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Relevance of Impact Categories and Applicability of Life Cycle Impact Assessment Methods from an Automotive Industry Perspective

Natalia Mikosch [1,*], Tina Dettmer [2], Benjamin Plaga [2], Marko Gernuks [3] and Matthias Finkbeiner [1]

1 Department of Sustainable Engineering, Institute of Environmental Technology, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany; matthias.finkbeiner@tu-berlin.de

2 Group Research & Development, Life Cycle Optimisation, Volkswagen AG, Berliner Ring 2, 38440 Wolfsburg, Germany; tina.dettmer@volkswagen.de (T.D.); benjamin.plaga@volkswagen.de (B.P.)

3 Group Components, Circular Economy, Volkswagen AG, Berliner Ring 2, 38440 Wolfsburg, Germany; marko.gernuks@volkswagen.de

* Correspondence: natalia.mikosch@greenzero.me

Abstract: Climate change impacts have been extensively addressed in academia, politics and industry for decades. However, particularly within the scientific community, the importance of considering further impact categories to ensure holistic environmental assessment and avoid burden shifting is strongly emphasized. Since considering all impact categories might become overwhelming for industry, a prioritization approach can support practitioners to focus their efforts on the most relevant impacts. Therefore, within this paper, an approach for the identification of relevant impact categories is developed for the automotive sector together with Volkswagen AG. The evaluation is conducted using a criteria set including criteria groups "relevance for automotive sector" and "relevance for stakeholders". For the impact categories identified as relevant, an evaluation of LCIA methods is conducted considering the methodologies CML and ReCiPe 2016 and the methods recommended by PEF. The results demonstrate that climate change is by far the most relevant impact category followed by resource use, human toxicity and ecotoxicity from both automotive and stakeholder perspective. Based on the evaluation of the LCIA methods, a combination of different methods can be recommended. This work provides guidance for the automotive sector to prioritize its focus on the most relevant impact categories and to select applicable LCIA methods for their quantification.

Keywords: impact categories; life cycle impact assessment; CML; ReCiPe 2016

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1. Introduction

For the last few decades, there has been an ongoing debate in the life cycle assessment (LCA) community with regard to the relevance of different impact categories and the selection of appropriate life cycle impact assessment (LCIA) methods for their quantification. This is reflected, for example, by the Product Environmental Footprint (PEF) initiative, which sets weighting factors for 16 impact categories based on a stakeholder evaluation [1]. Also, the German Environment Protection Agency developed an approach to determine the most relevant impact categories, which is based on three criteria: ecological hazard (i.e., how severe the impact is), distance-to-target (current distance of the impact category to a desired state) and specific contribution (contribution of the result to the total emissions in Germany) [2]. While the scientific community insists on the relevance and consideration of all or at least a comprehensive set of impact categories, this can often be overwhelming for industry and hamper the interpretation of the results and prioritization of mitigation measures. However, currently these prioritization approaches are generic and no approach is available to determine the relevance of the impact categories for a specific industrial sector.

The quality and application of different LCIA methods have also been extensively debated in the LCA community. Recommendations for the selection of certain methods were provided by the European Commission in the International Reference Life Cycle Data System (ILCD) Handbook [3], by the United Nations Environmental Program [4,5], and in the Product Environmental Footprint Category Rules Guidance [1]. However, as demonstrated by Bach et al. [6], these recommendations are often based on the preferences and understanding of the scientific community only (e.g., the desire for the application of newly developed and the most sophisticated characterization models), while the needs of the practitioners, for example, with regard to robustness (i.e., established well known methods) and availability of inventory data, are often left to slide. This challenge was, for example, confirmed in the PEF pilot phase as "the evaluation of the impact assessment methods proposed in the PEF/OEF Guide showed that the predefined methods for water consumption, land use, and abiotic resources are not adequate because of modeling artefacts, missing inventory data, or incomplete characterization factors" [7].

Volkswagen AG has applied LCA for more than 25 years and continuously works on improving their internal tools and the fitness for internal decision-making purposes [8]. As part of this process, Volkswagen intended to update their LCIA approach by considering the relevance of impact categories and the applicability of the state-of-the-art impact assessment, respectively, characterization models from an automotive industry perspective. To address this challenge, the SEE group of TU Berlin developed a criteria-based approach and performed an evaluation of impact categories and LCIA methods for this purpose. As a result, this paper presents the relevant impact categories and LCIA methods for their quantification as identified for the Volkswagen AG. More specifically, the aims of this paper are (1) to identify the impact categories that are relevant for the automotive sector and (2) to select the LCIA methods that fit best for the quantification of these impact categories from the automotive sector perspective. The set of evaluated methodologies includes CML [9], ReCiPe 2016 [10] and the methods recommended by PEF Category Rules Guidance [1].

2. Materials and Methods

2.1. Identification of Relevant Impact Categories

The following impact categories are considered for the evaluation: climate change, eutrophication, acidification, photochemical ozone formation, ozone depletion, ionizing radiation, human toxicity, ecotoxicity, water use, resource use, particulate matter formation and land use. They represent the most commonly addressed impact categories in LCA.

The relevance of the impact categories is evaluated by means of a criteria set, which includes two criteria groups: (1) relevance for the automotive sector and (2) relevance for stakeholders (Table 1). The first one tries to capture the automotive sector priorities specifically, while the second one focusses on broader stakeholder priorities in order to capture both perspectives. The relevance is evaluated as low, medium, high and very high using a semi-quantitative approach developed for each criterion. In the following, all criteria and the evaluation procedure are described.

The criteria group "relevance for automotive sector" includes following criteria: current contribution to the impact category, expected future contribution to the impact category, contribution to the Sustainable Development Goals (SDG) targets and reporting frequency. The contribution to the impact categories is evaluated based on normalized LCIA results for the production and use phase of passenger vehicles using the data provided by Volkswagen AG (internal data). The current contribution is evaluated by means of the LCIA results for a vehicle with an internal combustion engine (ICE), while for the criterion "future contribution", results for an electric vehicle (EV) are used. The criterion "contribution to the SDG targets" is based on the studies of Lisowski et al., who determined to which extent automotive industry influences SDG indicators [11,12]. The SDG indicators identified by Lisowski et al. as relevant (i.e., influenced by the automotive sector) are linked to one or several impact categories. For example, the indicator 9.4.1 "CO_2 emissions from fuel combustion" is linked to the impact category *climate change* and indicator 12.4.2 "Hazardous waste generation" is linked to the impact categories *human toxicity* and *ecotoxicity*. The relevance of each impact category is evaluated based on the cumulative contribution (%)

of the automotive sector over all SDG indicators and rates from very high (contribution over 30%) to low (contribution under 10%). To evaluate the criterion "reporting frequency", the impact categories considered in LCA reports published by six automotive companies (Daimler [13], Ford [14], Honda [15], Renault [16], BMW [17] and Volvo [18]) are reviewed. The relevance is evaluated based on the number of companies that report a certain impact category (Table 1).

The criteria group "relevance for stakeholders" is divided into two criteria: relevance for politics and relevance for other stakeholders (see Table 1). The criterion "relevance for politics" includes the following sub-criteria: existing legislation, future legislation, PEF and Environmental Performance Index (EPI). To evaluate the criterion "existing legislation", European Union (EU) legislation including eight regulations and 32 directives is reviewed. The scope of the reviewed legal acts, i.e., addressed environmental issues, are linked to one or several impact categories. The relevance of each impact category is evaluated based on the number of legal acts that address this impact category. The impact categories for which quantitative targets and/or thresholds are provided are counted as fully addressed (i.e., one legal act is counted as one time addressed). For example, this is the case for the impact category *climate change* addressed by the Regulation 2019/631, which provides limits for the CO_2 emissions of new vehicles [19]. If no targets or thresholds are set, the impact category is counted as partly addressed (i.e., impact category considered in one legal act without thresholds or targets is counted as 0.5 times addressed). For example, this applies to the Directive 2011/92, which regulates environmental impact assessment of public and private projects, but does not provide any thresholds or targets for any of addressed impact categories [20]. The criterion "future legislation" is evaluated based on nine policy areas of the EU Green Deal: climate action, biodiversity, farm to fork, sustainable agriculture, clean energy, sustainable industry, building and renovating, sustainable mobility and eliminating pollution [21]. The reason for considering the EU Green Deal is its potential impact on the European legislation in the upcoming years. The relevance of the impact categories is evaluated using the same procedure as for existing legislation based on addressed environmental issues and provided targets/thresholds. For example, the impact category *climate change* is evaluated as fully addressed by the policy area "climate action", since specific targets for the reduction of greenhouse gas emissions are provided. The impact category *water use* is evaluated as partly addressed by the policy area "sustainable agriculture", since it includes the topic "quality and quantity of water", but does not provide any specific targets or thresholds for water usage and/or pollution. The criterion PEF is evaluated based on the PEF final weighting factors provided in the Product Environmental Footprint Category Rules Guidance [1]. The EPI evaluates a country's environmental performance based on eleven issue categories, which include 32 indicators [22]. These indicators are linked to one or several impact categories. For example, the indicator "PM2.5 exposure" is linked to the impact category *particulate matter formation* and the indicator "SO_2 growth rate" to the impact categories *eutrophication* and *acidification*. The relevance of the impact categories is evaluated based on the weight of each issue category and indicator provided by EPI, which reflects their importance for the index.

The criterion "relevance for other stakeholders" includes four sub-criteria: World Economic Forum, Planetary Boundaries, Dow Jones Sustainability Index (DJSI) and Global Reporting Initiative (GRI). The criterion "World Economic Forum" is considered for the evaluation of impact categories from an economic point of view and is based on the Global Risk Report 2020 [23]. The latter provides an overview of the annual global risk landscape including environmental risks. To evaluate the relevance of the impact categories, addressed environmental risks are linked to corresponding impact categories (e.g., the risk "water crisis" is linked to the impact category *water use*). Each addressed impact category is rated with high relevance. The criterion Planetary Boundaries is based on the assessment of environmental impacts, which include the impacts within PBs (below boundary, evaluated as low relevance), beyond PBs (beyond zone of uncertainty, evaluated as high relevance) and in the zone of uncertainty (evaluated as medium relevance) [24,25]. Since for several impact categories PBs have not been quantified yet, the relevance of these impact categories was evaluated as medium. This allows to prevent the effect that the impact categories, for which no evaluation is possible, would have low relevance due to missing results.

Table 1. An overview of applied criteria and evaluation procedure for the identification of relevant impact categories.

Criteria Group/Criterion	Data and Source	Relevance Evaluated Based on	Relevance
1 Automotive sector			
1.1 Current contribution to impact categories			
1.1.a Production phase	LCA of an ICE vehicle (Volkswagen AG)	Normalized LCIA results	Internal data of Volkswagen AG
1.1.b Use phase	LCA of an ICE vehicle (Volkswagen AG)	Normalized LCIA results	Internal data of Volkswagen AG
1.2 Future contribution to impact categories			
1.2.a Production phase	LCA of an EV (Volkswagen AG)	Normalized LCIA results	Internal data of Volkswagen AG
1.2.b Use phase	LCA of an EV (Volkswagen AG)	Normalized LCIA results	Internal data of Volkswagen AG
1.3 Contribution to SDGs	Contribution of automotive industry to SDG indicators [11,12]	Contribution (%)	Very high (>30%), high (20–30%), medium (10–20%), low (<10%)
1.4 Reporting frequency	LCA reports of six automotive companies	Number of companies that report the impact category	Very high (6), high (3–5), medium (1–2), low (0)
2 Stakeholders			
2.1 Politics			
2.1.a Existing legislation	8 regulations and 32 directives	Number of times an impact category is addressed and if a quantitative threshold and/or target is provided	Very high (>10), high (7–10), medium (3–7), low (<3)
2.1.b Future legislation	EU Green Deal, 9 policy areas [21]	Number of times an impact category is addressed and if a quantitative threshold and/or target is provided	Very high (>4), high (2–4), medium (1–2), low (<1)
2.1.c Product Environmental Footprint	Weighting factors for environmental footprint [1]	Final weighting factors for each impact category	Very high (>20), high (7–20), medium (4–7), low (<4)
2.1.d Environmental Performance Index	11 issue categories including 32 indicators [22]	Weight of issue categories and indicators	Very high (>20%), high (10–20%), medium (3–7%), low (<3%)
2.2 Other stakeholders			
2.2.a World Economic Forum	The Global Risk Report 2020 [23]	Environmental issues addressed	All addressed issues are evaluated with a high relevance
2.2.b Planetary boundaries	Steffen et al. [25]	The status of the impact categories with regard to planetary boundaries	High (beyond zone of uncertainty), medium (in zone of uncertainty), low (below boundary)
2.2.c Dow Jones Sustainability Index	31 indicators for environmental dimension [26]	Number of times addressed	Very high (>15), high (10–15), medium (3–7%), low (<3%)
2.2.d Global Reporting Initiative	32 indicators for environmental issues [27]	Number of times addressed	

The criterion Dow Jones Sustainability Index (DJSI) is considered to address the relevance for ratings [26]. For the evaluation, 31 indicators included in the environmental dimension of the index are reviewed and linked to the impact categories. The relevance is evaluated based on the number of times an impact category is addressed. The criterion Global Reporting Initiative (GRI) represents the relevance for reporting platforms [27]. It includes 32 environmental performance indicators, which are linked to the impact categories. The relevance is evaluated based on the number of times an impact category is considered. An overview of the criteria and evaluation procedure is provided in Table 1.

As the next step, the results are transformed into a quantitative scale by rating the relevance of the impact categories in each criterion in the following way: very high relevance is rated with three points, high relevance with two points, medium relevance with one point and low relevance with zero points. Next, the results for each criteria group (automotive sector and stakeholders) are summed up and scaled from zero to one. The total relevance of each impact category is determined using the following thresholds:

- Total result over 1.0: very high relevance

- Total result over 0.75: high relevance
- Total result equal to or over 0.5: medium relevance
- Total result below 0.5: low relevance.

Based on this approach, the results for the impact category evaluation are presented in Section 3.1.

2.2. Identification of Relevant LCIA Methods

As described in the introduction part of this paper, the evaluation of relevant LCIA methods is conducted for the CML [9] and ReCiPe 2016 [10] methodologies and for the methods recommended by PEF Category Rules Guidance [1] as they represent the state-of-the-art LCIA methods in a European context.

The evaluation procedure follows the approach applied in existing studies [3,7,28] and includes the following two criteria groups: (1) applicability and (2) environmental relevance (Table 2). The criteria group "applicability" includes six criteria, which evaluate how well an LCIA method can be used by the automotive sector and how well the results can be communicated. The criterion "the method is globally valid" evaluates whether the method is based on a global spatially resolved model, i.e., multi-regional model or regionalized nested model, or is location-independent (for example, when the calculation is based on stoichiometry and does not include fate modelling). The criterion "characterization factors are available" evaluates if the characterization factors (CFs) needed for the application of the method can be easily accessed by automotive companies, for example, downloaded from a web page. The criterion "inventory data are adequate" describes if the inventory required for the application of the method, e.g., with certain spatial resolution, is usually available in the automotive sector. The criterion "the method is integrated in an LCA Software" evaluates if the method is available in a software commonly used for conducting LCA in the automotive sector. The criterion "the method is robust for communication" evaluates if provided results are mature enough for communication and the criterion "the method is understandable for the non-LCA community" evaluates whether the results can be understood not only by LCA practitioners (Table 2).

Table 2. An overview of the criteria applied for the evaluation of LCIA methods.

Criteria Group/Criterion	Description
1 Applicability	
1.1 The method is globally valid	CFs are applicable only for a specific region (e.g., Europe) or worldwide
1.2 Characterization factors are available	CFs for the application of the method are provided (e.g., online for download)
1.3 Inventory data are adequate	The inventory data needed for the application of the method are available in the automotive sector
1.4 The method is integrated in an LCA Software	The method is available in a software, e.g., GaBi [29] or SimaPro [30]
1.5 The method is robust for communication	The method and provided results are mature enough for communication
1.6 The method is understandable for the non-LCA community	The calculation procedure and results (including units) are understandable for non-LCA experts
2 Environmental relevance	
2.1 Relevant substances are considered [1]	All substances contributing to the impact category are considered
2.2 Relevant distribution pathways are considered [2]	The fate modelling is included in the method
2.3 Relevant damage areas are considered	All relevant damage areas (e.g., both terrestrial and aquatic ecosystems for eutrophication) are considered

[1] For *water use*, the criterion is changed to "spatial resolution of the input data is adequate". [2] For *land use*, the criterion is changed to "relevant soil parameters are considered".

The criteria group "environmental relevance" includes three criteria. The criterion "relevant substances are considered" evaluates if all substances that contribute to an impact category are considered. The criterion "relevant distribution pathways are considered" describes whether the method includes fate modelling and the criterion "relevant damage areas are considered" evaluates if all relevant damage areas, for example, both terrestrial and aquatic ecosystems in case of eutrophication and acidification, are considered (Table 2).

Further criteria often used in literature [3,7,28], for example, *documentation* and *stakeholder acceptance*, were not considered. The reason for this is the overall very good documentation and a high acceptance of the reviewed methodologies.

The evaluation is conducted in a semi-quantitative way. A fulfilled indicator is evaluated with three points, a partly fulfilled indicator with one point and a not fulfilled indicator with zero points. Next, the results are scaled from zero to one and plotted on a chart with the result for the criterion "applicability" on the *x*-axis and "environmental relevance" on the *y*-axis.

3. Results

3.1. Relevant Impact Categories

The evaluation of the impact categories demonstrates that *climate change* has high to very high relevance in almost all criteria for both the automotive sector and stakeholders. The only exception is the criterion "2.2.b planetary boundaries", where climate change reaches medium relevance (since it is in the zone of uncertainty (increasing risk), but not beyond it). *Human toxicity* and *ecotoxicity* reach high to very high relevance for the criteria current and future contribution to the impact category. Furthermore, these impact categories are extensively addressed in existing legislation and by the EU Green Deal (in particular through the thresholds for the use and emissions of heavy metals and chemical compounds and rules for the control of chemicals trade). The impact category *resource use* reaches very high relevance for the criteria current and future contribution of the automotive sector (production phase) and contribution to the SDG targets. Furthermore, it has a high relevance for four out of eight criteria in the group "stakeholders" including existing and future legislation (particularly through the targets and thresholds for resource efficiency, recycling and reuse rates), PEF and GRI (a strong focus on material and energy use, efficiency and recycling). The impact category acidification has high relevance for most criteria in the group "automotive sector" including both the production and use phase and a high reporting frequency. POCP has a high relevance in the criterion use phase (current contribution) and production phase (future contribution) of the automotive sector. Particulate Matter Formation rates high for the criteria PEF and EPI. Eutrophication reaches high relevance for existing and future legislation, which is mainly due to the existence of several regulations on the emissions of nitrogen oxides, wastewater treatment and nitrogen input through the application of fertilizers in agriculture. Ionizing radiation, water use and land use are the impact categories with the lowest relevance (see Figure 1).

Based on these results, the total relevance of the impact categories rates as following:

- Very high: climate change, human toxicity, ecotoxicity and resource use;
- High: acidification;
- Medium: POCP, ozone depletion, particulate matter formation;
- Low: eutrophication, ionizing radiation, water use, land use.

The goal of this step was also to preselect those impact categories, for which a detailed analysis of the associated LCIA methods was performed. To do this, first, all impact categories with high and very high relevance are considered for the evaluation of the LCIA methods. Next, additional criteria are applied which go beyond the direct interpretation of Figure 1: If an impact category had a strong automotive relevance, it is considered, even if general stakeholder importance was low. Examples include the impact category POCP (medium relevance overall, but high relevance for the automotive sector due to the use phase for current contribution, production phase for future contribution and reporting frequency) (see Figure 1) and the impact category particulate matter formation, which is also considered, since it is often associated with the automotive sector (emissions from traffic). Finally, the fact that some impact categories implicitly address biodiversity as an endpoint was considered. This led to the inclusion of the impact categories eutrophication, water use and land use. Although these impact categories reach low relevance in the applied evaluation scheme, they significantly contribute to the area of protection biodiversity. The evaluation of the criteria group "stakeholders" demonstrated that biodiversity impacts belong to the most relevant issues addressed by different stakeholders. For example, the EU Green Deal provides specific targets on the establishment of protected areas and restoration of river flows. Biodiversity has the highest importance for EPI and is addressed as one of the most significant risks (high impact and likelihood of biodiversity loss) by the World Economic Forum. The biodiversity issue is addressed in PBs as having high risk and rates high also for the GRI.

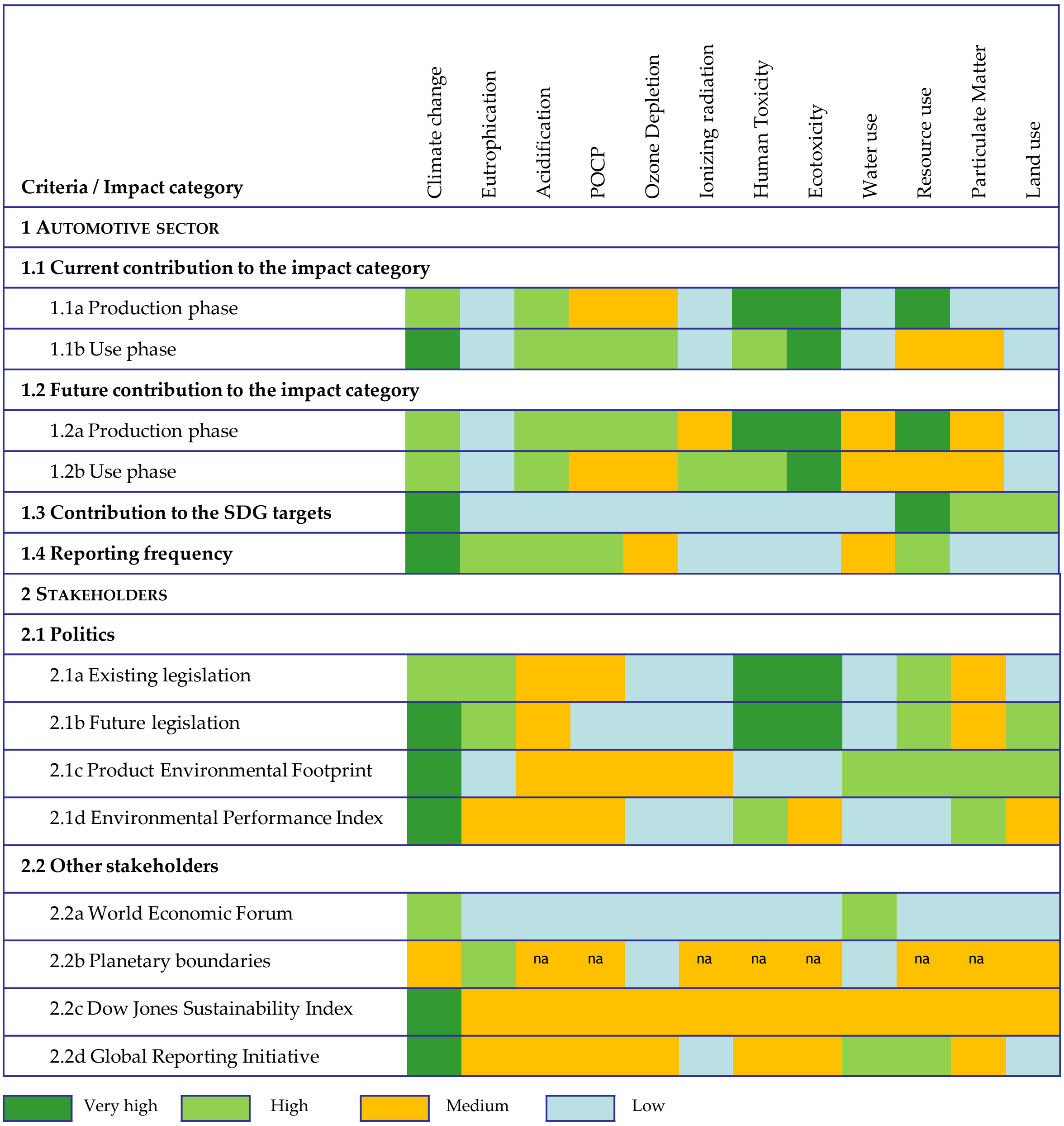

Figure 1. Evaluation of the relevant impact categories: results; "na" stands for "not applicable", i.e., the criterion could not be evaluated due to missing data, therefore the relevance was rated as medium.

Plotted results can be seen in Figure 2. For both the automotive sector and stakeholders, climate change is by far the most relevant impact category followed by the impact categories resource use, ecotoxicity, human toxicity and acidification.

Given the further selection described above, this step basically led to the exclusion of the impact categories ozone depletion and ionizing radiation. All other impact categories were identified as relevant and were considered in the next step.

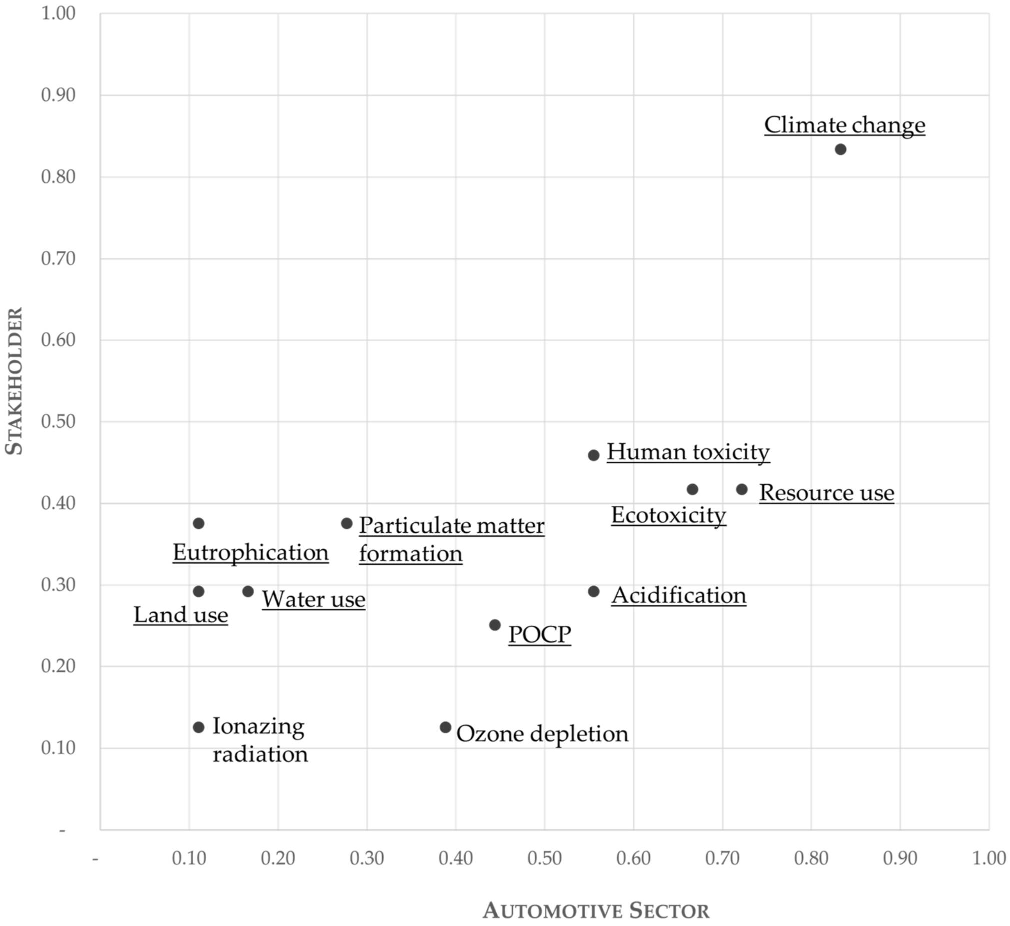

Figure 2. Evaluation of the relevant impact categories: plotted results for the criteria groups automotive sector and stakeholders. Impact categories that are considered for the evaluation of LCIA methods are underlined.

3.2. Relevant LCIA Methods

3.2.1. Considered LCIA Methods

In the following, the results of the evaluation of LCIA methods are described. As outlined in the methodological part, for the evaluation, the LCIA methods included in the CML and ReCiPe methodologies as well as recommended by PEF were considered. For the impact category *resource use*, *elements*, Abiotic resource depletion potential (ADP ultimate reserves) [31,32] (CML) and the Surplus ore potential (SOP) [33] (ReCiPe 2016) were evaluated. The recommendation of PEF is the ADP ultimate reserves method, i.e., same as by the CML methodology. For the impact category *resource use*, *fossils*, Abiotic resource depletion–fossil fuels (ADP-fossil) [31,32] (CML) and Fossil fuel potential (FFP) [34] (ReCiPe 2016) were considered. Also for this impact category, PEF recommendation is the method adopted in CML. Additionally, the method Cumulative Energy Demand (CED) was considered [35,36], since it has been broadly applied in LCA for the quantification of fossil resource use for decades [35]. For *human and ecotoxicity*, evaluated methods are USES-LCA adopted in CML [37], USES-LCA 2.0 [38] (ReCiPe 2016) and the USEtox method [39] recommended by PEF. The methods evaluated for the impact category *acidification* are the method of Guinee et al. 2002 [40] (CML), the method of Roy et al. 2014 [41] (ReCiPe 2016) and Accumulated Exceedance (AE) [42] recommended by PEF. For *eutrophication*, the method of Guinee et al. 2002 [40] (CML), Helmes et al. 2012 [43] (ReCiPe 2016) and Accumulated Exceedance (AE) [42] recommended by PEF were evaluated. For the impact category *POCP*, the method of Derwent et al. 1998 [44] (CML), van Zelm et al. 2016 [45] (ReCiPe 2016) and van Zelm et al. 2008 [46] (PEF recommendation) were considered. For the impact category *particulate matter formation*, the methods of van Zelm et al. 2016 [45] (ReCiPe 2016) and Fantke et al. 2017 [47] (PEF recommendation) were evaluated. CML methodology does not include this impact category (PM10 emissions to air are considered as part of the impact category *human toxicity*). The impact category *water use* is not addressed in the CML methodology as well. For ReCiPe 2016, the method of Döll and Siebert 2002 [48] and Hoekstra and Mekonnen 2012 [49] was evaluated. The PEF recommendation for *water use* is the method AWARE [50]. Additionally the methods WSI [51] and WAVE+ [52] were evaluated, since they are broadly applied in water footprinting. The impact category *land use* is not included in the CML methodology. The method of de Baan et al. 2013 [53] and Curran et al. 2014 [53] was evaluated for ReCiPe 2016 and the LANCA 2.0 method [54,55] for PEF recommendation. For the impact category *climate change*, both CML and ReCiPe as well as PEF recommendations refer to the method of IPCC [56], therefore, no comparison was conducted. An overview of all evaluated LCIA methods is provided in Table 3.

Table 3. Overview of considered LCIA methods.

Impact Category	CML	ReCiPe 2016	ILCD/PEF/UNEP Recommendation
Resource use, elements	ADP ultimate reserves (Guinée 2002 [31] and van Oers et al. 2002) [32]	SOP (Vieira et al. 2016) [33]	Same as in CML
Resource use, fossil [1]	ADP-fossil (Guinée 2002 [31] and van Oers et al. 2002) [32]	FFP (Jungbluth and Frischknecht 2010) [34]	Same as in CML
Human toxicity	USES-LCA (Huijbregts et al. 2000) [37]	USES-LCA 2.0 (van Zelm et al. 2009) [38]	USEtox (Rosenbaum et al. 2008) [39]
Ecotixicity	USES-LCA (Huijbregts et al. 2000) [37]	USES-LCA 2.0 (van Zelm et al. 2009) [38]	USEtox (Rosenbaum et al. 2008) [39]
Acidification	Guinee et al. 2002 [40]	Roy et al. 2014 [41]	AE (Seppälä et al. 2006) [42]
Eutrophication	Guinee et al. 2002 [40]	Helmes et al. 2012 [43]	AE (Seppälä et al. 2006) [42]
Photochemical Ozone Creation	Derwent et al. 1998 [44]	Van Zelm et al. 2016 [45]	Van Zelm et al. 2008 [46]
Particulate Matter Formation	n/a [2]	Van Zelm et al. 2016 [45]	Fantke et al. 2017 [47]
Water use	n/a [3]	Döll and Siebert 2002 [48], Hoekstra and Mekonnen 2012 [49]	AWARE (Boulay et al. 2018) [50]
Land use	n/a [4]	de Baan et al. 2013 [53], Curran et al. 2014 [53]	LANCA 2.0 (Bos et al. 2016, 2020) [54,55]

[1] Additionally, the method "Cumulative Energy Demand (CED)" was considered (VDI 4600 [36] and Frischknecht et al. 2015 [35]). [2] The impact category particulate matter formation is not addressed in the CML methodology. [3] The impact category water use is not addressed in the CML methodology. Additionally, the methods WSI (Pfister et al. 2009) [51] and WAVE+ (Berger et al. 2018) [52] were evaluated. [4] The impact category land use is not addressed in the CML methodology.

3.2.2. Results of the Evaluation of LCIA Methods

In the following, the results of the methods evaluation are presented, whereas in particular the criteria where the methods rate differently are described.

Resource use, elements

In the impact category *resource use, elements*, two methods were evaluated: CML (also PEF recommendation) and ReCiPe 2016. Both methods fulfill the criteria 1.1–1.4, since they are globally valid, CFs are available, inventory data are adequate and the methods are integrated in an LCA software. Both methods partly fulfill the criteria 1.5 and 1.6 due to some restrictions in robustness (e.g., anthropogenic stocks and dissipation are not considered) and comprehensibility of the results units (calculated as antimony-equivalents (CML) and copper-equivalents (ReCiPe 2016)). Both methods fulfill the criterion "relevant elementary flows are considered". The criterion "relevant distribution pathways are considered" is partly fulfilled by both methods due to aforementioned methodological limitations, i.e., not considering dissipation and anthropogenic stocks. The criterion "relevant damage areas are considered" is fulfilled by CML and partly fulfilled by ReCiPe 2016. The reason for this is the different scope of the methods: while CML is focused on resource depletion, ReCiPe 2016 uses the future efforts approaches [28]. Due to the focus of Volkswagen AG on the depletion impacts, the CML method achieved a higher result. Based on this evaluation, both methods achieved the same score in applicability, while CML rates better in environmental relevance (see Figure 3a).

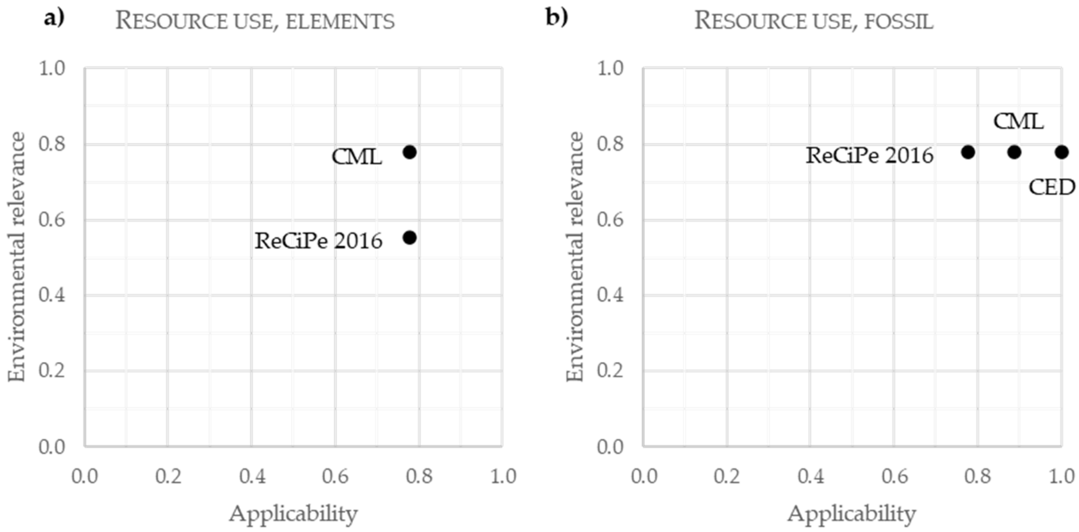

Figure 3. Results of the evaluation of the impact categories *resource use*, *elements* (**a**) and *resource use*, *fossil* (**b**).

Resource use, fossil

For the impact category *resource use, fossil*, the CML method (also PEF recommendation), ReCiPe 2016 and Cumulative Energy Demand (CED) were considered (see Table 3). All methods fulfill the criteria 1.1–1.4, since they are globally valid, CFs are available, inventory data are adequate and the methods are implemented in an LCA software. The criterion 1.5 "robust for communication" is fulfilled by CED, while two other methods partly fulfill this criterion due to some methodological restrictions. The criterion 1.6 "understandable" is fulfilled by CED and CML, since both methods provide results in the megajoule units, which are well-known also outside the LCA community. This criterion is partly fulfilled by ReCiPe 2016, since it calculates the results in oil-equivalents, which might be more difficult to comprehend compared to other methods. The criterion 2.1 "relevant elementary flows are considered" is fulfilled by CED and partly fulfilled by CML and ReCiPe 2016, both of which do not consider nuclear energy as it is done by CED. The criterion 2.2 "relevant distribution pathways are considered" is fulfilled by CML (calculation of depletion of fossil resources) and ReCiPe 2016 (increased future costs). This criterion is partly fulfilled by CED, which provides the result as a sum of inventory without further impact assessment. The criterion 2.3 is fulfilled by all methods. Based on this evaluation, all methods have the same score in environmental relevance, while CED has the highest score in applicability (see Figure 3b).

Human toxicity

In the impact category *human toxicity*, the USEtox method performs better in the criterion "the method is globally valid", since it has a global coverage (global average and subcontinental CFs based on a regionalized nested model). In contrast, the USES-LCA method adopted in CML and ReCiPe 2016 is based on European conditions and does not provide any spatial differentiation of the CFs (an important assumption of the method is that the emissions take place in Western Europe). The criteria 1.2–1.4 are evaluated as fulfilled by all methods, since the CFs are available, inventory data are adequate and all considered methods are implemented in an LCA software. The criteria 1.5 and 1.6 are evaluated as not fulfilled, since the robustness of the methods for the quantification of toxicity impacts is considered as low (as it is also addressed by PEF [1]). The reason for this is, among others, low suitability of multi-media nested models (which are implemented in both USEtox and USES-LCA) for metals, amphiphilics and dissociating organic chemicals. The criterion "relevant substances are considered" is evaluated as not fulfilled for CML, since the USES-LCA model adopted in this methodology includes only around 1.000 substances. This criterion is evaluated as partly fulfilled for USES-LCA adopted in ReCiPe 2016 and the USEtox model, both of which include around 3.500 substances. For none of the methods is this criterion is completely fulfilled, since the aforementioned databases are still not sufficient to cover the broad range of substances applied in industry nowadays. The criterion "relevant distribution pathways are considered" is only partly fulfilled for all methods due to the missing groundwater compartment. The criterion "relevant damage areas are considered" is partly fulfilled by the CML methodology, since it does not differentiate between cancer and non-cancer impacts, which is the case in ReCiPe 2016 and USEtox. As a result, USEtox rates best with regard to applicability, while both USEtox and ReCiPe 2016 rate best for environmental relevance (see Figure 4a).

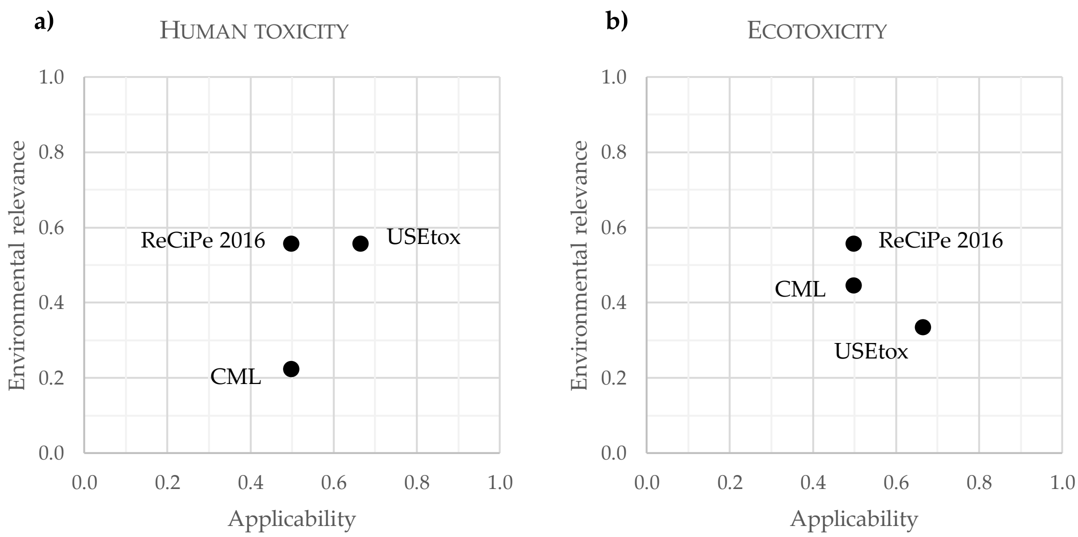

Figure 4. Results of the evaluation of the impact categories *human toxicity* (**a**) and *ecotoxicity* (**b**).

Ecotoxicity

For *ecotoxicity*, the methods rate the same in all criteria except "relevant damage areas are considered". Here, CML and ReCiPe 2016 fulfill the criterion completely, since the USES-LCA method adopted by these methodologies includes freshwater, terrestrial and marine ecotoxicity. Since in USEtox only freshwater ecotoxicity is covered, this criterion is evaluated as partly fulfilled. Other criteria are evaluated the same as for *human toxicity*. This results in the fact that USEtox rates best in applicability, but achieves a lower result than two other methods for environmental relevance (see Figure 4b).

Acidification

All analysed methods rate differently in the criterion "the method is globally valid". CML methodology partly fulfills this criterion, since it provides generic location-independent CFs calculated based on stoichiometry, but also CFs with fate modelling, which is based on European conditions. The method of Seppälä et al. recommended by PEF does not fulfill this criterion, since it provides CFs only for European countries. The method adopted in ReCiPe 2016 fulfills this criterion, since it provides region-specific CFs with spatial resolution on a country, continental and global average scale. The criteria 1.2–1.4 are evaluated as fulfilled for all methods. The criteria 1.5 and 1.6 are evaluated as partly fulfilled due to medium robustness of the methods, which is also addressed by PEF [1]. For the criterion "relevant substances are considered", CML rates better (fulfilled), since it considers twelve substances compared to only four substances considered by Seppälä et al. and in ReCiPe 2016 (partly fulfilled). CML fulfills the criterion "relevant damage areas are considered", since it includes both terrestrial and freshwater acidification in a combined calculation. In contrast, the method of Seppälä et al. and ReCiPe 2016 include only terrestrial acidification, therefore, this criterion is only partly fulfilled. In the criterion 2.2 "relevant distribution pathways are considered" CML achieves a lower result (partly fulfilled) compared to other methods, since it provides fate modelling for only four substances. For other methods, this criterion is evaluated as completely fulfilled. Based on this evaluation, CML rates best with regard to environmental relevance, while ReCiPe 2016 achieves a better result in applicability (see Figure 5a).

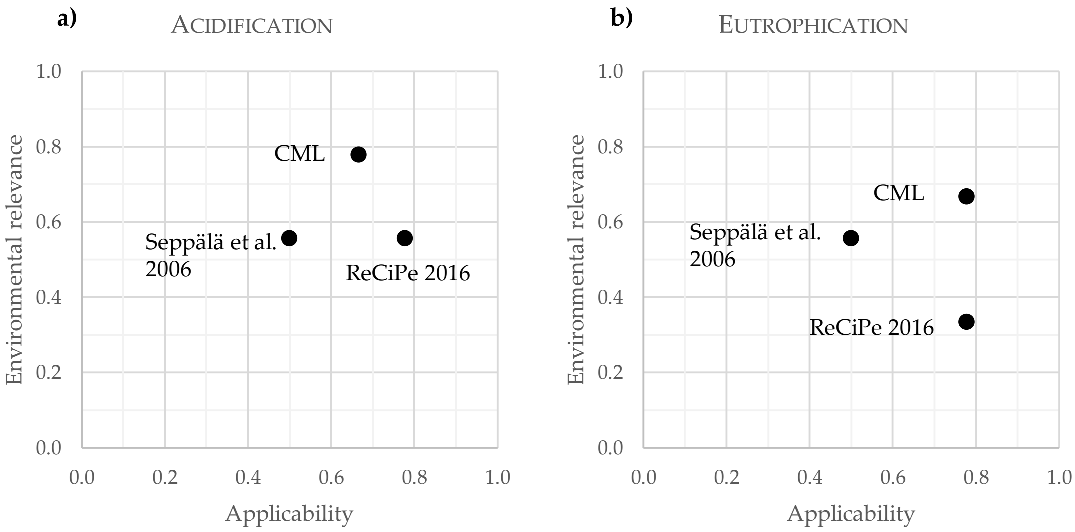

Figure 5. Results of the evaluation of the impact categories *acidification* (**a**) and *eutrophication* (**b**).

Eutrophication

The criterion "the method is globally valid" is fulfilled by CML (location-independent CFs based on stoichiometry) and ReCiPe 2016 (region-specific CFs with spatial resolution at a country and continental level and as global averages). The method of Seppälä et al. does not fulfill this criterion, since it provides CFs only for European countries. The criteria 1.2–1.4 are evaluated as fulfilled for all methods and the criteria 1.5 and 1.6 as partly fulfilled. The criterion "relevant substances are considered" is fulfilled by CML, which provides CFs for twelve substances, and partly fulfilled by the method of Seppälä et al. (CFs for five substances) and ReCiPe 2016 (CFs for two substances). The criterion "relevant distribution pathways are considered" is not fulfilled by CML, since the CFs are based solely on stoichiometry, i.e., no fate modelling is conducted. This criterion is partly fulfilled by ReCiPe 2016, since out of two CFs provided by the method, fate modelling is conducted only for the emissions of phosphorus, while the CFs for phosphate are based on stoichiometry. The method of Seppälä et al. fulfills this criterion, since it has fate modelling for all provided CFs. The criterion "relevant damage areas are considered" is fulfilled by the CML methodology, which includes both terrestrial and freshwater eutrophication in a combined calculation. This criterion is partly fulfilled by the method of Seppälä et al. and ReCiPe 2016, which include only terrestrial eutrophication. Based on these results, CML rates best with regard to environmental relevance. ReCiPe and CML achieve the same result for applicability and rate better than the method of Seppälä et al. (see Figure 5b).

Photochemical ozone creation potential

The criterion "the method is globally valid" is fulfilled only by ReCiPe 2016, which includes a region-specific model with global coverage and provides CFs with the spatial resolution at a country level and as global average. The CML methodology does not fulfill this criterion, since it provides CFs calculated based on Northwestern European conditions. The method of van Zelm et al. (PEF recommendation) models global propagation of emissions, however the fate model adopted in this methodology assumes that the emission takes place in Europe. Therefore, it partly fulfills this criterion. The criteria 1.2–1.4 are evaluated as fulfilled by all methods (i.e., CFs are available, inventory data are adequate and methods are implemented in an LCA software). The criteria 1.5–1.6 are evaluated as partly fulfilled due to limitations in the robustness of all methods. The criterion "relevant substances are considered" is fulfilled by CML and ReCiPe 2016, which provide 127 CFs and 121 CFs, respectively. This criterion is evaluated as partly fulfilled by the method of van Zelm et al., which provides only two CFs. The criterion "relevant distribution pathways are considered" is fulfilled by ReCiPe 2016 and the method of van Zelm et al., which adopts sophisticated fate modelling, and partly fulfilled by CML, which includes a simplified fate calculation. The criterion "relevant damage areas are considered" is fulfilled by all methods. This evaluation leads to ReCiPe 2016 reaching the best result in both applicability and environmental relevance (see Figure 6a).

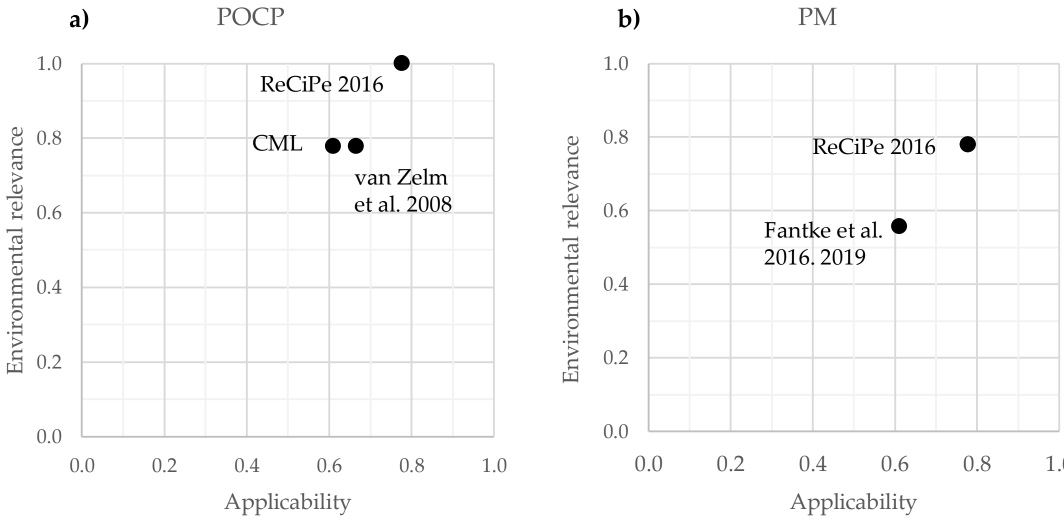

Figure 6. Results of the evaluation of the impact categories *POCP* (**a**) and *particulate matter formation* (**b**).

Particulate matter formation

In the following, only ReCiPe 2016 and the method of Fantke et al. are evaluated, since CML does not calculate the impact category *particulate matter formation*. The criteria 1.1–1.3 are evaluated as fulfilled by both methods. The criterion 1.4 "the method is integrated in an LCA software" is not fulfilled by the method of Fantke et al., since it is provided only as an Excel calculation tool. The criteria 1.5 and 1.4 are evaluated as partly fulfilled due to some limitations in the robustness of both methods. The criterion "relevant elementary flows are considered" is partly fulfilled by the method of Fantke et al., which currently includes only primary PM 2.5 in contrast to ReCiPe 2016, which includes primary PM 2.5 (individualist perspective), primary PM 2.5 and secondary PM from sulphur dioxide (hierarchist perspective) and primary PM 2.5 and secondary PM from sulphur dioxide, nitrogen oxides and ammoniac (egalitarian perspective). The criterion "relevant distribution pathways are considered" is evaluated as partly fulfilled by both methods. ReCiPe 2016 adopts a multi-regional model and provides CFs as a global average and at a country and continental level. However, it does not differentiate between archetypes, e.g., rural/urban, as it is done in the method of Fantke et al. The method of Fantke et al. is based on a regionalized nested model (world average and 16 subcontinental regions, countries) and includes archetypes for rural and urban locations as well as indoor and outdoor conditions. However, it considers only ground level (ten meter reference high) emissions. The criterion "relevant damage areas are considered" is evaluated as fulfilled by both methods. Based on this evaluation, ReCiPe 2016 rates best in both applicability and environmental relevance (see Figure 6b).

Water use

As described in Section 3.2.1, for the impact category *water use*, two further methods are evaluated alongside ReCiPe 2016 and AWARE (PEF recommendation): WAVE+ and WSI. The CML methodology does not include this impact category and is therefore not considered in the evaluation. All methods fulfill the criteria 1.1–1.4, since they are globally valid, CFs are available, inventory data are adequate and the methods are implemented in an LCA software. The criteria 1.5 and 1.6 are evaluated as partly fulfilled by all methods due to some restrictions in the robustness of the methods. The criterion 2.1 "spatial resolution of the input data" is evaluated as partly fulfilled by ReCiPe 2016 and WSI, since both methods are based on an older version of the hydrological model WaterGap [50,51]. This criterion is fulfilled by the methods WAVE+ and AWARE. The criterion "relevant distribution pathways are considered" is evaluated as partly fulfilled by WAVE+, since it includes internal evaporation recycling (but not the external evaporation recycling). For other methods, this criterion is evaluated as not fulfilled. The criterion "relevant damage areas are considered" is evaluated as not fulfilled by ReCiPe 2016, since the method does not provide any impact assessment (instead, the liters of consumed water are counted). The WSI partly fulfills this criterion, since it conducts an impact assessment. Finally, the methods WAVE+ and AWARE fulfill this criterion completely, since, within the impact assessment, WAVE+ considers natural aridity and WAVE+ accounts for environmental flow requirements. Based on this evaluation, all methods achieve the same result in applicability, but WAVE+ rates best in environmental relevance (see Figure 7a).

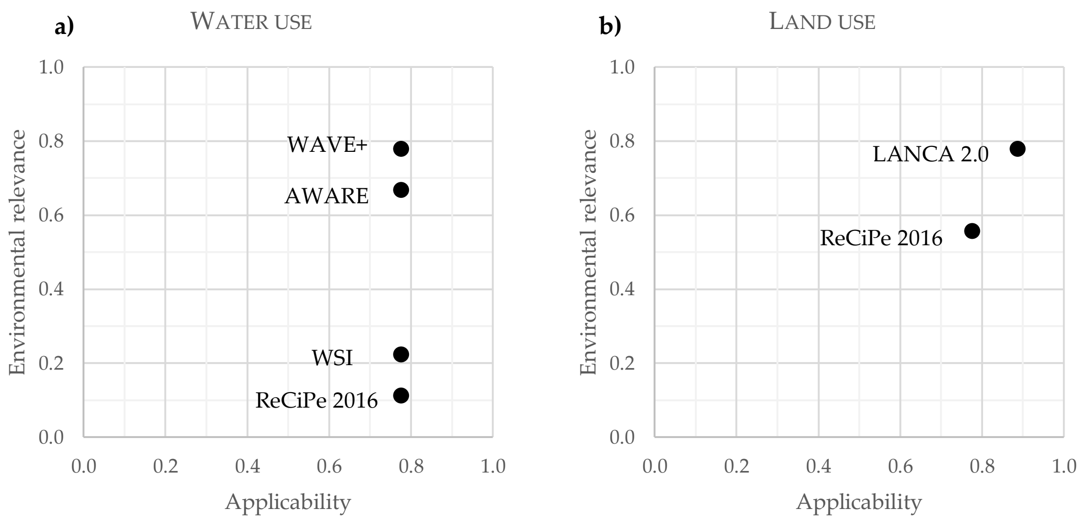

Figure 7. Results of the evaluation of the impact categories *water use* (**a**) and *land use* (**b**).

Land use

In the impact category *land use*, two methods are evaluated: ReCiPe 2016 and LANCA (PEF recommendation). The CML methodology does not include this impact category and is therefore not considered by the evaluation. Both methods fulfill the criteria 1.1–1.4 and partly fulfill the criterion 1.5. The criterion 1.6 "the method and results are understandable for the non-LCA community" is evaluated as fulfilled by the LANCA method, since it calculates soil quality indicators (erosion resistance, mechanical filtration, physiochemical filtration, groundwater regeneration and biotic production), which are understandable also for the practitioners outside the LCA community. The method adopted in ReCiPe 2016 partly fulfills this criterion since it provides the result as occupation and time-integrated land transformation (relation of the relative species loss compared to that occurring due to annual crop production), which might be difficult to comprehend outside the LCA community. Both methods fulfill the criterion 2.1 "relevant elementary flows are considered". The criterion 2.2 "relevant soil parameters are considered" is evaluated as fulfilled by LANCA (includes seven soil quality parameters) and partly fulfilled by ReCiPe 2016, which considers only one parameter (species richness). The criterion "relevant damage areas are considered" is evaluated as partly fulfilled by both LANCA (focus on the midpoint level, no biodiversity impacts) and ReCiPe 2016 (focus on the endpoint, not soil quality assessment). This evaluation leads to LANCA having a higher score in both applicability and environmental relevance (see Figure 7b).

The summary of the results is provided in Table 4, which includes an overview of the relevant impact categories and the LCIA methods recommended for their quantification based on the evaluation conducted in this work. For four impact categories (*human toxicity*, *ecotoxicity*, *acidification* and *land use*), two methods are recommended, whereas ReCiPe is recommended as the second choice.

Table 4. Summary of the results: relevant impact categories and recommended LCIA methods.

Relevance	Impact Category	Recommended LCIA Method
Very high	Climate change	IPCC (adopted in both CML and ReCiPe)
	Human toxicity	USEtox/ReCiPe
	Ecotoxicity	USEtox/ReCiPe
	Resource use, elements	CML
	Resource use, fossil	Primary Energy Demand
High	Acidification	CML/ReCiPe
Medium	POCP	ReCiPe
	Particulate matter formation	ReCiPe
	Eutrophication	CML
	Water use	WAVE+
	Land use	LANCA 2.0/ReCiPe

4. Discussion and Conclusions

The evaluation of the impact categories conducted within this work demonstrated that for both the automotive sector and stakeholders *climate change* has by far the highest relevance. An interesting fact is that for both the automotive sector and stakeholders, it is followed by *resource use*, *human toxicity* and *ecotoxicity*. While for the automotive sector this is caused by the high current and future contribution to these impact categories, for the stakeholders, existing legislation and the Green Deal contribute to high relevance, e.g., through the regulations on resource efficiency and circularity (effect on impact category *resource use*) and restrictions for the use and emissions of chemicals (relevance for *human toxicity* and *ecotoxicity*).

For the evaluation of LCIA methods, two criteria groups were used: applicability and environmental relevance. For applicability, most differences occur in the criterion "the method is globally valid". This can be explained by the fact that recent methods (e.g., ReCiPe 2016) were developed with the specific aim of global coverage, while older methods (e.g., CML, Seppälä et al. 2006) are usually based on European conditions and therefore provide the CFs that do not have global coverage. This advantage of global LCIA methods can lead in some cases to limitations in the criterion "number of considered substances". Since calculating emissions fate with global coverage is often challenging, in some impact categories, global models provide CFs for only few substances as it is also addressed in the work of Bach and Finkbeiner [6]. This is the case particularly with ReCiPe 2016 for the impact category *eutrophication*. Therefore it is important for practitioners to check whether relevant substances are included in the applied methodology and consider the trade-offs between global coverage and completeness of scope. In several impact categories, differences between the methods occur in the criterion "relevant damage areas are considered". For example, this is the case for *ecotoxicity*, *acidification* and *eutrophication*. The differences between the results (e.g., calculation of terrestrial vs. freshwater eutrophication) need to be considered by the practitioners when interpreting the results.

The conducted evaluation shows that none of the evaluated methodologies achieve the highest result in all impact categories, e.g., CML rates best for *resource use (elements)* and *eutrophication*, USEtox for *human* and *ecotoxicity*, ReCiPe 2016 for *POCP* and *particulate matter formation*. For *land use* and *water use*, further methods not included in CML or ReCiPe 2016 achieve the best results (see Table 4). Therefore, to apply the "best" methodology for the quantification of all impact categories, practitioners need to "mix" different methods. Although this practice is used, for example, by PEF, some practitioners prefer to apply a consistent methodology for all impact categories and mixing different methods for different impacts violates this principle. If one consistent methodological framework is preferred, ReCiPe 2016 can be applied, since it achieves the highest and second highest scores for most impact categories (an exception is water use).

Within this work, two criteria that evaluate the suitability of the methods for communication were evaluated: the criterion 1.5 "the method is robust for communication" and 1.6 "the method is understandable outside the LCA community". Based on the results, three levels of the communication for all recommended LCIA methods can be proposed: level one (public communication), level two (public communication with a description of methodological restrictions), and level three (internal communication only). While level one is achieved by the LCIA methods recommended for the impact categories *climate change* and *resource use, fossil*, for most other impact categories, level two communication is recommended, i.e., methodological restrictions with regard to considered substances, distribution pathways and damage areas need to be communicated alongside the results. This applies to the impact categories *resource use, elements*, *acidification*, *POCP*, *particulate matter formation*, *eutrophication*, *water use* and *land use*. Level three communication is recommended for the impact categories *human toxicity* and *ecotoxicity*. The reason for this is high uncertainty of the results (see Section 3.2.2). Overall, these recommendations are similar to the robustness evaluation used in PEF [1].

It should be considered that the evaluation of some criteria is partly subjective, which is the case for the criterion 1.5 "the method is robust for communication" and 1.6 "the method is understandable outside the LCA community". Still, the evaluation of these criteria is aligned with the evaluation provided by PEF (robustness). Besides, most methods achieve the same score for these two criteria, therefore, in most cases they do not impact the final result significantly.

It is also interesting to note that the results of this work do not align with the PEF recommendations for most impact categories. The reason for this is threefold. Firstly, the focus of the current evaluation is set on the needs of the automotive industry. Secondly, the recently developed methodology ReCiPe 2016 is considered, which is not the case by PEF and last, but not least, this work has a stronger focus on applicability while the PEF recommendations are more dominated by theoretical advantages of methods (e.g., Seppälä et al. for acidification and eutrophication).

Within this paper, the CML and ReCiPe 2016 methodologies and the methods recommended by PEF were evaluated. Further recently published methodologies, e.g., Impact World+ [57] and LC Impact [58], need to be considered in future studies to provide a more complete perspective for the practitioners.

While several criteria had a global perspective, others had a European focus (e.g., the coverage in legislation). As such, the method would need to be transferred into other regional contexts for users from other regions. However, this is possible based on the overall approach, it just needs an adaption of the evaluation of the criteria.

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