. Goedkoop and Spriensma (2001) set the characterisation factor equal to the surplus energy (SPE), expressed in MJ, needed to extract one kilogram of a mineral from a lower grade ore or, in the case of fossil resources, the surplus energy needed to produce one kilogram of crude oil or coal from oil shale, tar sands or coal shale mix (see equation 6). This approach was developed by Müller-Wenk (1998).

$$CF_i = SPE_i \quad (6)$$

where SPE_i is the surplus energy (MJ) needed to extract one kilogram of a resource from a lower grade ore or from oil shale, tar sands or coal shale mix.

For the estimation of the SPE of minerals, first the ore grade is estimated at a point in the future when 5 times the cumulative amount of the ore extracted before 1990 will have been extracted. Afterwards the surplus energy needed to extract one kilogram of the mineral from the ore grade estimated by the first model, is calculated. Future efficiency increases as a result of technological improvements in mining are not taken in to account.

2.3 Application of the methods to steel production

The five methods described in section 2.2 are applied to the resource consumption of Arcelormittal Gent in 2005 (see section 3.1). For each resource, the abiotic depletion

according to the different methods is calculated by multiplying the consumption in kilograms by the characterisation factors (or weighing factors in the case of the EPS-method) given in table 1. Then, the total abiotic depletion, which equals the sum of the abiotic depletion of the individual resources, is set to 100% in order to obtain the relative contribution of each resource in %. In this way, the methods can be compared regardless of the units in which they express the abiotic depletion. The five methods are first applied to the non-energetic, mineral resources iron ore, lime(stone) and iron scrap as recycled product. For the CML- EPS and Eco-indicator 99 methods, the depletion of lime(stone) is calculated using the characterisation factor for the element calcium since these methods do not yet propose a characterisation factor for limestone itself. The five methods are also applied to the energetic resources (natural gas, coke gas, fuel, cokes, anthracite, powdered coal and electricity) consumed by the steelwork. Finally, the relative contribution of all the considered resources to the total abiotic depletion is evaluated. The relative contributions in the mass and energy-method only serve as a reference for the evaluation of the other methods since the summation of the masses of different resources implies properly speaking full substitution between these resources, which is certainly not the case for the resources considered.

3. Results and discussion

3.1 Relative contribution to abiotic depletion of resources consumed by ArcelorMittal Gent

Figure 2 gives the relative contribution of the non-energetic resources to the total abiotic depletion of this resource group. The first bar, giving the contribution of the resources

on a pure mass basis, serves as a reference. A first conclusion that can be drawn is that the contribution of lime(stone) or calcium is negligible for all methods that make use of characterisation or weighing factors. The element calcium is abundantly present in nature, so this conclusion can easily be explained for the CML-method, which is based on reserve and extraction. The CExD-method leads however to a similar result based on the exergies of iron (ore and scrap) and limestone. Calcium is so abundantly present in nature that it can be considered a sustainable resource or that no surplus energy for its extraction is to be foreseen in the future, according to the EPS- and Eco-indicator 99-method respectively. Of the assessment methods using characterisation or weighing factors, only the CExD-method takes iron scrap into account. However, recycling of iron scrap in the steel production process at ArcelorMittal Gent does not require extra exergy as iron scrap which is added to the converter melts by absorbing excess process energy, which otherwise would be lost to the environment during the steel casting. The exergy which was earlier used to produce the iron scrap and which is accounted for in its total exergy, is in a way double counted. When iron scrap is recycled during the production of steel, as is the case for ArcelorMittal Gent, double counting could be avoided by making an exergy balance. The difference between the exergy of the inputs (iron ore, scrap, limestone and energetic resources) and outputs (steel products) could be interpreted as a measure of the abiotic depletion by the process (the more exergy efficient the process, the smaller the depletion). The other assessment methods using characterisation or weighing factors only take resources extracted from nature into

account and consider that recycling of resources diminishes the consumption of ores, preventing abiotic depletion.

In figure 3, the five methods are applied to the energetic resources (natural gas, coke gas, heavy fuel, coke, anthracite, powdered coal, electricity) consumed by the steelwork. The electricity consumption is converted into consumptions of uranium, natural gas, coal and fuel according to the Belgian electricity mix for the year 2004 (Federal Public Service of Economy, 2009). The relative contributions of natural gas and fuel represent the sum of the consumption at ArcelorMittal Gent and the consumption in the power plants that generated the electricity consumed. As a reference, the first bar gives the contributions of the resources to abiotic depletion calculated by multiplying their mass with their heating value. The relative contributions of the different resources appear rather similar to this reference bar for the CML-, CExD- and Eco-indicator 99-methods. This is easy to explain for the CML-method (second bar in figure 3) in which full substitution of energetic resources is assumed and characterisation factors are based on heating values (see 2.2). The assumed full substitution does however not agree with the reality of the considered steel production process. In the current blast furnace technology e.g. injection fuels can replace only a part of the metallurgical coal. For the calculation of the depletion of uranium, the ADP based on the reserve and extraction of the element uranium as proposed by Guinée et al. (2001) is used, hence the difference with the depletion based on the 'heating value' of uranium in the first bar. The similarity between the relative contributions calculated with the CExD-method, visualized by the third bar in figure 3 and the reference-bar, can

be explained by the fact that the exergy to energy ratio (term $R_{ex/e}$ in equation (2)) is close to one for all the considered energetic resources, as can be seen by comparing the energy and exergy content given in table 1. Also the contributions calculated with the Eco-indicator 99-method (fifth bar in figure 3) appear very similar to those of the reference, the CML- and the CExD-bar, although the starting point for the development of the characterisation factors is completely different. According to Eco-indicator 99, uranium does not contribute to the total abiotic depletion. Goedkoop and Spriensma (2001) did not derive a surplus energy for this element due to a lack of reliable data on uranium consumption in Europe. The lack of a SPE-value for uranium is clearly a shortcoming for the correct assessment of abiotic depletion caused by electricity production in a country like Belgium where ca. 50% of the electricity is produced in nuclear power plants (FPS Economy, 2009). In contrast to the reference-, CML-, CExD- and Eco-indicator 99-method, the EPS-method shows an important relative contribution of gaseous energetic resources (fourth bar in figure 3). This can be explained by the fact that the average WTP for the production of biogas, which is considered the sustainable alternative for gaseous fuels, is relatively high compared to the WTP for the production of charcoal, which is considered the sustainable alternative for coal.

Abiotic depletion can be considered as a single impact category, without distinction between non-energetic and energetic resources. Figure 4 gives the relative contribution of the all the considered resources to the total abiotic depletion. The second bar shows that for the CML-method, in the steel production process, the contribution to the total abiotic depletion of non-energetic resources is negligible compared to the contribution

of the energetic resources: if only ultimate reserve and extraction rate are considered, the depletion of energetic resources is much more important than the depletion of non-energetic resources. The same conclusion can be drawn from the characterisation factors in table 1: the ADP-values for the considered mineral resources are ca. one million times lower than the ADPs for the fossil fuels. When the CExD-method is applied to the resource consumption data of the steelwork (third bar in figure 3), the difference between the contribution of energetic and non-energetic resources to the total abiotic depletion appears less pronounced than in the CML-method; the exergies of mineral resources are 1 to 3 orders of magnitude lower than those of energetic resources (see Table 1). Since for both types of resources the contribution is based on the same physical property, namely exergy, the summation of non-energetic and energetic resources is justified. A completely different image is shown in the fourth bar in figure 3, representing the relative contributions according to the EPS-method. Here the depletion of mineral resources (iron ore) appears the major problem in the steel production process. Steen (1999) demonstrates that the production of charcoal, which is considered the sustainable alternative for fossil coal and its derivatives used in the steel production process, causes less additional costs than the production of mineral concentrates out of the average earth's crust.

The last bar in figure 3 shows that according to the Eco-indicator 99-method, depletion of the considered energetic and non-energetic resources is of comparable importance. As can be concluded from Table 1, the surplus energy needed to extract iron from lower

grade ores is roughly comparable to the surplus energy needed to extract fossil energy carriers out of shales and tar sands.

From the comparison it can be concluded that in order to reduce abiotic depletion, ArcelorMittal should, according to the CML-method, focus on further reducing the specific energy consumption, which seems realistic considering today's experienced scarcity of energy carriers. When the surplus energy to extract decreasing ore quality is considered (Eco-indicator 99), the conclusion is that the steelwork should also focus on improving material efficiency. However, the surplus energies were calculated without consideration of future technological improvements in mining. Goedkoop and Spriensma (2001) recognize that although the grade of all ores decreases, the total energy requirements also decrease as a result of improved energy efficiency. So in case of the Eco-indicator 99-method the conclusion that ArcelorMittal Gent should also improve material efficiency in order to reduce abiotic depletion seems not based on realistic assumptions. The use of exergy as characterisation factor as in the CExD-method however also leads to the conclusion that the steelwork should focus on both energy and material efficiency improvement in order to decrease abiotic depletion. According to the EPS-method, improving material efficiency is the only way to reduce abiotic depletion. Steen (1999) calculated costs of extracting ore equivalents (concentrates) out of the earth's average crust, based on actual technology. The substitution of mineral ores by concentrates is however not foreseen within the next 1000 years (Müller-Wenk, 1998), so conclusions based on the use of today's technology do not seem realistic.

In steel production processes such as at ArcelorMittal Gent, the improvement of energy and material efficiency mostly go hand-in-hand (e.g. the switch of ingot casting to continuous casting realized in the early nineties was a major material and energy efficiency improvement). In this way, the recommendations of the different assessment methods lead to a similar result.

3.2 Critical evaluation of the assessment methods

Based on the experience gained and the observations made during the application of the assessment methods to the resource consumption of ArcelorMittal Gent, the five methods discussed in section 2 are critically compared making use of the following criteria (the first three criteria are based on ISO-14042):

- **Value choices and assumptions:** How is the problem of abiotic depletion defined? Which choices and assumptions are made for the development of the characterisation factors?
- **Scientific and technical validity:** Are the characterisation factors developed in a scientifically and technically valid way (e.g. based on a distinct identifiable environmental mechanism and/or reproducible empirical observation)?
- **Temporal aspects:** To which extent do the characterisation factors depend on temporal changes in data and models used for their development?
- **Applicability:** Are the characterisation factors readily available in literature? Is enough information provided for derivation of lacking characterisation factors?

The method based on mass and energy is only used as reference and will not be further discussed.

The choice of the ultimate reserve for the quantification of the resource reserve within the CML-method is somewhat arbitrary. Guinée and Heijungs (1995) recognise that in terms of depletion the ultimately extractable reserve is the only relevant reserve parameter, but it cannot be used because of lack of reliable data. The relation between extraction rates and reserve on the one hand and depletion on the other hand is straightforward. There are no models involved in the derivation of the characterisation factors, but the used ultimate reserves are only estimates since the average concentration of many elements in the earth's crust is not exactly known. If the extraction rates of resources change over time, as is the case for e.g. the iron ore and fuels consumed by ArcelorMittal, this has an implication on the ADPs; they are in principle time dependent. Another temporal aspect is the fact that the ADP only becomes very high if the reserve of the resource approaches zero, when it might already be too late to prevent total depletion. Since the reserves for fossil carbon are relatively limited, this can also explain why the ADPs for the energetic resources consumed by ArcelorMittal Gent are ca 1 million times higher than the ADPS for iron ore. CML worked out an elaborate database representing ADP characterisation factors for elements (e.g. Fe, Ca) present in nature. ADPs for resources are only available for a few metal ores (including iron ore) and not for lime(stone).

The physical property exergy, used as characterisation factor in the CExD-method, is a scientifically valid measure for this useful energy. It is time independent, but the link between exergy and depletion of a resource is not easy to comprehend without thorough knowledge of thermodynamics. Despite the fact that in recent years lists and books have

become available with relevant data (e.g. Atkins, 2001; Szargut, 2005), the characterisation factor for coke and coke gas had to be estimated using the heating value and exergy over energy ratio for hard coal and natural gas, respectively.

In the EPS-method, Steen (1999) had to make a lot of assumptions for the calculation of the cost of the sustainable alternative (production process), but the data used for the derivation of the WTPs are well documented and come from technically and scientifically sound sources. The alternative sustainable production process is based on today's technology and does not account for possible future technological developments. So if the WTPs for the fossil fuels consumed by ArcelorMittal Gent would be recalculated in ten years, taking new energies such as solar and wind-energy into account, they could differ significantly from the present ones. Another question regarding the temporal aspects of the EPS-method is if the sustainable production alternatives for fossil and mineral resources will take place at the same time in the future. The substitution of fossil fuels by e.g. bio-ethanol, bio-diesel and bio-gas has already started, whereas the substitution of mineral ores by concentrates is not foreseen within the next 1 000 years (Müller-Wenk, 1998). The WTPs needed for the calculation of the abiotic depletion by natural gas, fuel, coal, uranium, limestone (calcium) and iron ore were available in literature. For coke gas the same sustainable alternative and hence WTP as for natural gas was assumed; for coke, anthracite and powdered coal, the WTP for fossil coal (based on the production process of the sustainable alternative charcoal) was assumed.

Within the Eco-indicator 99-methodology, the models used by Müller-Wenk (1998) for the calculation of the surplus energy are scientifically sound and well documented but the calculation of the future ore quality is partially based on the grade-availability curves by Chapman (1983), for which the data sources are not clearly specified. If improvements in energy efficiency of the chosen extraction technologies are not considered, the characterisation factors are time independent. The SPEs for natural gas, fuel, coal, limestone (calcium) and iron ore could easily be found in literature. For coke gas the same SPE as for natural gas was assumed; for coke, anthracite and powdered coal, the SPE for hard coal was assumed.

4. Conclusions

Five different methods for the calculation of abiotic depletion were applied to the resource consumption of Arcelormittal Gent, a major Belgian steelwork. First, the non-energetic and energetic resources were considered separately. For the non-energetic resources, the contribution of limestone was insignificant for the methods using characterisation or weighing factors. Only the CExD-method takes recycled products (iron scrap) into account. In the case of steel production, double counting of the exergy of the energetic resources consumed during the initial production can be avoided by making an exergy balance of the process. The relative contribution of the individual energetic resources to the total depletion of this resource group appeared very similar for the mass- and energy-, CML-, CExD- and Eco-indicator 99-methods, despite their different starting points. The major difference with the EPS-method was the larger

relative contribution of the gaseous energy carriers (natural gas and coke gas). When the energetic and non-energetic resources consumed by ArcelorMittal Gent were considered as one group, it was clear that according to the CML-method, the depletion of energetic resources was far more important than the depletion of non-energetic resources. On the other hand, EPS stressed the depletion of non-energetic resources and the CExD- and Eco-indicator 99 methods considered depletion of both types of resources about equally important.

In order to reduce abiotic depletion, ArcelorMittal Gent should, depending on the assessment method applied, mainly further improve its energy efficiency (CML), further improve its material efficiency (EPS) or focus on the improvement of both energy and material efficiency (Eco-indicator 99 and CExD). For both the EPS- and Eco-indicator 99-method the characterisation factors are based on events in the (far) future without consideration of technological improvements that would occur in the meantime.

Therefore the conclusion that ArcelorMittal Gent should mainly improve its material efficiency in order to reduce abiotic depletion does not seem realistic. On the other hand, in the steel production process, the improvement of energy and material efficiency usually go hand in hand so it could be argued that the different recommendations would have more or less the same effect on abiotic depletion.

The five methods were also evaluated by means of three ISO 14042-based criteria (Value choices and assumptions, scientific and technical validity, temporal aspects) and their experienced applicability for the resources considered. The principle of the CML-method is easy to understand, but difficult to quantify correctly. The CExD-method is

simple and the characterisation factors are time independent, but the link between abiotic depletion and loss of exergy is less easy to comprehend. The EPS-method is well documented, but it is questionable if the actual costs and technologies used for the calculation of the WTP are relevant for events that will only take place in the (far) future. The Eco-indicator 99-method is well documented but partly based on data sources not clearly specified.

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Table 1: Overview of resource consumption (year 2005) and applied characterisation factors

	Consumption ton/year	Energy (MJ/kg)	CML kg Sb- eq/kg ^g	CExD MJ/kg	EPS ELU/kg ^j	Eco-Indicator '99 MJ/kg or MJ/MJ ^k
Iron ore	5.68 10 ⁶	-	8.43 10 ⁻⁸	0.42 ^h	0.654	0.029
Iron scrap	9.47 10 ⁵	-	-	6.7 ⁱ	-	-
Lime and limestone	9.22 10 ⁴	-	-	0.034 ^h	0	0
<i>Calcium equivalent</i>	<i>4.44 10⁴</i>		<i>7.1 10⁻¹²</i>			
Natural Gas	2.32 10 ^{5 a,b}	38.2 ^{d,e}	1.8 10 ^{-2 d}	36.0 ^{d,f}	1.1 ^d	0.089 ^d
Coke Gas	3.45 10 ^{5 a}	17.4 ^{d,e}	8.4 10 ^{-3 d}	16.4 ^{d,f}	1.1 ^d	0.089 ^d
Fuel	2.93 10 ^{4 b}	40.6 ^e	2.0 10 ⁻²	41.4 ^f	0.506	0.083
Coke	1.46 10 ⁶	29.8 ^e	1.4 10 ⁻²	30.7 ^f	0.0498	0.082
Anthracite	1.77 10 ⁵	29.5 ^e	1.4 10 ⁻²	30.4 ^f	0.0498	0.082
Coal	5.10 10 ^{4 c}	29.5 ^e	1.4 10 ⁻²	30.4 ^f	0.0498	0.082
Powdered Coal	8.14 10 ⁵	31.0 ^e	1.5 10 ⁻²	31.9 ^f	0.0498	0.082
Uranium	1.39 10 ^{1c}	560,000 ^f	2.9 10 ⁻³	560,000 ^f	1190	0

^a expressed in 10 m³/year

^b sum of mass (or volume) consumed on site and of mass (or volume) consumed for the production of the electricity which is consumed on site

^c mass consumed for the production of the electricity which is consumed on site

^d expressed in unit/m³

^e provided by ArcelorMittal Gent

^f from Bösch et al. (2007)

^g CML database available at <http://www.leidenuniv.nl/cml/ssp/index.html> or derived from the heating value as proposed by Guinée et al. (2002)

^h from Finnveden and Östlund (1997)

ⁱ from Ignatenko et al. (2007)

^j from Steen (1999)

^k from Goedkoop and Spriensma (2001)

Table 2: Evaluation of the applied assessment methods by means of three ISO-14042 based criteria and the experienced applicability

	Value choices and assumptions (Problem definition)	Scientifically and technically valid	Temporal aspects	Applicability
CML - <i>reserve & extraction</i>	Depletion linear with ratio of global extraction rates and ultimate reserves	No environmental mechanisms or models involved	<ul style="list-style-type: none"> Extraction rates and hence characterisation factors are in principle time dependent Characterisation factor only becomes high when reserves are already very low 	Characterisation factors readily available for elements, less for resources
CExD - <i>exergy</i>	Depletion linear with loss of exergy	Only physical properties, no environmental mechanisms or models involved	Time independent	Characterisation factors for a limited set of resources available in literature
EPS – <i>willingness to pay</i>	Depletion linear with cost of resources, sustainable alternative	Technically well documented and described	<ul style="list-style-type: none"> Actual costs of technologies relevant for events that will only take place in the (far) future? Different time scale for sustainable alternative of fossil fuels (0-100 years) and minerals (1000 tot 10⁶ years) 	Characterisation factors for a limited set of resources available in literature
Eco-indicator 99 – <i>surplus energy</i>	Depletion linear with surplus energy needed to extract lower grade ores/ produce crude oil from oil shale, tar sand or coal shale mix	Used models well described, but based on grade-availability curves by Chapman for which data sources are not clear	Time independent if improvements in energy efficiency of the chosen extraction technology are not considered	Characterisation factors for a limited set of resources available in literature

Figure 1: Schematic representation of the plant boundary and considered resource flows

Figure 2: Comparison of the relative contributions to abiotic depletion of non-energetic resources according to the different assessment methods

Figure 3: Comparison of the relative contributions to abiotic depletion of energetic resources according to the different assessment methods

Figure 4: Comparison of the relative contributions to abiotic depletion of all considered resources according to the different assessment methods

Figure 1

Figure 2

Figure 3

Figure 4