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EXERGY AND LCA

Thermodynamic resource indicators in LCA: a case study on the titania produced in Panzhihua city, southwest China

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Abstract

Purpose While life cycle assessment (LCA) has standardized methods for assessing emission impacts, some comparable methods for the accounting or impact assessment of resource use exist, but are not as mature or standardized. This study contributes to the existing research by offering a comprehensive comparison of the similarities and differences of different resource indicators, in particular those based on thermodynamics, and testing them in a case study on titania (titanium dioxide pigment) produced in Panzhihua city, southwest China.

Materials and methods The system boundary for resource indicators is defined using a thermodynamic hierarchy at four levels, and the case data for titania also follow that hierarchy. Seven resource indicators are applied. Four are thermodynamics-based—cumulative energy demand (CED), solar energy demand (SED), cumulative exergy demand (CExD), and cumulative exergy extraction from the natural environment (CEENE)—and three have different backgrounds: abiotic resource depletion potential, environmental priority strategies, and eco-indicator 99. Inventory data for the foreground system has been collected through on-site interviews and visits. Background inventory data are from the database ecoinvent v2.2. Characterizations factors are based on the CML-IA database covering all major methods. Computations are with the CMLCA software.

Results and discussion The scores of resource indicators of the chloride route for titania system are lower than that of the sulfate route by 10–35 %, except in terms of SED. Within the four thermodynamic indicators for resources, CED, CExD, and CEENE have similar scores, while their scores are five orders of magnitude lower than the SED score. Atmospheric resources do not contribute to the SED or CEEND score. Land resources account for a negligible percentage to the SED score and a small percentage to the CEENE score. Non-renewable resources have a dominant contribution to all seven resource indicators. The global production of titania would account for 0.12 and 0.14 % of the total anthropogenic non-renewable resource demand in terms of energy and exergy, respectively.

Conclusions First, we demonstrate the feasibility of thermodynamic resource indicators. We recommend CEENE as the most appropriate one within the four thermodynamic resource indicators for accounting and characterizing resource use. Regarding the case study on the titania produced in China, all the resource indicators except SED show that the sulfate route demands more resource use than the chloride route.

Keywords Energy · Exergy · Indicator · Resource · Titania

1 Introduction

Natural resources are the ultimate inputs to our civilization and the non-substitutable basis for economic growth (Daly 1991; Ayres 1998). As these are available in a limited amount, the long-term well-being of both mankind and the environment cannot maintain without sound stewardship or sustainable utilization of natural resources. In human–environment systems, resource uses in parallel to emissions are

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an important source of environmental impacts. It has been demonstrated that a number of emission-related impacts are strongly related to resource use, in particular energy input (Huijbregts et al. 2010). However, while the life cycle assessment (LCA) community has standardized methods for assessing emission impacts, some comparable methods for the accounting or impact assessment of resource use exist, but are not as mature or standardized (Baral and Bakshi 2010). In the ILCD handbook (EC JRC 2010a, b), resource depletion is the only impact category for which no single recommended method has been identified. Examples of methods for characterizing resources in LCA are the abiotic resource depletion potential (ADP) developed by CML (Guinée et al. 2002), willingness to pay developed within the environmental priority strategies (EPS) framework (Steen 1999a, b), and surplus energy developed in Eco-indicator 99 (EI99) (Goedkoop and Spriensma 2000a, b).

In addition, thermodynamic metrics such as energy, exergy, and entropy have been used as a basis for resource indicators, for instance, in the so-called life cycle exergy analysis (Gong and Wall 1997, 2001; Wall 2011) or exergetic LCA (Cornelissen 1997; Cornelissen and Hirs 2002; see the Electronic supplementary material (ESM) for an elaboration on the combination of thermodynamic metrics and LCA). Thermodynamic resource indicators are applied as screening impact indicators and to give an estimation of resource use. As compared to complete LCA studies, the calculation of thermodynamic resource indicators requires fewer information on emission estimates or impact assessment factors (Huijbregts et al. 2006); nevertheless, no thermodynamic resource indicator is recommended by the ILCD Handbook (EC JRC 2010a, b). Besides the LCA studies, thermodynamic resource indicators are applied in other aspects of the analysis of human–environment systems due to their physical validation and quantitative formulation (Dewulf et al. 2008; Sciubba and Wall 2007). However, different resource measures apply to different system levels in human–environment systems (Liao et al. 2011). Meanwhile, there is no consensus on the most appropriate resource measure or even on what the issue is for the impact of resource use (Baral and Bakshi 2010; EC JRC 2010a, b). Studies that compare multiple resource indicators are not uncommon (Rugani et al. 2011; Caneghem et al. 2010; Baral and Bakshi 2010; Bösch et al. 2007). Rugani et al. (2011) compare solar energy demand (SED) with cumulative energy demand (CED), cumulative exergy demand (CExD), and cumulative exergy extraction from the natural environment (CEENE) for 2,326 products in the ecoinvent database v2.1. Caneghem et al. (2010) compare ADP, EPS, CExD, EI99, and the total resource mass for the steel. Baral and Bakshi (2010) compare CExD with ecological cumulative exergy consumption (ECEC) by applying them to transportation fuels. Bösch et al. (2007) compare CExD with CED, EI99, and ADP for 1,197 products in the ecoinvent database v1.2.

This study contributes to the existing research by offering a comprehensive comparison of the similarities and differences of different resource indicators, in particular those based on thermodynamics, and testing the indicators in a case study on the titania produced in Panzhihua city, southwest China. This study is focused on thermodynamic resource indicators, i.e., CED, SED, CExD, and CEENE. These are also compared with ADP, EPS, and EI99. Table 1 summarizes the indicators used.

2 Methodology

2.1 System boundary

The principle of system definition is that it should include all relevant processes. A diagram for resource indicators as well as titania under consideration in this study is shown in Fig. 1. The technosphere (also called anthroposphere) is the boundary of most resource indicators, i.e., CED, CExD, CEENE, ADP, EPS, and EI99; the ecosphere is the

Table 1 Overview of resource indicators addressed in this study

Name	Abbreviation	Unit	Levels considered[a]	Reference
Cumulative energy demand	CED	MJ	B+C+D	VDI (1997); Huijbregts et al. (2006, 2010)
Solar energy demand	SED	MJ_{se}-eq	A+B+C+D	Rugani et al. (2011)
Cumulative exergy demand	CExD	MJ_{ex}-eq	B+C+D	Bösch et al. (2007)
Cumulative exergy extraction from the natural environment	CEENE	MJ_{ex}-eq	B+C+D	Dewulf et al. (2007)
Abiotic resource depletion potential	ADP	kg_{sb}-eq	B+C+D	Guinée et al. (2002)
Environmental priorities strategies	EPS	MJ-eq	B+C+D	Steen (1999a, b)
Eco-indicator 99	EI99	ELU	B+C+D	Goedkoop and Spriensma (2000a, b)

[a] See Fig. 1

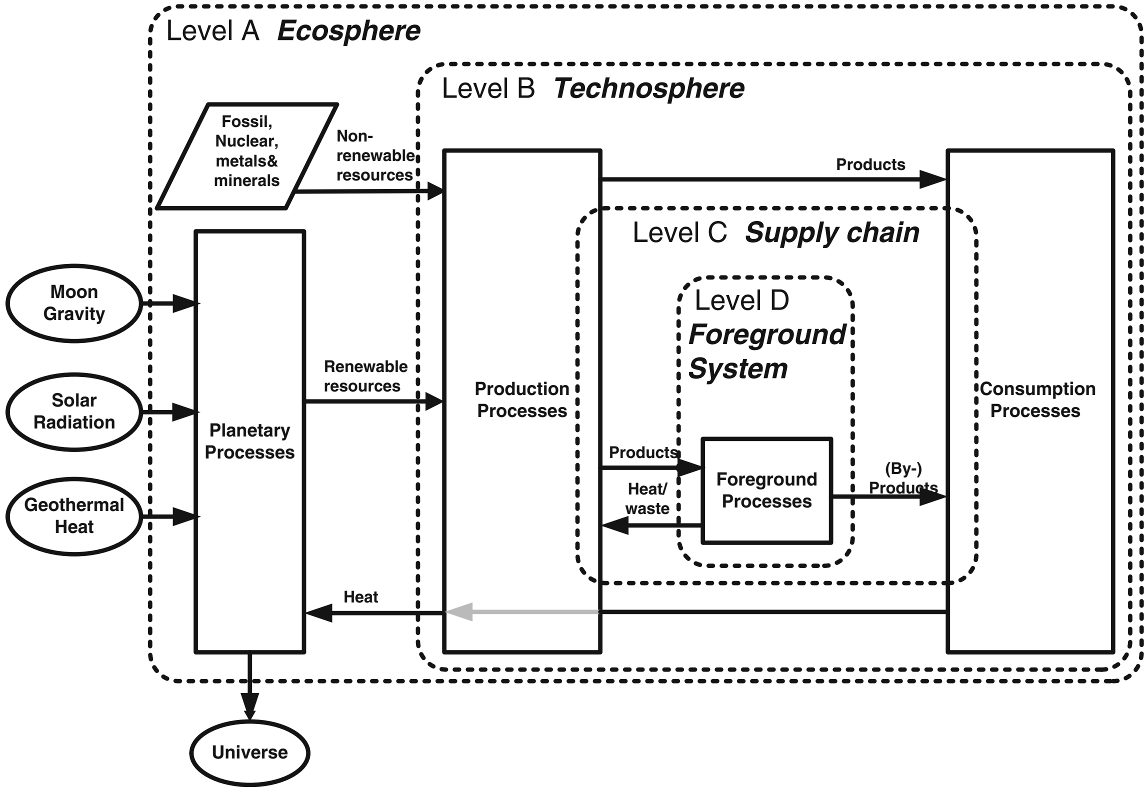

Fig. 1 System boundary of various resource indicators. The *ellipses* stand for sources or sinks, the *parallelogram* for stock, and the *rectangles* for processes

boundary of SED since it traces back the primary energy and material resources to include the planetary processes.

2.2 Choice of impact and indicators

2.2.1 General remarks

In LCA studies, four classes of indicators have been proposed for the impact assessment of resource use: (1) those based on energy or mass, e.g., CED and material input per unit service; (2) those based on the relation of use to deposits, e.g., ADP; (3) those based on future consequences of resource extractions, e.g., EPS and EI99; and (4) those based on exergy consumption or entropy generation, e.g., CExD and CEENE (Finnveden and Östlund 1997; Stewart and Weidema 2002; Steen 2006). The indicator of ECEC, as defined by Hau and Bakshi (2004), has been left out of consideration because of its inconsistent allocation method with CED, SED, CExD, and CEENE. Two allocation methods have been identified by Hau and Bakshi (2004) for fully and partially defined networks, respectively. While the allocation of ECEC in fully defined networks is a type of standardized allocation in LCA, the allocation in partially defined networks is similar to that in emergy analysis, i.e., all resource consumption of a specific process is considered to be essential for making each co-product and all co-products from the process have the total resource consumption (Rugani 2010). Various ecospheric processes are usually partially defined networks. Thus, in practice, ECEC is implemented by using emergy-type of allocation or even is referred to as emergy, e.g., in the analysis of natural resource consumption of transportation fuels by Baral and Bakshi (2010). Entropy-based indicators of resources, for example as in Goessling-Reisemann (2008a, b), have been left out of consideration due to the lack of support from on-site data or ecoinvent data.

2.2.2 Energy and energy-based indicators

Energy is defined as the ability to do work (Isaacs et al. 1999).[1] Various types of measures are used in energy

[1] This statement has been challenged by one of the reviewers. He or she writes to agree that energy is often defined as such, but that “this is still not correct! To repeat a false statement many times does not make it true!” The reviewer points to a debate (Wall 1977, 1986) where energy is described as “motion or ability of motion (e.g., the disordered motions of the hot molecules in a cup of coffee); measured in joules (J).” Although we appreciate the critical attitude of the reviewer, we prefer to stick to mainstream science in the context of developing LCA while applauding the debate on such fundamentals in more dedicated journals. As a sign of the mainstream, even in thermodynamics, it suffices to point to some standard textbooks (Guggenheim 1957; Zemansky and Dittman 1981) where energy is always defined in relation to the work done on or by the system.

analysis of various products and economic sectors. While the analysis can focus on the secondary energy requirement, e.g., coke, diesel, petrol, electricity, etc. (Luo et al. 2009), most energy analysis aims at determining the direct and indirect primary energy requirements of a product. Almost all primary energy originates from solar energy, ultimately.

The CED indicator represents the direct and indirect primary energy use (in megajoules) throughout the life cycle of a product (Rugani et al. 2011). CED is also referred to as gross energy requirement (IFIAS, 1974), embodied energy (Costanza 1980), or energy cost (Bullard and Herendeen 1975). This study uses the same definition of CED as that used by Huijbregts et al. (2006, 2010). The SED indicator represents the direct and indirect solar energy use (in megajoule solar energy, MJ_{se}-eq) throughout the life cycle of a product (Rugani et al. 2011). Compared with CED, SED includes the conversion from solar energy to the primary energy. SED is not the same as emergy (another form of cumulative solar energy demand; see Odum 1996) since emergy analysis uses computation rules that differ from those of LCA. Furthermore, SED, in contrast to emergy, does not take into account human labor, information, and many ecosystem services (Rugani et al. 2011).

2.2.3 Exergy and exergy-based indicators

Exergy is defined as the maximum work (i.e., useful energy) which can be obtained as a system is brought into equilibrium with the reference environment. It has the same unit as energy, viz., joules. This study adopts the reference environment proposed by Szargut et al. (1988, 2005) with the natural environment subsystem by Gaggioli et al. (1977). Exergy is consumed in all real processes in proportion to the entropy being produced. Exergy applies to both energy carriers and non-energetic materials. Various exergy-based indicators exist for resource accounting.

The CExD indicator represents the total exergy of all natural resources that is required throughout the life cycle of a product (in megajoules, MJ_{ex}-eq; Bösch et al. 2007). CExD is equivalent to cumulative exergy consumption defined by Szargut (2005), both used to measure the potential loss of "useful" resources. The cumulative degree of thermodynamic perfection (CDP) can be determined by associating the CExD with the specific exergy of the product (Szargut et al. 1988). The CEENE indicator represents the total exergy of resources that is taken away from the ecosphere and used as "fuel and stock" for the anthroposphere (expressed in megajoule, MJ_{ex}-eq; Dewulf et al. 2007). CEENE distinguishes itself from CExD by taking the actual transformed exergy into account. The resulting exergy values of biomass and solar energy are not implemented to avoid double accounting (Dewulf et al. 2007).

2.2.4 Other methods and indicators

The ADP method takes the decrease of the resource per se as the key problem. In resource accounting, ADP, as a function of natural reserves of the resources combined with their extraction rates (expressed in kilograms of antimony equivalents (kg_{sb}-eq) per unit of resource extraction), is used to characterize each extraction of elements (in metal ores and minerals) and fossil resources. The overall ADP factor of fossil resources is set equal to 4.81E−04 kg_{sb}-eq/MJ of fossil

Table 2 Synthesis of resource indicators and resource groups addressed in this study

Resource group[a]	Type[b]	CED	SED	CExD	CEENE	ADP	EI99	EPS
Atmospheric	n.d.		×		×			
Fossil	NRR	×	×	×	×	×	×	×
Land	n.d.		×		×			
Metal ores	NRR		×	×	×	×	×	×
Minerals	NRR		×	×	×	×	×	×
Nuclear	NRR	×	×	×	×			×
Renewable energy	RR	×	× [c]	×	×[d]			
Water[c]	RR		×	×	×	×		

n.d. not defined, *RR* renewable resources, *NRR* non-renewable resources

[a] This is just one categorization. However, as pointed out by the ILCD Handbook (EC JRC 2010a), other categorizations, such as Finnveden (1998) and Guinée et al. (2002) split resource differently

[b] It should be noted that in SED, the atmospheric and land resource are considered as NRR and RR, respectively

[c] Bromine, iodine, and magnesium in water are included

[d] The value of converted solar energy and the gross caloric value of biomass (including primary forest) are not implemented in SED and CEENE to avoid double accounting. Primary forest in this study is considered as a renewable energy resource, which is the same as the consideration in SED and CEENE, but different from that in impact indicators CED and CExD in the ecoinvent database v2.2

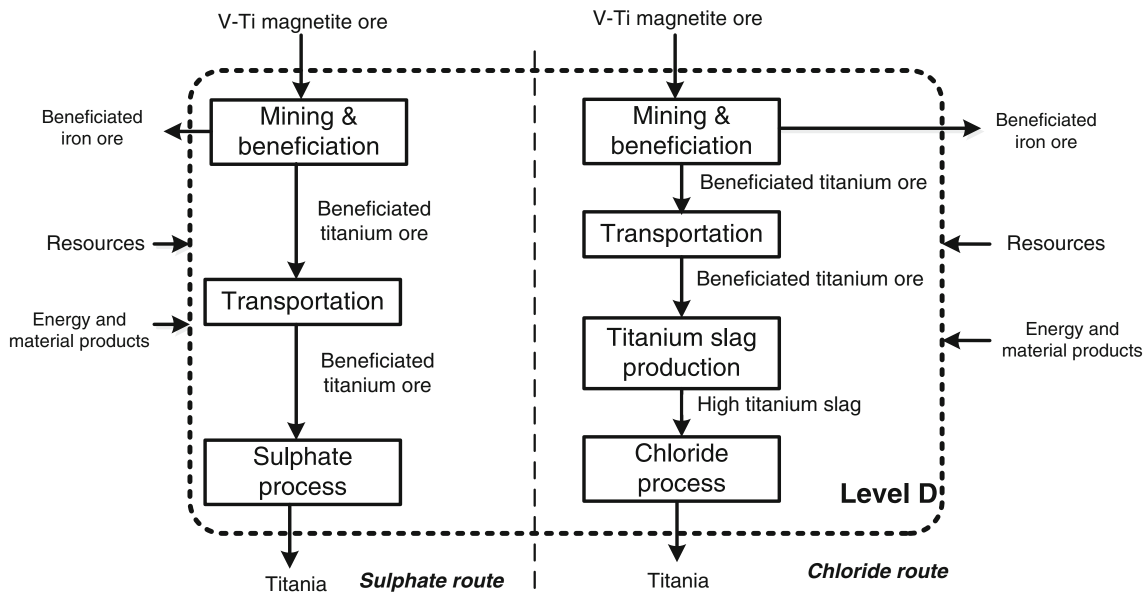

Fig. 2 Flowchart of titania production foreground system, at level D in Fig. 1

fuel (Guinée et al. 2002). The ADP calculated for the ultimate reserve is used in this study.

The EPS method takes the higher production cost of the alternative resource as the key problem. It describes the environmental impacts, which are related to the development of products, as impacts to specific protection subjects, e.g., resources, biodiversity, human health, etc. (Steen 1999a, b). In resource accounting, the impact to resource use is evaluated according to the willingness to pay to avoid negative effects. The willingness to pay for resources is set equal to the cost of the sustainable alternative of the resource, expressed in environmental load value (ELU).

The EI99 method takes the increasing energy needed for the future extraction of lower grade resource as the key problem. Similar with the EPS method, the EI99 method calculates the environmental impacts to specific protection subjects (Goedkoop and Spriensma 2000a, b). In resource accounting, the surplus energy (expressed in megajoule equivalents) needed to produce 1 kg of a fossil resource from oil shale, tar sands, or coal shale mix, or to extract 1 kg of a metal ore or mineral from a lower grade ore is used to characterize corresponding resource flows. The EI99 indicator based on an egalitarian perspective is used in this study.

Table 3 Main resource and product inputs needed to produce 1 kg of the titania in Panzhihua city, southwest China

No.	Input	Type	Unit	Chloride route	Sulfate route
1	V–Ti magnetite ore	Resource	kg	5.071	5.576
2	Steel ball	Product	kg	0.001	0.002
3	Anthracite	Product	MJ	10.076	–
4	Coke	Product	kg	0.693	–
5	Liquid chlorine	Product	kg	0.25	–
6	Iron powder	Product	kg	–	0.09
7	Aluminum powder	Product	kg	0.006	–
8	Oxygen	Resource	kg	0.643	–
9	Liquid caustic soda (30 %)	Product	kg	0.3	0.35
10	Sulfuric acid (98 %)	Product	kg	–	4.05
11	Saturated steam (1.3 MPa)	Product	kg	5.5	8
12	Coal	Resource	kg	–	2
13	Petrol	Product	kg	0.017	0.018
14	Diesel	Product	kg	0.011	0.111
15	Process water[a]	Resource	kg	53.758	101.787
16	Electricity	Product	kWh	2.85	1.578

[a]Process water, as a direct resource input, is not implemented considering the very high uncertainty of its surveyed value

Table 4 Scores of various resource indicators of 1 kg of the titania produced in Panzhihua city, southwest China

Route	CED (MJ)	SED (MJ_{se}-eq)	CExD (MJ_{ex}-eq)	CEENE (MJ_{ex}-eq)	ADP (kg_{Sb}-eq)	EPS (ELU)	EI99 (MJ-eq)
Chloride route	106	7.91E+07	129	123	0.0536	1.50	8.66
Sulfate route	117	6.63E+07	151	143	0.0735	2.32	10.6

Table 2 summarizes the categorization of resource groups as considered by the different resource indicators addressed in this study.

3 Case study

3.1 Case description

Titania is an important fine chemical product with a broad range of applications in paints, plastics, inks, paper, cosmetics, ceramics, rubber products, etc. The chloride route and the sulfate route, as two current mature routes for the commercial production of titania, are analyzed in this study as two alternatives for the titania produced in Panzhihua city, southwest China. This study is a cradle-to-gate analysis of the titania system. The functional unit in this study is defined as 1 kg of titania (titanium dioxide pigment) at plant.

Both the chloride route and the sulfate route are used in Panzhihua city, southwest China, to extract titania from vanadium-bearing titaniferrous magnetite ore (V–Ti magnetite ore, 10.25 % (*w*/*w*) of TiO_2; see ESM Table S1 for the composition of the ore). After the mining and beneficiation of V–Ti magnetite ore, the titanium ore (48.8, *w*/*w*, of TiO_2) can be either used directly as the feedstock for the sulfate process or it proceeds to the production of high titanium slag (94.0, *w*/*w*, of TiO_2). Figure 2 shows the flowchart of the foreground system of titania (99.0, *w*/*w*, of TiO_2) production. The foreground system of the sulfate route is divided into three unit processes, while that of the chloride route system includes four unit processes. ESM Tables S2 to S6 show the raw input data of every unit process. It is noted that these processes do not comprise the full life cycle of the titania since the utilization and other end-of-life processes are left out of consideration.

Beneficiated titanium ore and beneficiated iron ore are co-produced in the process "mining and beneficiation" in both the chloride route and the sulfate route. Allocation of resource use is based on their mass. The transport distance for the beneficiated titanium ore to the titania plant is 80 km. As for the distance between the titanium slag plant and the titania plant, the value is set to zero since they are locally close to each other. The transport of other auxiliary raw materials is left out of consideration due to data unavailability.

3.2 Data source and software

In this study, only the input data and the (co-)product of each unit process are required. Data on the processes of mining and beneficiation, titanium slag production, chloride process, and sulfate process have been collected mainly through interviews and site visits at local enterprises, located in Panzhihua city, southwest China. A consistent set of data on energy and material inputs is obtained by sending them a standardized questionnaire. Table 3 shows the inventory of main resource and product inputs of the two routes based on our survey.

Data on road transport are derived from Yang et al. (2002). Background data on electricity produced in China and other energy and material product inputs are obtained from the ecoinvent database v2.2 (Swiss Centre of Life Cycle Inventories 2009; see ESM Table S7 for their corresponding dataset names).

7Data on the characterization factors for CED, SED, CExD, and CEENE are obtained from Rugani et al. (2011), while the characterization factors for ADP, EPS, and EI99 are

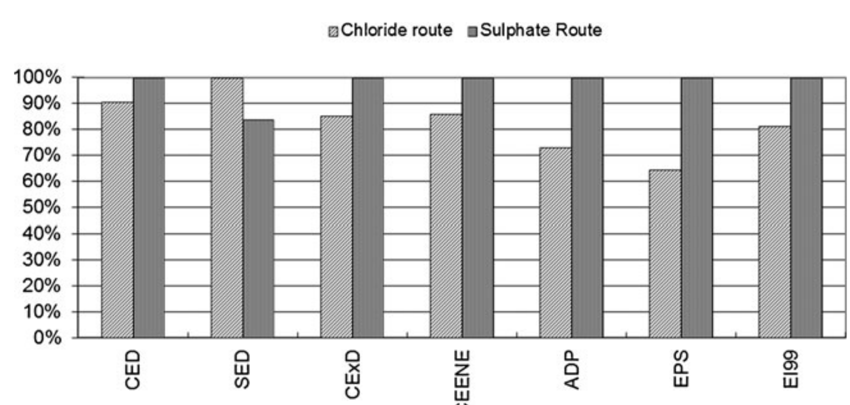

Fig. 3 Comparison of scores of resource indicators between the chloride route and the sulfate route for the titania produced in Panzhihua city, southwest China

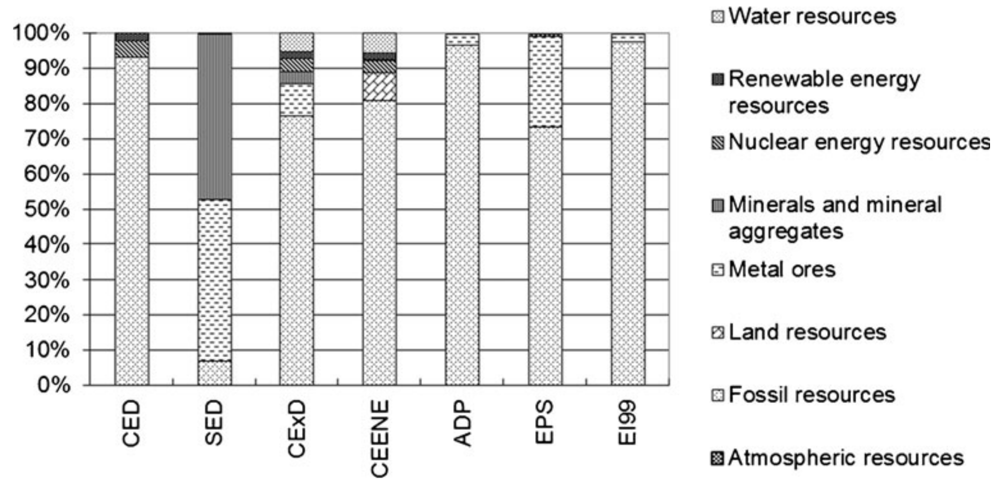

Fig. 4 Relative contributions of resource groups to the different resource indicators (CED, SED, CExD, CEENE, ADP, EPS, and EI99) in the chloride route

based on the CML-IA Database (2010) (ESM Table S8). Data gaps are partially filled by making various assumptions and referring to some trivial literature (e.g., see the calculation of CExD characterization factor of V–Ti magnetite ore in the ESM). Computations are with the software CMLCA (Chain Management by Life Cycle Assessment) developed by Heijungs (2011) in this study.

4 Results and discussion

4.1 Resource scores

Table 4 gives the scores of seven resource indicators addressed in this study for 1 kg of titania produced via both the chloride route and the sulfate route. Within the four thermodynamic resource indicators, CED, CExD, and CEENE have similar scores with each other, while their scores are five orders of magnitude lower than the score of SED. This is mainly because the SED includes the ecospheric processes (see Fig. 1) for forming various resources. The CExD of 1 kg of the titania produced in Panzhihua city, southwest China, is 118 and 138 MJ_{ex}-eq for the chloride route and the sulfate route, respectively. Considering the specific chemical exergy of titania (11.326 MJ_{ex}/kg), this corresponds to a CDP of 0.096 and 0.082 for the chloride route and the sulfate route, respectively, which is in the lower bound of the range of CDP for normal energy and material products (0.05–0.84; Szargut et al. (1988)).

Figure 3 compares the resource indicators between the chloride route and the sulfate route. It shows that titania produced via the chloride route uses less resources than the sulfate route by 10–35 %, except in terms of SED. The higher score of SED of the chloride route compared to the sulfate route can be explained by the fact that rather more sodium chloride as a resource flow is used in the chloride route than in the sulfate route, while the difference of other resource demands between the two routes is not so significant. Of the sodium chloride (as shown in ESM Table S8), 0.364 and 0.179 kg are used in the chloride route and the sulfate route, respectively. They correspond to SED scores of 3.60E+07 and 1.77E+07 MJ_{se}-eq, respectively, which account for 45 and 27 % of the total SED in the chloride route and the sulfate route, respectively.

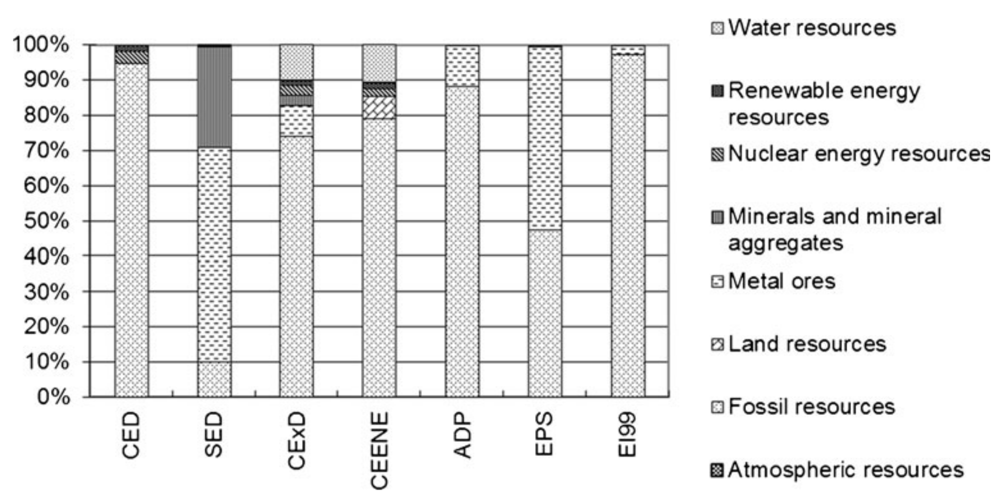

Fig. 5 Relative contributions of resource groups to the different resource indicators (CED, SED, CExD, CEENE, ADP, EPS, and EI99) in the sulfate route

Table 5 Cumulative non-renewable energy demand (CED_{NRR}) of 1 kg of the titania produced in Panzhihua city, southwest China

Route	CED_{fossil} (MJ)	$CED_{nuclear}$ (MJ)	CED_{NRR} (MJ)
Chloride route	98.7	5.01	104
Sulfate route	111	3.97	115

4.2 Resource contributions

The relative contribution of each resource group to the scores of different resource indicators is represented in Figs. 4 and 5 for the chloride route and the sulfate route, respectively. Within the seven resource groups analyzed (see Tables 1 and 2), atmospheric resources and land resources are considered in SED and CEENE only. Atmospheric resources do not contribute to the SED or CEENE score since their characterization factors are set to zero. Land resources account for a negligible percent to the SED scores (0.01 % in both the chloride and sulfate routes) and have a small contribution to the CEENE scores, i.e., 8 and 6 % in the chloride and sulfate routes, respectively. This indicates that, at least in the titania system analyzed, atmospheric resources and land resources could be left out of consideration in the SED indicator despite the SED indicator being regarded to give a more comprehensive overview of the resource demand than the indicators of CED, CExD, ADP, EPS, and EI99.

In Figs. 4 and 5, it appears that non-renewable resources have a dominant contribution to the scores of all seven resource indicators in both the chloride and sulfate routes, while renewable energy sources have a small contribution (<2 %). Fossil resources have a relatively high contribution to the scores of CED, CExD, CEENE, ADP, and EI99 (more than 74 %) in all types of non-renewable resources. Metal ores and fossil fuels have comparable contributions to the score of EPS. This can be explained by the fact that the average willingness to pay for the production of metals ores by a mining–crushing–grinding–leaching–precipitation process, which is considered as the sustainable alternative for the current mining practice, is several orders of magnitude higher than that for the production of sustainable alternatives for fossil resources (e.g., charcoal, rapeseed, etc.), while the demand of metal ores is several orders of magnitude lower than that of fossil resources (except for V–Ti magnetite ore whose EPS characterization factor is unavailable). The score of SED is dominated by the demand of metal ores (mainly V–Ti magnetite ore) and minerals (mainly sodium chloride), with contributions of 92 % in the chloride route and 89 % in the sulfate route, respectively.

4.3 Sensitivity analysis of CED

There has been a debate on the question whether the energy of all types of energy carriers, viz., fossil, nuclear, and renewable, should be integrated into a single score. Frischknecht et al. (1998) recommend refraining from aggregating renewable and non-renewable energy demand because of the different nature of the resources. Furthermore, it is recognized that the demand of non-renewable energy resources is dominantly responsible for global warming and the depletion of non-renewable energy resources (Pacala and Socolow 2004; Rosa and Ribeiro 2001). If renewable energy sources are excluded, the cumulative non-renewable energy demand (CED_{NRR}) can be defined as: $CED_{NRR}=CED_{fossil}+CED_{nuclear}$. Table 5 gives the CED_{NRR} that is required in the supply chain of 1 kg of the titania produced in Panzhihua city, southwest China.

Figure 6 shows the relative contribution of different non-renewable energy carriers to CED_{NRR}. It appears that normal fossil fuels, i.e., hard coal, crude oil, and natural gas, have a dominant contribution (more than 90 %) in both routes.

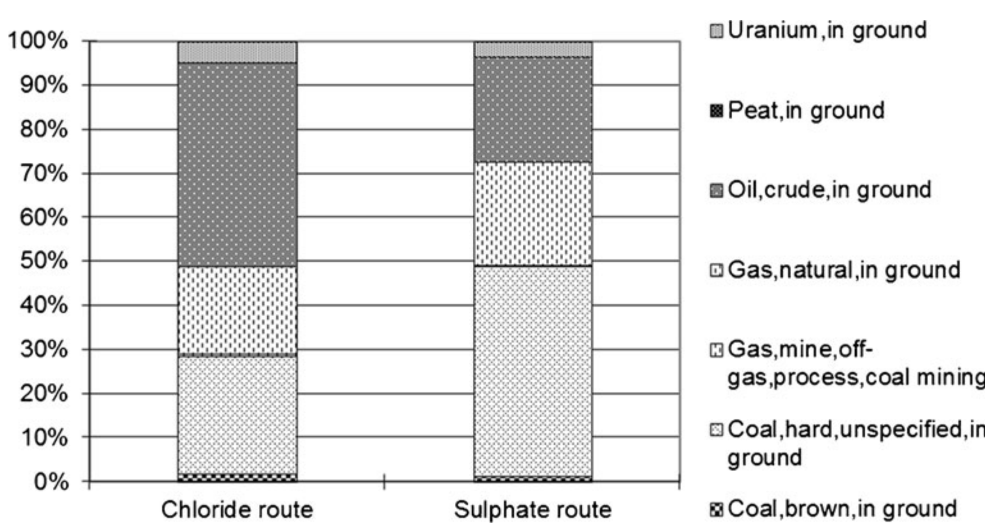

Fig. 6 Relative contribution of non-renewable energy carriers to CED_{NRR}

4.4 Normalization

Similar to CED_{NRR}, the cumulative non-renewable exergy demand ($CExD_{NRR}$) can be defined as: $CExD_{NRR}=CExD_{fossil+CExDnuclear}+CExD_{metals}+CExD_{minerals}$. Considering the CED_{NRR} and $CExD_{NRR}$ of 1 kg of titania produced by the chloride and sulfate routes (104–115 MJ and 120–134 MJ_{ex}-eq, respectively), the global production of titania, which is reported to be 4.5E+09 kg/year for 2004 (Linak and Inoguchi 2005),[2] would correspond to the CED_{NRR} and the $CExD_{NRR}$ of global titania of 4.67E+11–5.17E+11 MJ/year and 5.40E+11–6.03E+11 MJ_{ex}-eq/year, respectively. A total anthropogenic non-renewable energy/exergy demand, i.e., the demand of non-renewable energy/exergy by all human activities in the anthroposphere, is reported to be around 4.11E+14 MJ/year and 4.15E+14 MJ_{ex}-eq/year (for the year 2008; the International Energy Agency 2008; British Petroleum 2010; Liao et al. 2012).[3] The normalization shows that the global production of titania would account for about 0.12 % of the total anthropogenic non-renewable energy demand and about 0.14 % of the total anthropogenic non-renewable exergy demand. Similar normalizations in other resource indicators can also be implemented if corresponding values of the total anthropogenic demand are available.

5 Conclusions and recommendations

In this study, we compared different resource indicators, in particular those based on thermodynamics. The different resource indicators have been shown to give different results in a case study on titania, although most indicators pointed in the same direction. Compared with other non-thermodynamic resource indicators, the basic added value to the impact assessment of resource use by using thermodynamic resource indicators in LCA lies in the completeness of resource scope and scientific robustness and validity, while thermodynamic resource indicators have lower environmental relevance in terms of expressing the resource scarcity and depletion (EC JRC 2010a, b). Within the four thermodynamic resource indicators addressed, SED and CEENE seem to be the most comprehensive indicators since they account for the largest number of resource groups. However, SED has a different system boundary and perspective than the other three indicators. While the other three indictors account for the intrinsic value of the resources (i.e., what resources can contribute to the anthroposphere, which is a mere utilitarian perspective), SED attempts to characterize the previous effort spent by the ecosphere in generating resources. In addition, at least in the case of the two routes for titania, it differs considerably from the other three by focusing on metal ores and minerals whose issue of scarcity per se could be better expressed via other non-thermodynamic resource indicators. Thus, we recommend CEENE as the most appropriate thermodynamic indicator for accounting and characterizing resource use, energetic and otherwise. As for the other two indicators, CED and CExD do not account for atmospheric and land resources (biomass is accounted in a different way) and focus on the energy content and exergy content of resources, respectively. CExD accounts for non-energetic materials (mainly metal ores and minerals), which are excluded in CED.

We also demonstrated the feasibility of thermodynamic resource indicators by testing them in the case study on the titania produced in Panzhihua city, southwest China. Conclusions can be drawn with regard to the case study: (1) all the resource indicators, except SED, under consideration show that the sulfate route demands more resource use than the chloride route; (2) non-renewable resources, in particular fossil resources, have a dominant contribution to all resource indicators addressed, except SED; (3) the global production of titania would account for 0.12 and 0.14 % of the total anthropogenic non-renewable resource demand in terms of energy and exergy, respectively.

It is a challenge to promote thermodynamic resource indicators. As pointed out by the ILCD Handbook: "(a thermodynamic resource indicator) does not take into account the future scarcity of a resource while it somehow considers the aspect of dispersion which is also an indicator of availability" (EC JRC 2010a, b), more efforts are needed to clarify the relevance between resources' thermodynamic properties and their scarcity for humans if thermodynamic indicators are used for the impact assessment besides the accounting and characterization of resource use. In addition, future study can refine the characterization factors of minerals containing similar elements and set characterization factors to more resource flows based on reliable data, on one hand, and give more information on uncertainty, on the other hand. In this case, thermodynamic indicators would serve as more useful methods for the accounting and impact assessment of resource use.

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