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LCA COMMUNICATION AND LCA FOR ISO LABELS

Establishing a harmonised framework for life cycle impact assessment: consensus for zero emission vehicles

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Abstract

Purpose This study focuses on developing a harmonized Life Cycle Impact Assessment (LCIA) methodology tailored for Zero-Emission Vehicles (ZEVs) within the European context. It also addresses the need for consistency, transparency, and scientific robustness across environmental impact assessments of ZEVs.

Methods A structured three-step consensus-building process comprising state-of-the-art review, recommendation formulation, and stakeholder voting was implemented. This included expert input from academia, industry, and policy, supported by data from key LCA studies databases and software's.

Results and discussion Through stakeholder voting, seven impact categories including climate change, particulate matter, acidification, eutrophication, photochemical ozone formation and cumulative energy demand (CED) are defined as mandatory together with hydrogen emission flow. Normalisation using planetary boundary-based factors are recommended, while weighting was excluded due to its subjective nature. Optional impact categories and areas requiring further development, such as dissipation and biodiversity, are also discussed and recommendations made.

Conclusions and recommendations The proposed framework establishes a robust, transparent, and science-driven LCIA framework for ZEVs. It enables consistency in environmental evaluations and informs policy and industry practices. Future revisions should incorporate emerging indicators and evolving data quality improvements.

Keywords LCIA · ZEVs · Impact categories · Normalisation · LCA

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1 Introduction

Life Cycle Impact Assessment (LCIA) is a crucial component of Life Cycle Assessment (LCA), for evaluating the environmental impacts of a product or process throughout its entire life cycle. LCIA classifies, characterizes and quantifies, the potential environmental impacts associated with various life cycle stages, from raw material extraction to end-of-life disposal. While LCIA has been widely adopted, inconsistencies in methodology and data can hinder accurate and reliable impact assessments (Sala et al. 2020a, b).

Zero Emission Vehicles (ZEVs) (this study also considers ICE-H2 other than BEVs in the definition, which is not zero-tailpipe emissions since it can emit some NOx and particles during the use stage) present a significant opportunity for reducing the environmental impacts of transportation (Rimpas et al. 2025) in Europe. The development of a European-wide harmonized and unified LCA approach for ZEVs should allow an adaptive (depending on the goal, the practitioner, and the level of knowledge), comprehensive, and data-driven assessment, including all life cycle stages along with mature and robust impact categories (not focusing only on Global Warming Potential (GWP). This approach should cover a wide range of Zero Emission technologies while allowing confidentiality, standardization, differentiation, and auditability. With this turn in the primal focus, the requirements for a harmonized and transparent framework to execute LCIA tailored to ZEVs has been brought up as a crucial factor (TranSensus LCA Deliverable 1.2, 2024). These necessities have been observed and discussion among LCA experts and stakeholders are concluded for gaining consensus in this study.

To address this challenge, the framework proposed in this study standardizes key elements of LCIA, including impact categories, impact category indicators, impact assessment methods, and normalisation factors, which enables comparison between LCA studies of ZEVs (along with a harmonized Goal and Scope definition, Life Cycle Inventory Analysis and Interpretation phase (TranSensus LCA Deliverable 2.3, 2025)). But the phases other than LCIA are outside the scope of this study. TranSensus LCA (https://lca4transport.eu/) aims to establish a harmonised, European-wide LCA approach for zero-emission road transport, integrating real-world data, methodologies, tools, and datasets into a unified framework. This framework conceptualises the aspects of four phases of LCA as in ISO 1404/44 standards.

By aligning with widely accepted standards, guidelines, scientific articles, and policy documents, the framework seeks to foster consistency and comparability in LCIA across studies. The analysis of the LCIA results was carried out within the framework of literature reviews and TranSensus D1.1(Review of Current Practices on Life Cycle Approaches along the Electromobility Value Chain) (TranSensus LCA Deliverable 1.1, 2023), which was conducted prior to this study, and the findings from TranSensus LCA D2.3 (TranSensus-LCA final harmonized approach) (TranSensus LCA Deliverable 2.3, 2025).

In the context of recommending a standardized LCA methodology aimed at enhancing harmonization and enabling comparability across various ZEVs, the identification of mature and robust set of impact categories is also a key proposal put forward by the stakeholders of the TranSensus LCA project.

This impact category prioritization approach is adopted from a pragmatic perspective to enable the selection of a limited and manageable set of environmental impact categories. Given that considering all possible impact categories in an LCA can be complex and resource-intensive for industry, prioritization serves as a practical tool to help practitioners concentrate on the most mature and robust environmental impacts. The impact categories considered for this prioritization are proposed to be classified into mandatory and optional sets of impact categories. A mandatory set in this study includes standardized impact categories which must be assessed across LCAs for comparability and regulatory alignment. Conversely, an optional set contains context-driven impact categories which provide deeper understanding into the application-based material and energy demands associated with ZEVs. From the points of view of circular economy and critical raw materials, an optional set of impact categories are increasingly relevant for understanding trade-offs in electric mobility.

In ISO 14044:2006, normalisation and weighting which convert diverse impact results into a single score or prioritized ranking, are considered optional steps in LCIA. Specifically, normalisation harmonises category-specific results by comparing them to a reference scenario, while subsequent weighting across multiple categories entails societal or policy-based preferences among impact categories (Pizzol et al. 2017). In the EU, recommended practices follow the Environmental Footprint (EF) methodology, which offers region-specific normalisation factors and weighting sets based on stakeholder consensus and scientific relevance (Crenna et al. 2019). However, this study focuses on deriving insight on the robustness and transparency in the use of these methods, as they can influence conclusions significantly.

Importantly, this process actively involved the Scientific and Industrial experts, who functioned as stakeholders in the study. Their participation ensured that the final LCIA framework would reflect a broad range of expert perspectives and industry needs, thereby enhancing its applicability and acceptance within the field.

Overall, the findings underscore the importance of methodology and data quality in accurately assessing environmental impacts. As a novel contribution, this study develops a robust framework for LCIA to address the existing gaps and lack of consensus among ZEV industry experts, scientific researchers, and policymakers. Conducting an LCA of ZEVs in the European regulatory context requires a thoughtful selection of both mandatory and optional sets of impact categories which is also applicable to regions outside of Europe. Coupled with rigorous normalisation and weighting aligned with EU guidelines, this ensures the assessment captures both the immediate and long-term environmental implications of transitioning to zero-tailpipe emissions in mobility.

2 Theoretical background

The emergence of sustainable alternative modes of transportation from the conventional fuel-based ones has demanded intense updates in LCA methodologies (Spreafico et al. 2020). From TranSensus D1.2 (Establishing a unified framework for life cycle impact assessment – Integrative review and methodological consensus) (TranSensus LCA Deliverable 1.2, 2024), where the gaps and needs found in LCA are reviewed, it became evident that there is a need for a unified LCA framework that integrates both stakeholder input and scientific best practices, along with a common structure for goal and scope definition, system boundaries, inventory modeling, and impact assessment, to be adopted across LCA studies of ZEVs. The extended research done in TranSensus D1.2 (TranSensus LCA Deliverable 1.2, 2024) marked the undertaking of a significant step towards harmonization through the identification of discrepancies in the LCA studies reviewed. It highlighted the divergence in impact category selection, modeling approaches, and indicator choices between practitioners, which ultimately leads to varied and sometimes contradictory conclusions. These findings pointed to a need for LCIA to be not only meaningful, but also actionable in the context of European ZEV policies, to ensure cross-comparability of results. The need for such a harmonized framework demands critical environmental assessment tools that extend beyond GWP. This underscores the importance of not only defining a mandatory set of impact categories for regulatory and policy harmonization but also maintaining an optional set to accommodate other environmental concerns, including newly emerging ones in the context of LCA (hydrogen emission flow, material criticality, circularity and dissipation aspects).

Another fundamental aspect is the adoption of normalisation and weighting in LCIA. TranSensus D1.2 (TranSensus LCA deliverable D1.2, 2024) stressed that the existing normalisation and weighting factors often risk hiding potential impact shifting to those impact categories that are considered – disputably - as of lesser relevance. In both normalisation and weighting, the purpose is linked to the goal and scope of the study and therefore depends on the number and types of alternatives and impacts included, and on the system boundaries and intended audience. For the purpose of communicating clearly (as these may not be easily understood by audiences beyond LCA experts), it is recommended to integrate uncertainty assessment, at least in a qualitative way, for normalisation and weighting results (e.g., uncertainties and biases introduced in the resulting impact scores) (Pizzol et al. 2017). Hence it is required to consider normalisation and weighting factors as harmonized and commonly agreed through stakeholder perspectives.

The reviewed literature underscores the need for a harmonized, scientifically sound LCIA methodology tailored to ZEVs especially, due to the evolving aspects of sustainable transportation. As ZEVs become central to sustainable transportation and climate mitigation pathways, the integrated consensus-based stakeholder involvement supports the development of more transparent, consistent and robust environmental evaluations and to inform coherent policy decisions in the transition towards sustainable mobility.

3 Materials and methods

3.1 Methodological approach towards decision making

The standardised framework for conducting LCIA was designed with a well-defined set of steps and methodological approaches. In the present scenario for LCA, several impact categories exist within its wide-area application. However, it is necessary to select appropriate impact categories for the context of ZEVs that ensure maturity, robustness, effort to collect data and policy alignment in this transition phase of the technology. The impact categories were selected using a set of scoring criteria, insights from various LCA studies, and expert opinion, as described in the following sections. In addition, a unified normalization and weighting method applicable to ZEVs was defined. A consensus-based approach was then applied to recommend a harmonized LCIA framework, encompassing both the classification of impact categories and the associated normalization and weighting methods. The overall methodology followed for this purpose of decision making is illustrated in Fig. 1.

Step 1: A comprehensive summary of the state-of-the-art was compiled, based on the TranSensus deliverables D1.1 and D1.2 (TranSensus LCA Deliverable 1.1, 2023; TranSensus LCA Deliverable 1.2, 2024), which analyzed

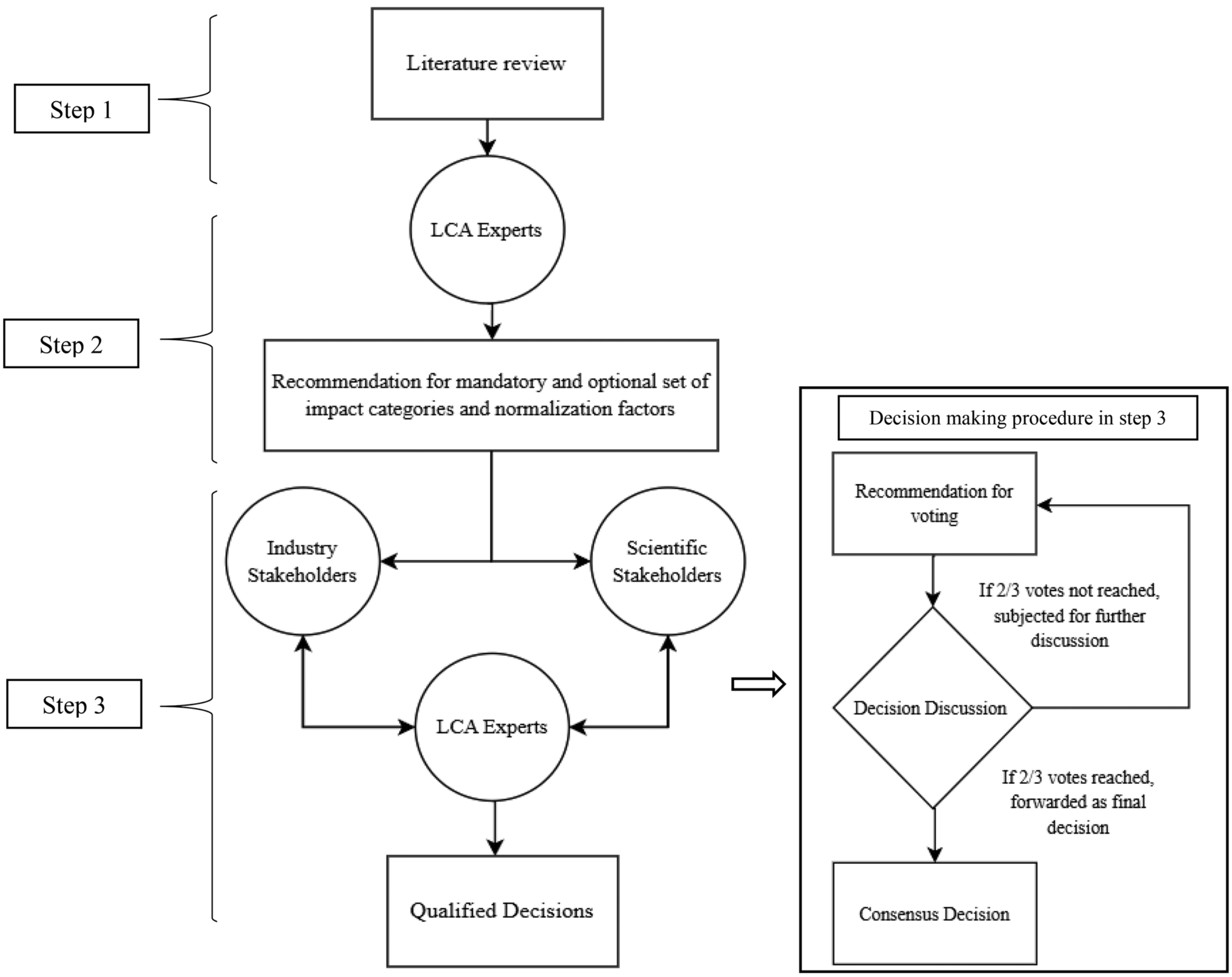

Fig. 1 Methodology adopted for decision making

current practices, needs and gaps in LCIA methodology. The required methodological approaches identified are then selected and evaluated in order to assess their applicability, strengths, and limitations. This evaluation considered scientific rigor, feasibility, and alignment with the study's objectives.

Step 2: Internal knowledge was shared within LCA experts, focusing on current practices in academic, industrial and policy settings, problem clarifications, potential solutions, and diverse opinions. A scoring system was established for the impact categories which are evaluated using science-based and other criteria as explained in Sect. 3.2.1 and Table 2. After the scoring procedure, if a lack of common interests was identified, the topic was assigned for discussion and forwarded for a formal vote among the stakeholders (refer to https://lca4transport.eu/?page_id=623 to see all the stakeholders involved in this study).

Step 3: The most relevant methodological approaches are selected, accompanied by a pros and cons analysis especially for selection of suitable normalisation factors, topic discussions and ultimately formulating an agreed-upon recommendation through voting and consensus building which ensured that the final recommendation reflected collective agreement. The voting results are analyzed, and if necessary, further efforts are made to build consensus.

The three structured steps, voting rules and majority process are designed to ensure a balanced and inclusive decision-making mechanism involving both industrial and scientific experts. A total of 20 partners from industries (automobile manufacturers) and scientific community (academia, public institutions, research institutions) and 2 associated partners (industry), actively engaged in the development of the LCIA framework, formed a voting panel. Each participating entity is allocated one vote to contribute to the consensus-building process on the topics under discussion. To facilitate this process, an internal voting system is prepared to broaden agreement among participants. This is followed by a one-day online meeting to present the voting procedure and to clarify any uncertainties. Subsequently, an off-line voting process was conducted using the EU survey platform, enabling all partners involved in the study to cast their votes efficiently and transparently.

The voting exercise served as a crucial intermediate step in the consensus-building process, as illustrated in step 3 of Fig. 1. This step was designed to generate a well-founded proposal for discussion among all partners and to identify key issues requiring more in-depth examination. To transform the voting outcomes into a consensual, harmonized LCIA framework, additional task meetings are conducted. These meetings focused on a detailed, question-by-question analysis of the voting results, with the aim of expanding consensus-building efforts.

Qualified majority in the voting process needs to be reached $\geq$2/3 or 66.67% threshold (as agreed by stakeholders within the study) to qualify as an answer of the topics under discussion and to be proposed for recommendation. Recommendations reaching this threshold are considered mature enough to be submitted as consensus to a larger acceptance. If a particular topic reaching step 3 did not meet the threshold in the voting but showed a majority agreement, then it was considered as less mature, but still eligible to seek parallel consensus among the study's partners and among the members of the final decision board. These topics underwent further analysis and are presented for voting again as presented in Fig. 1, till a concrete decision on whether to include them as final consensus or label them as non-agreed topics. Non-agreed topics related to LCIA and normalisation from the voting panel are then left for further research and updates for the future.

3.2 Process for recommending LCIA harmonized practices

This section describes further the process followed by LCA expert in step 1 and 2 of Fig. 1 to recommend impact categories, indicators, normalization and weighting factors. Figure 2 presents each main step adopted to first identify a list of impact categories deemed relevant for consideration (hereinafter referred to as the "Restrictive" set), and subsequently to categorise them into "Mandatory" and "Optional" sub-sets; the same figure also illustrates the process used for the selection of suitable normalisation factors for a harmonized LCIA framework of ZEVs.

The definitions of Restrictive set, Mandatory set and Optional set of impact categories according to this study are as follows:

- Restrictive set of impact categories: the widely used present set of impact categories according to policies at country level and European commission, scientific papers and company reports which are also present in EF impact categories (see Sect. 3.2.1). In addition, this set incorporates impact categories identified based on the opinions of LCA experts involved in this study (see Sect. 3.2.1).
- Mandatory set of impact categories: impact categories from the restrictive set that must be included in LCAs of ZEVs.
- Optional set of impact categories: impact categories (including emerging ones and those not considered in restrictive set but included in EF) for future consideration and refinement, as the associated data, methods and importance evolve.

For gathering opinions on whether to establish a final mandatory set, the question "Should a mandatory set of the most relevant impact categories, indicators, and LCIA methods (based on the restrictive set) be recommended?" was posed to the voting panel. Participants were given two options to vote on, and the resulting voting pattern is presented in Table 3. The options provided for voting are: "Option 1: Yes, this study should recommend a mandatory set of the most relevant impacts categories, indicators and LCIA methods, based on the restrictive set. Option 2: No, this study should NOT recommend a mandatory set of the most relevant impacts categories, indicators and LCIA methods."

From the outcome of the voting as shown in Tables 3, 68.18% of those who voted agreed on option 1, in which a recommendation should be provided on a mandatory set of the most relevant impact categories, indicators, and LCIA methodologies, based on the restrictive set (see the definition of restrictive set above) of impact categories. Even though most participants chose option 1, slight alignment to option 2 remarked that relevant impact categories vary on the purpose of the study, and LCA is about evaluating solutions for a wide range of environmental problems.

3.2.1 Restrictive set identification and scoring

The LCA experts involved in this study identified the need for a mandatory set of impact categories through a consensus approach by voting (see voting results in Table 2), which can be recommended to LCA practitioners and which would aid in achieving a better understanding and comparison of the environmental impacts and LCAs of ZEVs. For this purpose, the LCA experts involved in this study analyzed the environmental impacts related to LCA reported in various reports, frameworks, and directives at the country, European, and international levels (refer to Table S1 in

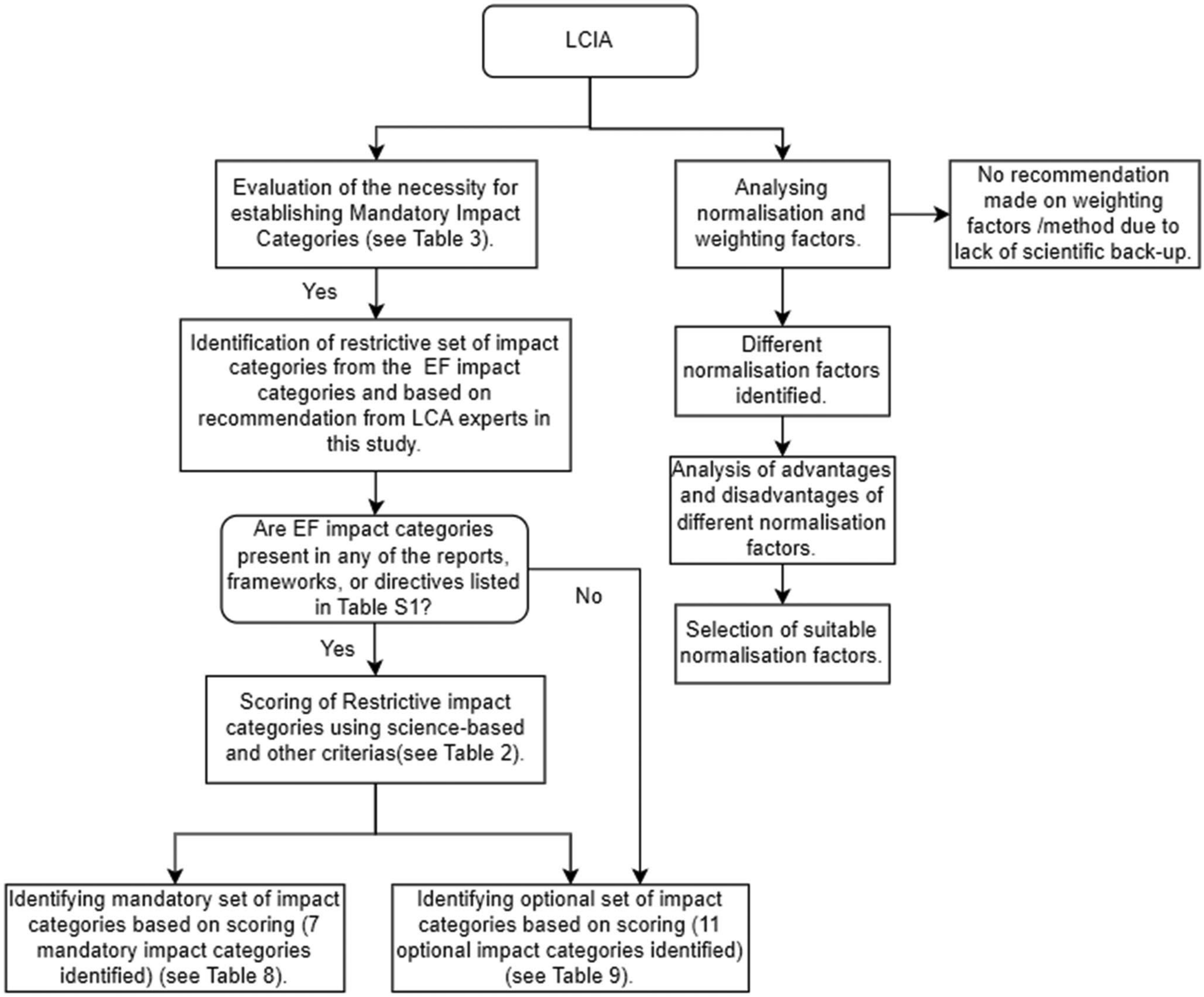

Fig. 2 Analysis flowchart for evaluation of mandatory and optional set of impact categories and normalisation factors for LCIA

the supplementary material in Sect. 1). They then mapped (see Table 1 below) the identified impacts to the EF impact categories (Zampori and Pant 2019) and conducted internal discussions to reach common ground.

The impact categories from the EF (Zampori and Pant 2019) that are reported in any of the sources listed in Table S1 are selected for inclusion in the restrictive set of impact categories. Additionally, categories recommended by the LCA experts involved in this study such as CED, dissipation and criticality are also included in the restrictive set. The recommendation of a restrictive set of impact categories includes, primarily due to the need for comprehensiveness, considerations of circularity, biodiversity, CED, dissipation and criticality.

Each identified restrictive impact category in Table 2 is evaluated using a scoring system based on five criteria (for more detail about criteria see Sect. 2 in supplementary material), leading to the proposal of a mandatory list of impact categories; those not included in the mandatory list are classified as either optional (with a recommendation for impact category indicator and characterisation model). Criteria for scoring are divided into two set as follows:

- Science based criteria: (1) robustness of the impact, and (2) relation to planetary boundaries.
- Other criteria: (3) importance for ZEVs, (4) data availability, and (5) ease of use and interpretation.

The scoring system used for the evaluation was designed with a range of “A” to “E”, where “A” represents the highest possible score, indicating the most favourable assessment or the highest level of compliance with the criteria evaluated. Conversely, “E” denotes the lowest score, reflecting significant deficiencies or areas in need of improvement.

Table 1 Mapping reported impact categories to unified categories

Impact Category	Reported impacts
Depletion of abiotic resources	Resource depletion/consumption of abiotic resources/ Resource use/ large amounts of resources needed/ depletion of CRMs and REEs/mining of raw materials (mainly for battery production)/ mining of battery raw materials such as cobalt nickel and lithium/ resource depletion (metals, minerals, fossils)/ use of metals and minerals for battery production/ extraction of raw materials/ mining of minerals/ material extraction/ use of critical materials/ extraction of minerals and metals / mining of metals/use of raw materials / key metals used in lithium-ion technology (such as cobalt, lithium and nickel)/ require rare earth metals.
Land use	Biodiversity loss /biodiversity management /Biodiversity/loss of biodiversity
Photochemical ozone formation	NOx, Nitrogen oxide/photochemical ozone formation/ Photochemical pollution
Renewable and non-renewable energy resources/CED*	Energy needed/energy use/energy consumption/ energy intensive/electricity generation/ primary energy demand/higher energy demand for pyro metallurgical recycling
Climate change	GHG emission/CO2/ carbon intensive
Human Toxicity/Ecotoxicity	Human toxicity/toxic pollutants/ toxicity (marine, freshwater, terrestrial)/human and ecological toxicity/ uses of toxic materials in manufacturing/ release of toxic gases/human health (lead as toxicant)/ Toxic emission/toxic substances
Water Use	Water use/water needed/ water consumption/ large volume of water required for operation/stress on water resource/water use (for recycling)/ water management (water use)
Acidification	NOx, NOx emission/ acidification of water bodies and wetlands/ sulfur oxides/sulphur/nitrogen oxide/ acidification potential/SOx
Freshwater /Marine Eutrophication	Eutrophication potential
Particulate matter	Emission of PM/particulate matter (PM2.5)/ tyre wear and brake wear emission/fine dust and microplastics (from tyre and brake abrasion)/ particulate matter, for example, due to wear of tyres, brakes and roads/air quality (PM)/NOx/NOx emission
Ozone depletion	Stratospheric ozone depletion

*CED is analysed even though it is not mentioned in EF set as it is found important from European Commission (EC) point of view

This hierarchical system of letter grades is intuitive, as it is based on rating systems known from educational contexts and allows for quick and clear comparisons and decision-making processes. For more detailed statistical evaluation, a refined rating scale was used, converting standard letter grades into a more granular format. This scale introduces '+' and '−' modifiers to the basic letter grades, allowing for more precise representation of variations in performance or compliance levels. Scoring provided for each impact category in restrictive set is provided in Table 2.

For instance, regarding the scoring on the criteria relation to Planetary Boundaries (PBs), the Joint Research Centre (JRC) has worked for several years to establish a link between LCA and PBs through different methods, mapping most of the EF impact categories to the PBs (IPCC 2013), (van Zelm et al. 2008). Those studies show on two scales (Global and European) the results for each impact category, some of them exceed the limit no matter the scale and the method and find themselves in the high-risk zone. This workgroup considered that such impact categories are of the utmost importance to integrate into the TranSensus LCA methodology. Thus, we provided a rating for the impact categories considering how many times they are found in the safe operating space ("E"), the zone of uncertainty ("D", "C") or the high-risk zone ("C", "B", "A"). Similarly, scoring is provided also based on other criteria, for more details see Supplementary Material.

The stakeholders associated in this study decided to propose impact categories which reached a total score of A+, A, A- or B+ (as in Table 2) to be subjected for discussion and to be classified as mandatory impact categories. Below this threshold limit, it was considered that impact categories are not mature enough, due to insufficient methodology or data, and therefore such categories should be considered as optional, but that does not mean they should be ignored. Ensuing from the conclusion of scoring, discussions and voting among the panel, final mandatory (see Table 8) and optional sets (see Table 9) are proposed.

3.3 Normalisation

Normalisation and Weighting are additional steps in LCIA that have been the object of many debates and discussions. As introduced, normalisation involves expressing the impact potentials in relation to a reference situation, in order to place the results of an LCA on a familiar "standard" scale. It allows for the comparison of results with a reference situation and informs the interpretation phase of LCA by comparing the results' order of magnitude to a known reference quantity. On the other hand, weighting assigns a relative importance (according to subjective criteria) to different impact categories, thereby enabling to the calculation of a single score for the environmental impact of a product or scenario. This is intended to help the comparison of different products or scenarios and supports decision-making.

Table 2 Scoring of restrictive impact categories

	Science based criteria		Other criteria			
Impact category	**Robustness**	**Relation to PBs**	**Importance for ZEVs**	**Easy to use**	**Data availability**	**Score**
Climate change	A+	A+	A+	A+	A+	A+
Photochemical ozone formation	B-	D+	A-	A	A+	B+
Acidification	B	D	A	A	A	B+
Freshwater eutrophication	B	B-	B-	A	A+	B+
Particulate matter	A	A+	A	A+	A	A
Depletion of abiotic resources (Resource use minerals and metals)	C-	B	A+	A+	A-	B+
CED	A-	C+	A	A-	A	A-
Ozone depletion	A-	D	C	A	A	B
Human toxicity (cancer and non-cancer)	D+	C+	B+	B+	B+	B
Marine eutrophication	B	C-	C+	A	A+	B
Ecotoxicity (freshwater)	C-	D	B+	B	B+	B-
Dissipation	B	D	A	A	A	B
Land use	D+	A+	C+	B	B	B
Water use	C-	D	B+	A-	A	B-
Criticality	D-	E+	B+	C	C	C-

Green colour denotes Mandatory impact categories; Brown colour denotes Optional impact categories.

Although normalisation and weighting are potentially useful in LCA for communication of impact results and for comparing different products or scenarios, their subjective nature and potential to influence study conclusions make them controversial aspects of LCA (for more information, refer Sect. 8 of the Supplementary Material). Multiple guidelines, standards and scientific literature address normalisation and weighting, but in very different ways. Following this understanding, the question "What approach for normalisation and weighting should be recommended by this study", is put into vote among the voting panel with the following options as answers: "Option 1: normalisation and weighting are optional and reported separately – factors will not be recommended"; "Option 2: normalisation and weighting are optional and reported separately – factors will be recommended". The result of this voting question is reported in Table 6.

4 Results

This section provides the voting results and also the final proposed list of mandatory and optional impact categories together with the selected impact assessment methods/characterisation models and indicators.

4.1 Voting Results

The voting process for Step 3, as illustrated in Fig. 1, was conducted in multiple phases, including a first and second voting session, as presented in the tables in the following subsections. Results from first voting includes consensus on topics like the need for restrictive and mandatory sets of impact categories for ZEV, impact categories to be added in the restrictive set (Table 3), and finally the voting on recommending normalisation and weighting (Table 6). The results from second voting find consensus on mandatory and optional sets of impact categories (Table 4), along with the normalization factors (Table 7). The third voting session established consensus on additional impact categories including hydrogen emission flows (Table 5) for inclusion in the final mandatory and optional sets.

4.1.1 Voting Outcome for Recommendations on Impact Categories

The questions in Table 3 were designed to promote clarity and maximize stakeholder participation, using standardized response options ("agree," "disagree," and "no preference") across all items. To address potential response bias related

Table 3 First Voting Outcome: Recommended Restrictive and Mandatory Set of Impact Categories, Indicators, and LCIA Methods

Topic	Questions/ Statements	Votes (%)			Result
		Agree	Disagree	No preference	
Mandatory set on relevant impact categories, category indicators and LCIA methods	Option 1: This study should recommend a mandatory set of impact categories, indicators and LCIA methods, based on the restrictive set with guidance on how to analyze, report and communicate these two sets (Mandatory and Optional).	68.18	18.18	13.64	Qualified majority reached for option 1
	Option 2: This study should not recommend a mandatory set of impact categories, indicators and LCIA methods. The restrictive set defined by this study (See Sect. 3.2.1) only be recommended.	18.18	68.18	13.64	
EF	This study proposes to include the impact categories, indicators and characterization methods of EF (EF3.0 & EF3.1) in the restrictive set of relevant Impact categories, category indicators, LCIA methods	81.82	9.09	9.09	Qualified majority reached
Circularity indicators	This study proposes not to include circularity indicators and aspects in the restrictive set of relevant Impact categories, category indicators, LCIA methods	90.91	4.54	4.54	Qualified majority reached
CED	Recommendation under this study to include CED in the restrictive set of impact categories, indicators, LCIA method: CED (total), based on aggregation of different energy sources by equal weighting, as driver level indicator (characterization factors as defined by Frischknecht (2015) as it is most widely used in ecoinvent and other databases).	77.27	13.64	9.09	Qualified majority reached
	Recommendation under this study to include CED in the restrictive set of impact categories, indicators, LCIA method: CED (non-renewable), based on aggregation of different non-renewable energy sources by equal weighting, as an alternative indicator for the impact category 'abiotic resources fossil fuels', as midpoint impact level indicator (characterization factors as defined by Frischknecht (2015) as it is most widely used in ecoinvent and other databases).	72.73	18.18	9.09	Qualified majority reached
Criticality	This study recommends including criticality in the restrictive set of impact categories, category indicators, LCIA methods. The GeoPolRisk method is recommended for its robustness, acceptability, credibility, ease of use and relevance (identified through the evaluation of relevant methodologies in the ORIENTING project (https://orienting.eu/)).	72.73	13.64	13.64	Qualified majority reached
Dissipation	Recommendation under this study to explore a shift from the concept of depletion to the concept of dissipation; it favors the recommendation of a new impact assessment method if, through tests to be performed, this is found to be relevant building on application to case studies. Environmental Dissipation Potential (EDP) and Average Dissipation Rate (ADR) to be tested; Furthermore, this study recommends that the consideration of dissipative flows of mineral resources in Life Cycle Inventory (LCI), following the JRC-LCI methodology (see supplementary material for more details), be introduced as an optional approach	81.82	4.54	13.64	Qualified majority reached
Biodiversity Indicator	This study proposes NOT to include biodiversity impacts in the restrictive set of impact categories, category indicators, LCIA methods because of the lack of maturity and robustness of the existing two main indicators (Global Biodiversity Score (GBS) and (Product Biodiversity Footprint) PBF)	86.36	4.54	9.09	Qualified majority reached

Table 4 Second Voting Outcome: Mandatory Set of Impact Categories

Topic	Questions	Votes (%)			Result
		Agree	Disagree	No preference	
Climate Change	This study recommends including the impact "Climate Change" in the mandatory list of impact categories	100	0	0	Qualified majority reached
Depletion of abiotic resources	This study recommends excluding depletion of abiotic resources from the mandatory list of impact categories	63.2	36.8	0	Qualified majority not reached
Land use	This study recommends excluding Land use in the mandatory list of impact categories	88.2	11.8	0	Qualified majority reached
Photochemical ozone formation	This study recommends including photochemical ozone formation in the mandatory list of impact categories	100	0	0	Qualified majority reached
Human toxicity & Ecotoxicity	This study recommends excluding toxicity from the mandatory list of impact categories	93.3	6.7	0	Qualified majority reached
Water scarcity	This study recommends excluding Water scarcity from the mandatory list of impact categories	87.5	12.5	0	Qualified majority reached
Acidification	This study recommends including acidification in the mandatory list of impact categories	94.7	5.3	0	Qualified majority reached
Freshwater & Marine eutrophication	This study recommends including freshwater eutrophication and exclude marine eutrophication in the mandatory list of impact categories	83.3	16.7	0	Qualified majority reached
Particulate matter	This study recommends including particulate matter in the mandatory list of impact categories	94.4	5.6	0	Qualified majority reached
Ozone depletion	This study recommends excluding ozone depletion from the mandatory list of impact categories	78.9	21.1	0	Qualified majority reached
Prospective and Fleet Level LCIA	This study found Goal and Scope and Inventory phases has differences in Prospective and Fleet Level LCA compared to Product LCA but not on Impact Assessment phase. All characteristics (Impact Categories, LCIA methods, indicators) applicable for conventional product level LCIA is also applicable for Prospective and Fleet level LCIA	100	0	0	Qualified majority reached

Table 5 Third Voting Outcome: Impact Categories Lacking Consensus

Topic	Questions	Votes (%)			Result
		Agree	Disagree	No preference	
Mandatory and optional impact categories	Study proposes CED to be part of the mandatory list of impact categories including the split of renewable and non-renewable CED. Also, the study proposes using CED with the method based on the energy harvested approach	83	17	0	Qualified majority reached
	Study proposes the use of the last version of EF method (at the moment EF3.1) and associated indicators for all mandatory impact categories	100	0	0	Qualified majority reached
	Study proposes including depletion of abiotic resources in the mandatory list and dissipation in the optional list of impact categories	89	11	0	Qualified majority reached
Cumulative H2 Emissions	This study recommends to include a mandatory hydrogen (H2) emission flow indicator, and to include a sensitivity including H2 emission impacts as a greenhouse gas, until a formalised GWP is available according to IPCC/within the EF LCIA method	88	12	0	Qualified majority reached

to differences in question formulation (i.e., inclusion vs. exclusion), responses to the diverging questions were subsequently verified through targeted follow-up discussions with stakeholders.

While circularity was identified as an important topic during the study, a consensus on a relevant impact assessment methodology for evaluating circularity within the LCA framework could not be established. In contrast, criticality could be operationalized using available and agreed-upon LCA indicators, which is why it was included in the assessment. This distinction reflects methodological feasibility and stakeholder valuation and aligns with the current capabilities of life cycle assessment for vehicle systems within the European context.

Certain impact categories which did not find any consensus from the first set of voting (as for Depletion of abiotic resources) were considered for discussion again among LCA experts, in order to provide meaningful recommendations

Table 6 First voting outcome: adoption of normalization and weighting

Topic	Options	Votes (%)			Result
		Agree	Disagree	No preference	
Which approach for normalisation and weighting should be recommended?	Option 1: normalisation and weighting are optional and reported separately – factors will not be recommended	50	40.91	9.09	Qualified majority not reached
	Option 2: normalisation and weighting are optional and reported separately – factors will be recommended (based on further analysis)	40.91	50	9.09	Qualified majority not reached

Table 7 Second Voting Outcome: Normalization Factors

Topic	Questions	Votes (%)			Result
		Agree	Disagree	No preference	
Normalisation Factor	Use Global PB based normalisation factors	94.4	5.6	0	Qualified majority reached
Impact result and normalisation result	This study recommends to mandatorily calculate the midpoint impact assessment results and then the normalized results as optional	100	0	0	Qualified majority reached

on them for the purpose of building a concrete LCIA framework to be followed. For this, the idea of inclusion of CED in the mandatory list (cf. Section 2 of Supplementary Material) of impact categories was considered. The concern was expressed that there could be a bias while using CED since, under some circumstances, it could under-estimate the impact on natural ecosystems due to human-induced degradation of high-quality forms of renewable energy resources (e.g., visible sunlight) into lower-quality heat. Similarly, the inclusion of depletion of abiotic resources in the mandatory list (cf. Section 3 of Supplementary Material) and dissipation in the optional list (cf. Section 5 of Supplementary Material), as well as the use of EF 3.1 and its associated indicators, was reconsidered for discussion among the panel. The corresponding voting pattern is provided in Table 5.

4.1.2 Voting Outcome for Recommendations on Normalisation and Weighting

A qualified majority was not reached after the voting regarding the recommendation of normalisation and weighting. The partners who voted for option 1 for the voting question in Table 6 argued that, since normalisation and weighing are subjective, they should not be promoted, while partners who voted for option 2 argued that factors for both normalisation and weighting should be given if the study is required to recommend a particular method. Utilization of the normalisation and weighting factors enable the creation of a scale of relative importance, albeit at the cost of introducing significant subjectivity in the assessment. Due to the significant differences in opinions, participants after further discussions reached an agreement to recommend normalisation factors but to not recommend weighting factors.

The European consumption-based input/output set of normalisation factors was adapted for Economic input/output LCA and not for process-based LCAs (De Laurentiis et al. 2023). The other European sets of normalisation factors are not deemed fit for systems with international supply chains. ZEVs come from international supply chains, so only global sets of normalisation factors are relevant.

The advantages of using global PB-based normalisation factors (Sala et al. 2020a, b) are primarily providing an absolute basis for normalisation (instead of a relative one), which makes the normalized results dependent on absolute thresholds ("boundaries"), instead of on total previous impact, which is always a moving target. This also avoids potentially controversial interpretation if or when an impact contributes to a category already affected by significant overall impact globally. Adaptability to international supply chains, no inverse proportionality, increased transparency, and reduced susceptibility to data coverage issues are also some of its advantages. But it has also several disadvantages such as non-applicability to all LCIA Impact categories, potential issues with upscaling local environmental pressures to the global level (some impact categories are context-specific and more relevant on a local scale) (cf. Section 8 of Supplementary Material). By taking into consideration both the advantages and disadvantages (cf. Table S10 of Supplementary Material for more information), a consensus on the adoption of global PBs was reached by the voting panel, as reported in Table 7.

4.2 Final agreed-upon recommendations for LCIA

4.2.1 Mandatory set of Impact Categories

The final results of voting sessions led to a list of 7 impact categories to be considered as mandatory as shown in Table 8. Short Description of all mandatory impact categories is provided in Sect. 10 of supplementary material.

Table 8 Mandatory environmental impact category list

Mandatory Impact Category	Impact Category Indicator	Unit	Characterization model
Climate change, total (see note 1 below)	Radiative forcing as global warming potential (GWP100)	kg CO_2eq	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Photochemical ozone formation, human health	Tropospheric ozone concentration increases	kg NMVOCeq	LOTOS-EUROS model (Van Zelm et al. 2008) as implemented in ReCiPe 2008
Acidification	Accumulated Exceedance (AE)	mol H^+eq	Accumulated Exceedance (Seppälä et al. 2006; Posch et al. 2008)
Particulate matter	Impact on human health	disease incidence	PM method recommended by UNEP
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al. 2009) as implemented in ReCiPe
Cumulative Energy Demand (see note 2 and 3 below)	Renewable and non-renewable cumulative energy demand (CED)	MJ	Hischier et al. 2010 Frischknecht et al. 2015
Resource use minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002

Note 1: The "Climate change, total" is comprised of three constituent sub-indicators: Climate Change (fossil), Climate Change (biogenic), and Climate Change (land use and land use change). Should any of these sub-categories exceed a 5% contribution to the total climate change score, it is imperative to report them separately

Note 2: CED should be considered as a total as well as separated into renewable and non-renewable shares

Note 3: This study recommends using CED indicator with care and considering the uncertainties that come with. The assumptions taken while using CED should be clearly stated as it can influence the results (refer to supplementary material for more details)

Hydrogen (H2) emission flows shall also be included as mandatory indicator. Sensitivity analysis including hydrogen emission greenhouse gas impacts for LCAs of hydrogen fuelled ZEVs shall be performed, until a formalised GWP is available according to IPCC/within the EF method. That is why this is not included in the restrictive set of impact categories in Table 3. By default, hydrogen emission impact calculation shall follow two principles below:

i. If supplier-specific data on fugitive hydrogen emissions within the supply chain is unavailable, apply default estimated H_2 emission rates for hydrogen produced either from natural gas or via electrolysis (Cooper et al. 2022).
ii. For the sensitivity analysis, use a GWP_{100} value of 11.657 to characterize the impacts of hydrogen emissions.

Comprehensive details about H2 emission flow can be found in Supplementary Material Section 9. Furthermore, Cooper et al. (2022) have recently reviewed the significance of emissions across various hydrogen production and supply chains. Estimated hydrogen supply chain emission rates from their study are presented and summarized in Table S11 of the supplementary material. In the future, once a formalized GWP becomes available through the IPCC, within the EF method, or via the UNECE IWG, hydrogen emissions and their associated impacts will, by default, be accounted for under the Climate Change impact category. At that point, it may no longer be necessary to report hydrogen emissions as a separate mandatory indicator or to perform the supplementary sensitivity analysis.

4.2.2 Optional set of Impact Categories

The results of voting sessions led to a list of 11 impact categories to be optional as provided in Table 9. These concerned optional Impact categories may be a priority for R&D activities to include it as mandatory within a future revised methodology for ZEV. Short Description of all optional impact categories is provided in Section 11 of supplementary material.

4.2.3 Normalisation

Normalisation is proposed to be optionally used in LCAs and when reporting LCAs, midpoint impact data should always be reported before normalized values. Global PB based normalisation factors should be used whenever normalisation is performed. Normalisation based on PBs ensures that impacts are evaluated against absolute environmental thresholds rather than relative consumption patterns, allowing for more precautionary and globally applicable decision-making. This recommendation is significant for ZEVs, which are embedded in globalized supply chains where environmental hurdles often shift across regions. Global PBs based normalisation factors recommended here are based on the scientific article Sala (2020). Also note that the Global PBs based normalisation factors are not mature enough for use, hence practitioners must follow the updates regarding these normalisation factors.

The selected mandatory impact categories also correspond to the principal contributors to the single score when applying the EF weighting set for ZEVs. Consequently, impact categories with weighting factors % exceeding 4% namely climate change, particulate matter, resource use (minerals and metals),

Table 9 Optional impact category list

Optional Impact Category	Impact Category Indicator	Unit	Characterization model
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	Steady-state ODPs as in (WMO 2014 + integrations)
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model 2.1
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model 2.1
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U^{235} eq	Human health effect model as developed (Dreicer et al. 1995; Frischknecht et al. 2000)
Eutrophication, terrestrial	Accumulated Excedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006; Posch et al. 2008)
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al. 2009) as implemented in ReCiPe
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model 2.1
Land use	- Soil quality index24 - Biotic production - Erosion resistance - Mechanical filtration - Groundwater replenishment	-Dimensionless (pt) - kg biotic production - kg soil - m3 water - m3 groundwater	Soil quality index based on LANCA (Beck et al. 2010; Bos et al. 2016b)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq	Available WAter REmaining (AWARE) as recommended (UNEP 2016)
Criticality	GeoPolRisk	kg Cu eq	(Santillán-Saldivar et al. 2022; Koyamparambath et al. 2024)
Dissipation (See Note 4 below)	Average Dissipation Rate (ADR) Environmental Dissipation Potential (EDP)	kg Fe eq kg Cu eq	Charpentier Poncelet et al. 2019, 2021, 2022 Van Oers et al. 2020

Note 4: As part of the methodology, both studied impact assessment methods are proposed as options for application; answering to two potential scenarios of technical and economic development. For more information see LCIA Annex

acidification, and photochemical ozone formation are included in the mandatory impact category set.

5 Discussion

The outcomes of this study mark a significant step toward improving the methodological consistency and scientific credibility of LCIA for ZEVs in Europe. By developing a harmonized LCIA framework through a structured, consensus-based process, the study not only addressed current inconsistencies in environmental impact assessments but also responded to an urgent need for transparency and robustness across industry, policy, and academia. The incorporation of expert input and stakeholder validation enhances the framework's legitimacy and applicability in real-world decision-making contexts.

A key achievement of the study is the identification and agreement on seven mandatory impact categories: climate change, particulate matter, acidification, eutrophication, photochemical ozone formation, and cumulative energy demand offering a clearer, more standardized basis for evaluating ZEVs. The recommendation to use normalization based on PBs further strengthens the scientific grounding of the methodology, aligning it with global sustainability thresholds. Equally important is the deliberate exclusion of weighting, which reflects a thoughtful balance between methodological rigor and the avoidance of subjectivity.

The decision-making process focused on including the interests of all stakeholders involved in this study. The final results show a careful balance between scientific accuracy and practical, field-based methods. This approach has encouraged industries to align their practices with academic standards. However, the strong role of academic views also reveals limits in terms of how easily research can be applied to real industrial situations. In addition, academic researchers working on similar topics often hold different opinions, making it hard to reach agreement on issues such as scoring methods, CED, dissipation, and ADP (Mankaa et al.,. 2023). This situation shows the need for a more developed decision-making system that values scientific validity over majority opinion.

While the study delivers a foundational framework, certain limitations remain. For example, some impact areas such as circularity, criticality, energy demand, resource dissipation, hydrogen emission flow, and biodiversity are identified as needing further methodological development. Additionally, although stakeholder consensus is achieved on several core components, the framework's long-term utility will depend on its adaptability to emerging indicators, evolving data sources, and shifts in European policy priorities. Future work should therefore focus on iterative refinement, continuous stakeholder engagement, and integration of advanced data analytics to keep the framework both relevant and scientifically sound.

6 Conclusion

This study marks a pivotal step toward standardizing LCIA methodologies for ZEVs in the European context. By considering a wide range of impact categories through a transparent, participatory process involving stakeholders from academia, industry, and policy, a clear set of mandatory and optional impact categories, indicators, and LCIA methods is established. The approach in this study emphasized scientific robustness, alignment with PBs, practical relevance for ZEVs, data availability, and usability. This multidimensional assessment enabled the proposal of a mandatory impact set including climate change, particulate matter, acidification, eutrophication, photochemical ozone formation, abiotic resource depletion, and cumulative energy demand thereby reinforcing a consistent and meaningful environmental assessment framework.

The inclusion of normalisation using global PB based factors and also avoiding weighting due to its subjective nature, promotes integrity in interpretation while maintaining scientific rigor. Although consensus is reached for most methodological aspects, certain impact categories such as biodiversity (cf. Section 7 of Supplementary Material), and circularity (cf. Section 6 of Supplementary Material), indicators require further development before inclusion. The voting methodology proved effective for decision-making but highlighted the dynamic nature of LCIA, requiring periodic reassessment as data and methods evolve.

In summary, this study lays the groundwork for a robust, academic-based and industry-driven LCIA methodology tailored to ZEVs. It strengthens the credibility and comparability of environmental assessments and supports informed decision-making across industry and policy. The proposed LCA framework, with its transparent structure and adaptability, can serve as a reference point for future advancements in LCA methodologies, fostering more sustainable and accountable mobility systems.

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Declarations

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