

The Environmental Sustainability Guideline for the Chemical Industry

Methodological
Framework for
Environmental Impact
Assessment



Together for Sustainability
Chem-X consortium

The Environmental Sustainability Guideline for the Chemical Industry

Methodological Framework for Environmental Impact
Assessment

Version 2.9 - October 2026

For Public Consultation



For more information,
please visit www.chem-x.de

Funded by the Federal Ministry of
Economic Affairs and Energy
BMWE



**Funded by
the European Union**
NextGenerationEU

Supported by:



Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

Participating partners

Chem-X participating partners:

BASF SE	Siemens AG
coac GmbH	Spheryty GmbH
Cofinity-X GmbH	Wacker Chemie AG
Covestro Deutschland AG	Catena-X e.V.
DAW SE	Together for Sustainability (TfS) AiBSL
Henkel AG & Co. KGaA	Evonik Industries AG
Merck KGaA	Sika Services AG
SAP SE	



Together for Sustainability AISBL member companies (Status September 2026):



Note to the table of contents:

This document covers now all module releases (“Module 1”, “Module 2”, and “Module 3”) of “The Sustainability Guideline for the Chemical Industry” as part of project Chem-X. releases.

Note on the consultation process:

The current consultation relates only to the content of Chapters 6, 14, 15, 16, 17 and Appendix 21.3, 21.10, 21.11, 21.12. Only comments on these chapters shall be reviewed this time. The other chapters (Module 1 and Module 2) have already been subject to consultation. Chapters that are not for review are marked in the text with a watermark and in the Table of Contents with an “not for review” mark.

Table of Contents

1.	Not for review: Introduction	15
2.	Not for review: About the Guidelines document	16
2.1.	Background and context	16
2.2.	Description of the challenges	17
2.3.	Objectives and purpose of the guidelines	18
2.4.	Link to Digital Material Passport (DMP) and Digital Product Passport (DPP)	18
2.5.	Methodology and reference to existing standards and guiding documents	19
2.6.	Terminology	20
3.	Not for review: Relationship and reference to the TfS PCF Guideline	22
3.1.	Goal and Scope: 5.1.1 in the TfS PCF Guideline v3.0	22
3.2.	System boundaries: 5.1.2 in the TfS PCF Guideline v3.0	23
3.3.	Declared Unit: 5.1.3 in the TfS PCF Guideline v3.0	25
3.4.	Temporal Scope: 5.2.2 in the TfS PCF Guideline v3.0	26
3.5.	Cut-off criteria: 5.2.3 in the TfS PCF Guideline v3.0	26
3.6.	Data types and sources: 5.2.5 in the TfS PCF Guideline v3.0	28
3.6.1.	Data Granularity	30
3.7.	Electricity and thermal energy: 5.2.8.1 in the TfS PCF Guideline v3.0	32
3.8.	Multi-output Processes: 5.2.9 in the TfS PCF Guideline v3.0	33
3.9.	Mass balance & Chain of Custody (CoC): 5.2.10.5 in the TfS PCF Guideline v3.0	35
3.10.	Process Data Quality and Share of Primary Data: 5.2.11 in the TfS PCF Guideline v3.0	37
4.	Not for review: GHG emissions / PCF (Global Warming Potential)	40
5.	Not for review: Resource Use, fossils	41
5.1.	General Description	41

5.1.1.	Issues of Concern	41
5.1.2.	Key Components of Potential Impact	42
5.1.3.	Regulatory Compliance	42
5.1.4.	Importance for the Chemical Industry	42
5.2.	Methodology of Characterization	43
5.2.1.	Chosen Method: EF	44
5.2.2.	LCI Flows	46
5.3.	Assessment Examples.....	47
6.	Resource use, minerals and metals	49
6.1.	General Description	49
6.1.1.	Issues of Concern	49
6.1.2.	Key Components of Potential Impact	49
6.1.3.	Regulatory Compliance	50
6.1.4.	Importance for the Chemical Industry	50
6.2.	Methodology of characterization.....	51
6.2.1.	Chosen method: EF	51
6.2.2.	LCI Flows	54
6.3.	Assessment Examples.....	54
7.	Not for review: Water Scarcity	56
7.1.	General Description	56
7.1.1.	Issues of Concern	56
7.1.2.	Key Components of Potential Impact	57
7.1.3.	Regulatory Compliance	57
7.1.4.	Importance for the Chemical Industry	58
7.2.	Methodology of characterization.....	60
7.2.1.	Chosen method: EF	60
7.2.2.	LCI Flows	62
7.2.3.	Data Granularity.....	64
7.3.	Assessment Examples.....	67
8.	Not for review: Acidification Potential	69
8.1.	General Description	69
8.1.1.	Issue of Concern	69
8.1.2.	Key Components of Potential Impact	70
8.1.3.	Regulatory Compliance	70
8.1.4.	Importance for the Chemical Industry	71

8.2.	Methodology of Characterization	73
8.2.1.	Chosen Method: EF	73
8.2.2.	LCI Flows	75
8.3.	Assessment Examples.....	76
9.	Not for review: Ozone Depletion Potential	79
9.1.	General Description	79
9.1.1.	Issues of Concern	79
9.1.2.	Key Components of Potential Impact	81
9.1.3.	Regulatory Compliance	82
9.1.4.	Importance for the Chemical Industry	82
9.2.	Methodology of Characterization	83
9.2.1.	Chosen Method: EF	83
9.2.2.	LCI Flows	84
9.3.	Assessment examples.....	85
10.	Not for review: Photochemical Ozone Creation Potential	87
10.1.	General Description	87
10.1.1.	Issue of Concern	87
10.1.2.	Key Compounds of Potential Impact	88
10.1.3.	Regulatory Compliance	88
10.1.4.	Importance for the Chemical Industry	89
10.2.	Methodology of Characterization	90
10.2.1.	Chosen method: EF	90
10.2.2.	LCI Flows	93
10.3.	Assessment examples.....	93
11.	Not for review: Eutrophication	96
11.1.	General Description	96
11.1.1.	Issues of Concern	96
11.1.2.	Key Components of Potential Impact	97
11.1.3.	Regulatory Compliance	97
11.1.4.	Importance for the Chemical Industry	98
11.2.	Methodology of characterization	98
11.2.1.	Chosen method: EF	98
11.2.2.	LCI flows.....	103
11.3.	Assessment examples.....	104
12.	Not for review: Particulate Matter	106

12.1.	General Description	106
12.1.1.	Issues of Concern	106
12.1.2.	Key Components of Potential Impact	107
12.1.3.	Regulatory Compliance	108
12.1.4.	Importance for the Chemical Industry	108
12.2.	Methodology of characterization	109
12.2.1.	Chosen method: EF	109
12.2.2.	LCI Flows	112
12.3.	Assessment Examples	114
13.	Not for review: Ionising radiation (human health)	115
13.1.	General Description	115
13.1.1.	Issue of concern	115
13.1.2.	Key components of potential impact	115
13.1.3.	Regulatory compliance	116
13.1.4.	Importance for the chemical industry	117
13.2.	Methodology of characterization	117
13.2.1.	Chosen method: EF 3.1	117
13.2.2.	LCI flow	118
13.3.	Assessment examples	119
14.	Land use	121
14.1.	General Description	121
14.1.1.	Issues of Concern	121
14.1.2.	Key Components of Potential Impact	122
14.1.3.	Regulatory Compliance	123
14.1.4.	Importance for the Chemical Industry	124
14.2.	Methodology of characterization	124
14.2.1.	Chosen method: EF	126
14.2.2.	LCI Flows	128
14.3.	Assessment Examples	129
15.	Ecotoxicity, freshwater	132
15.1.	General Description	132
15.1.1.	Issues of Concern	132
15.1.2.	Key Components of Potential Impact	132
15.1.3.	Regulatory Compliance	133
15.1.4.	Importance for the Chemical Industry	134

15.2.	Methodology of characterization	135
15.2.1.	Chosen method: EF	135
15.2.2.	LCI Flows	139
15.2.3.	Data granularity	139
15.3.	Assessment Examples	140
16.	Human toxicity (cancer & non-cancer)	142
16.1.	General Description	142
16.1.1.	Issues of Concern	142
16.1.2.	Key Components of Potential Impact	142
16.1.3.	Regulatory Compliance	143
16.1.4.	Importance for the Chemical Industry	145
16.2.	Methodology of characterization	145
16.2.1.	Chosen method: EF	145
16.2.2.	LCI Flows	153
16.3.	Assessment Examples	154
17.	Normalization and weighting, single scoring in LCA	157
17.1.	Characterized results: the starting point	157
17.2.	Normalization: "How large is this impact compared with a reference?"	157
17.3.	Weighting: "How important is this impact category?"	158
17.4.	Single score: adding the weighted results	159
17.5.	Simple numerical example	159
17.6.	Interpretation	160
17.7.	Practical meaning	160
17.8.	Other alternative approaches using normalization and weighting	161
18.	Glossary	165
18.1.	Overview of abbreviations, terms and definitions	165
19.	Information Model	187
20.	Literature	188
21.	Appendix	213
21.1.	Not for review: Downloading EF 3.1	213
21.2.	Not for review: Resource Use, fossils	214
21.2.1.	Other LCIA methods: Resource Use, fossil	214
21.3.	Resource Use, minerals and metals	216
21.3.1.	Current Scientific Discussion	216
21.3.2.	Aggregates and Mineral Resources in Life Cycle Inventory Modelling	216

21.3.3.	Proposed Hierarchical Decision Hierarchy	217
21.4.	Not for review: Water Scarcity	218
21.4.1.	Example 1: Water scarcity impact for product with value chain in different countries	218
21.4.2.	Example 2: Water scarcity impact when input water country of origin is different from output water	219
21.4.3.	Examples on Corrective Considerations for Surplus Water Outputs	219
21.4.4.	Examples on Corrective Considerations for Surplus Water Inputs.....	220
21.5.	Not for review: Acidification Potential.....	222
21.5.1.	Other LCIA methods: Acidification Potential	222
21.6.	Not for review: Ozone Depletion Potential	224
21.6.1.	Other LCIA methods: Ozone Depletion Potential.....	224
21.7.	Not for review: Photochemical Ozone Creation Potential	226
21.7.1.	Other LCIA methods: Photochemical Ozone Creation Potential.....	226
21.8.	Not for review: Particulate Matter.....	229
21.9.	Not for review: Ionising radiation (human health)	232
21.10.	USEtox for Human Toxicity assessment in LCA	233
21.11.	ProScale for Human Toxicity assessment in LCA.....	236
21.11.1.	General principles	236
21.11.2.	Procedure and workflow	237
21.11.3.	Procedural guardrails	237
21.11.4.	Core formulas	239
21.11.5.	Data needs and data generation.....	245
21.11.6.	Interpretation of results	250
21.11.7.	Assessment examples	250
21.12.	ProScaleE for Eco-Toxicity assessment in LCA.....	255
21.12.1.	General Principles	255
21.12.2.	Core Procedure	256
21.12.3.	Data Quality and Uncertainty	256
21.12.4.	Data Needs	259
21.12.5.	Assessment examples	262

List of Figures

Figure 1: Chem-X DMP/DPP relations.....	19
Figure 2: System boundary definition.....	23
Figure 3: Decision tree on selection of emission factors for externally sourced electricity.....	33
Figure 4: Decision tree to show allocation rules and reduce assessment burden downstream.....	34
Figure 5: Assessment example for Resource use, fossils.....	48
Figure 6: Resource Use, minerals and metals calculation of Nickelsulfate	55
Figure 7: Definition of water scarcity footprint	56
Figure 8: Number of Member States that had met their national emission reduction commitments for the five main pollutants for 2030.....	72
Figure 9: Sectors and activities contributing to emissions of the five regulated air pollutants in EU Member States in 2023	73
Figure 10: Summary of stratospheric ozone chemistry.	81
Figure 11: Summary of limitations and challenges related to midpoint and endpoint characterization.....	82
Figure 12: Simplified example of an ODP calculation for a chemical process with ODP mass emission flows.	87
Figure 13: Representation of the six main sources of VOCs and NO _x in a typical industrial city in China	88
Figure 14: Comparison of previous and new process.....	95
Figure 15: Fate and transport considerations relevant for eutrophication modeling	98
Figure 16: Exemplary calculation of eutrophication impacts of fertilizer production	105
Figure 17: Calculation of impacts of a chemical process of the impacts of particulate matter	115
Figure 18: Example of impact assessment for different inputs of a chemical process linked with their characterization factors	121
Figure 19: Land use impact calculation of Ethanol from maize (US) and from sugar cane (BR) as feedstocks including land transformation and land occupation.....	133
Figure 20: Exemplified flows in formaldehyde production relevant for ecotoxicity, freshwater.	142
Figure 21: Human toxicity contributions for formaldehyde production.....	157
Figure 22: Example 1: Water scarcity impact for product with value chain in different countries.	223
Figure 23: Example 2: Water scarcity impact when input water country of origin is different from output water.	224
Figure 24: Overview of existing LCIA methods considering ODP in midpoint (blue ovals) and endpoint (red ovals) methods. White ovals represent data sources for ODP and model assumptions.	230
Figure 25: Comparison of photochemical ozone formation values (in kg NMVOC eq.) between the three methods: ReCiPe, EF 3.0 and IMPACT World.....	232
Figure 26: Comparison of photochemical ozone formation values (in kg NMVOC eq.) between the four methods: ReCiPe 2016, ILCD 2011, CML-IA baseline and IMPACT 2002+	232

Figure 27: Impact pathway followed for assessing human health effects from particulate matter (PM)	235
Figure 28: Impact pathway followed for assessing human health effects from ionising radiation (IR)	238
Figure 29: Hazard classifications of H-phrases to numerical numbers and visualization of the influence of OEL/DNEL	247
Figure 30: Hazard classifications of H-phrases to ProScale Hazard classes and H-phrases	248
Figure 31: Contributions to materials to the overall result of Formaldehyde production with ProScale	259
Figure 32: Integration of ProScale results based on REACH data and integration in overall LCA results interpretation	260
Figure 33: Stepwise illustration of the M-factor effect in the Substance A example. The blue path includes the M-factor and results in ScoreA = 60; the grey comparison path omits the M-factor and results in ScoreA = 6.	263
Figure 34: Illustrative ProScale-E score contributions for Substance A, Substance B, and Substance C. The total score is 92.5.	269

List of Tables

Table 1: Terminology used in this guideline.	21
Table 2: Sections of the TfS PCF Guideline v3.0 with content applicable also to other impact categories than PCF and described in this Guideline.....	22
Table 3: Activities to be included and excluded in the system boundaries and optional activities.....	24
Table 4: Data hierarchy for energy and material inputs regarding primary, secondary and proxy data	29
Table 5: Overview of average LCI flows recommended	45
Table 6: Description of relevant LCI flows concerning Resource use, fossil.....	47
Table 7: Overview of selected average LCI flows recommended.....	52
Table 8: Resource use minerals and metals for sodium chloride (rocksalt)	53
Table 9: Description of selected relevant LCI flows concerning Resource use, minerals and metals	53
Table 10: Water usage categories within chemical industries.....	59
Table 11: Checklist of Water Flows for Consumptive Use Assessment (Aligned with EF method – country-level resolution)	64
Table 12: Default water loss estimation when primary data is missing.....	68
Table 13: Example water scarcity	69
Table 14: Processes directly or indirectly related to acidification relevant in the chemical industry	74
Table 15: EF 3.1 Acidification average characterization factors	76
Table 16: Description of relevant LCI flows concerning Acidification.....	77
Table 17: Simplified example for the calculation of the Acidification Potential to produce fertilizer.....	79
Table 18: Categories directly or indirectly related to acidification relevant for the chemical industry	84
Table 19: Selection of ODP characterization factors for some substances	85
Table 20: Description of relevant LCI flows concerning Ozone Depletion	86
Table 21: This is a non-exhaustive list of process steps that should be considered for data collection on POCP.	91
Table 22: Overview of selected characterization factors.....	93
Table 23: Overview of LCI flows	94
Table 24: EF 3.1 Eutrophication, terrestrial average characterization factors, expressed in mol N-eq. per kg emissions to air	101
Table 25: EF 3.1 Eutrophication, marine average characterization factors, expressed in kg N-eq. per kg emissions to air and water	102
Table 26: EF 3.1 Eutrophication, freshwater average characterization factors, expressed in kg P-eq. per kg emissions to water and soil.....	104
Table 27: Description of relevant LCI flows concerning Eutrophication.....	104
Table 28: Overview of regulatory bodies and sources	109
Table 29: EF3.1 Particulate Matter characterization factors for Europe and for emissions to air, unspecified, expressed in disease incidence per kg.....	113
Table 30: Description of relevant LCI flows concerning Particulate matter	113
Table 31: Description of relevant LCI flows concerning ionising radiation	120
Table 32: Addressed environmental issues and damage pathway by LCIA metho	127
Table 33: LCI flows and their description used in LCA	130

Table 34: Land Use Impact in the Ethanol example	132
Table 35: EF3.1 Ecotoxicity, freshwater characterization factors, expressed in CTUe per kg emissions to air, soil and water (EF3.1)	140
Table 36: Description of relevant and exemplary LCI flows concerning Ecotoxicity, freshwater	140
Table 37: Contribution of flows to ecotoxicity, freshwater organics and ecotoxicity, freshwater inorganics.....	142
Table 38: Comparison of USEtox and ProScale methods.....	148
Table 39: Input factors for USEtox assessments.....	152
Table 40: Data needs in CTUh calculation in USEtox assessments.	153
Table 41: Selected EF 3.1 characterization factors for human toxicity, cancer - total.	154
Table 42: LCI Flows for human toxicity assessment in USEtox	154
Table 43: Generic product calculation of USEtox results	155
Table 44: Formaldehyde process calculation of USEtox with illustrative figures.	156
Table 45: Example of normalization and weighting of LCIA results to a single score	160
Table 46: Contributions of normalized and weighted results to the total result ..	161
Table 47: Development and overview of normalization factors from EF3.0 to EF 3.1	162
Table 48: Development and overview of weighting factors in EF 3.1	163
Table 49: Overview of Midpoint methods	220
Table 50: Approach to derive CFs from global mineral reserves stated in (U.S. Geological Survey, 2026) in comparison to CFs given in EF 3.1 and CML 2016 ...	222
Table 51: Input-output process water inventory before water balance correction	224
Table 52: Input-output process water inventory after water balance correction ..	225
Table 53: Input-output process water inventory before water balance correction	226
Table 54: Input-output process water inventory after water balance correction ..	227
Table 55: Description of the 15 LCIA methods selected for this review	229
Table 56: Overview of LCIA methods for POCP	231
Table 57: Input factors for CTUh calculation in USEtox assessments	241
Table 58: Summary of important key elements of ProScale assessments.	244
Table 59: Overview of data input needed for ProScale including proposals for the use and further explanations behind the terms..	251
Table 60: Overview of Person hour factors as averages from different productions..	252
Table 61: Prompt results for Benzene used as input information for ProScale calculation... ..	254
Table 62: ProScale calculation and results derived from data from prompt search and integration into ProScale calculation tool.... ..	255
Table 63: Example process calculation of results in ProScale.... ..	256
Table 64: Example process calculation of Formaldehyde production with ProScale.....	258
Table 65: Data needs and overview of source for the generation of inputs information in ProScaleE.... ..	265



Table 66: Data needs and overview of source for the generation of inputs information in ProScaleE for three different substances.....	267
Table 67: Simplified template below captures only the essential fields needed for a first ProScale-E calculation	268

1. Introduction

The chemical industry is undergoing a pivotal shift in how it approaches sustainability. As Digital Material Passports (DMPs) and Digital Product Passports (DPPs) gain momentum as tools for improving transparency, traceability, and regulatory alignment, there's a growing recognition that focusing solely on carbon emissions is no longer sufficient. While carbon remains a critical metric, it represents just one dimension of a product's environmental footprint. To provide a more complete picture, DMP/DPPs must begin to incorporate a broader set of impact categories – such as water consumption, land use change, ecotoxicity, human health risks, resource depletion, and ozone layer degradation. These impacts span the entire life cycle of chemical products, from raw material extraction through production, use, and disposal.

Expanding the environmental scope of DMP/DPPs is not just a technical upgrade – it is a strategic necessity. Customers, regulators, and investors are increasingly seeking comprehensive data to guide procurement, evaluate sustainability claims, and manage risk. Without consistent reporting on these additional impact areas, DMP/DPPs risk falling short of their potential to drive meaningful change and innovation.

However, this expansion brings its own challenges. Today, companies differ widely in how they assess and report non-carbon impact categories, leading to fragmented data and limited comparability. To overcome this, the industry must work toward harmonized approaches – standardizing life cycle inventory datasets, impact assessment methods (such as ReCiPe, EF 3.1, CML or TRACI), and reporting formats. This alignment will not only improve data quality and interoperability but also enable benchmarking and foster collaboration across the sector.

A promising example of such alignment is the recently developed TfS (Together for Sustainability) PCF Guideline v3.0 (Together for Sustainability AISBL, 2025), providing clear instructions for calculating and sharing Product Carbon Footprints (PCFs), with the goal of improving transparency across supply chains and enabling consistent reporting within the chemical sector. It outlines the methodology for PCF calculation and offers recommendations for sharing data, including key attributes. As the first and most highly regarded chemical industry-specific framework for PCFs, it empowers companies to generate high-quality, standardized data that aligns with ISO 14067 (ISO 14067, 2018) and the Greenhouse Gas (GHG) Protocol (GHG Protocol Product Standard, 2011) – setting a strong precedent for how other environmental impact categories can be addressed with similar consistency.

By building on this foundation and applying the same level of discipline to a wider range of environmental metrics, the chemical industry can unlock the full potential of digital product passports – not just as tools for compliance, but as drivers of innovation, accountability, and long-term sustainability.

2. About the Guidelines document

2.1. Background and context

Across the chemical industry and beyond there is an urgent need to measure, report, address and possibly improve environmental impacts considered within life cycle assessments (LCA). The environmental impacts of products usually do not arise within the scope of activities of a single manufacturer, but rather across several steps in the value chain. Therefore, a transparent and accurate exchange of product-level sustainability impact data along the supply chain is a key element to both inform consumer product choices and drive mitigation strategies toward climate resilience and responsible resource stewardship.

The TfS PCF Guideline (with its version 3.0 published in Dec 2024) has been broadly and globally recognized as valuable guidance for chemical manufacturers willing to assess the GHG emissions at product level (TfS, 2024). The guideline draws on the wealth of expertise and knowledge within the TfS member network to develop methodological guidelines for the chemical industry, while remaining fully compliant with existing generic standards including ISO Standards and the GHG Protocol. This guideline – the TfS Sustainability Metrics Guideline for the chemical industry – expands the scope of the TfS PCF Guideline v3.0 by covering additional environmental impacts that are addressed in Life cycle Impact assessments. This approach will benefit chemical manufacturers, their suppliers, and industry initiatives seeking to assess impact categories beyond global warming potential, serving as a practical drop-in methodology for the chemical sector. The Guideline has been developed within the publicly funded project Chem-X.

By applying this new Guideline, TfS members, companies in the chemical industry, and their value chain partners can holistically approach the integration of Life Cycle Impact Assessment (LCIA) of chemical products within their corporate data inventories.

This comprehensive guideline instructs companies on how to calculate and share the LCIA results of their own chemical products. It also provides guidance on using supplier-specific data, supporting transparency, and improving the environmental impact of the entire value chain.

About this version

Based on the TfS PCF Guidelines Version 3 published in 2024, including the related data model, this version adds new information on LCIA methodologies and the LCIA assessment for several defined impacts. Although this Guideline is separated from the TfS PCF Guideline v3.0, it does incorporate it as an integral chapter (see Chapter 3 for further details and guidance).

This document provides guidance on how to use and determine several LCA impact categories (Module 1). These impact categories include PCF (Chapter 4 referencing the TfS PCF Guideline v3.0, Resource Use, fossil (Chapter 5), Water Scarcity (Chapter 6), Acidification Potential (Chapter 7), Ozone Depletion Potential (Chapter 8) and Photochemical Ozone Creation Potential (Chapter 9). The choice to address this specific set of impact categories in this first version of this Guideline document was based on a prioritization done by the working group. Following versions of this Guideline will contain additional impact categories.

2.2. Description of the challenges

Developing sustainability guidelines involves navigating a complex and multifaceted landscape. Each sector—whether manufacturing, energy, or others—has unique considerations that must be addressed. This is especially critical for the chemical industry, which supplies products across numerous sectors. Because sustainability standards directly impact planetary health, community well-being, and long-term resilience, the responsibility and stakes are exceptionally high. This section revisits the core challenges through the lens of sustainability.

Sustainability brings together a diverse range of stakeholders—including industry leaders, environmental organizations, policymakers, community representatives, scientists, and the general public. Each group often holds distinct, and at times conflicting, priorities. For example:

- Businesses may focus on economic feasibility and operational efficiency;
- Environmental advocates might push for ambitious targets to protect natural resources and biodiversity;
- Policymakers balance legal, economic, and environmental outcomes for society;
- Communities may prioritize local impacts, such as jobs and health.

Reconciling these perspectives is complex, especially when interests appear at odds or when sustainability goals require trade-offs between short-term costs and long-term benefits.

Describing sustainability in precise terms is challenging. Concepts like "carbon-neutral," "circular economy," or "social responsibility" are nuanced and multi-faceted. Therefore, guidelines and standards must:

- Clearly define sustainability metrics (e.g., acceptable emission levels, resource efficiency, labor standards).
- Be understandable by stakeholders from different technical and cultural backgrounds.
- Address data collection and verification, ensuring claims are transparent and auditable.

Ambiguous language or technical loopholes can lead to misinterpretation or superficial compliance, ultimately undermining the purpose of the guideline or standard.

For a sustainability guideline or standard to be realistically implementable, it shall:

- Consider the economic impact on organizations, including small- and medium-sized enterprises.
- Ensure that monitoring and compliance do not demand unrealistic resources for many stakeholders.
- Deliver clear guidance, comprehensive training, and ongoing support to drive meaningful improvements rather than mere compliance.

If a guideline or standard sets overly ambitious targets, it may discourage participation or result in superficial compliance.

The relevance of indicators varies depending on the material being assessed. Mandatory elements are defined by the EU with category rules (PEFCR) at the material or product level. For final chemical industry products—which can differ significantly—general recommendations are therefore not feasible.

Assessing whether a sustainability guideline or standard delivers real-world benefits is crucial. Developing robust, science-based metrics for environmental impacts needs harmonized approaches and should establish mechanisms for independent monitoring and public reporting. In certain time frames, guidelines and standards must go for revision to consider current developments and to drive meaningful improvement. Continuous learning and adaptation in a consensus mode ensures the guideline or standard remains a force for positive change.

2.3. Objectives and purpose of the guidelines

Sustainability standards serve as a transparent assessment by which organizations can be assessed and held accountable. Key objectives in this area include the use of standards to provide concrete and measurable criteria for performance, making it easier to track progress and identify areas for improvement based on generic standards. Adherence to recognized standards strengthens the credibility and legitimacy of organizations in the eyes of investors, customers, regulators, and the wider public. Meaningful and established standards support third-party verification and certification processes offering independent assurance of compliance and performance, allow the exchange of data that were developed with a harmonized and commonly agreed approach, and allow performance tracking on product and company level.

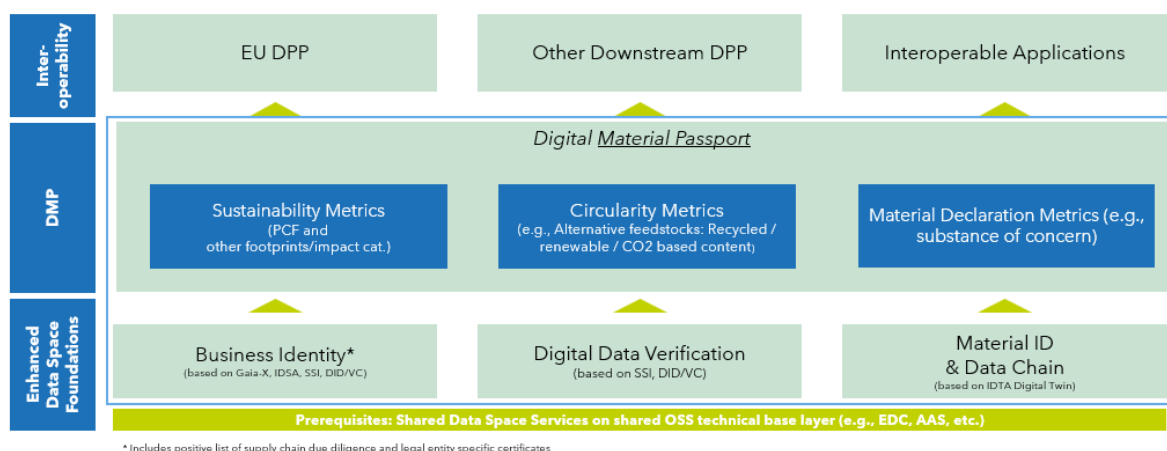
The proliferation of diverse sustainability initiatives across countries and industries can lead to confusion, duplication, and inefficiency. Well-defined sustainability standards aim to promote international consistency on information level and enable to facilitate cross-border collaboration and trade, ensuring that sustainability criteria are understood and accepted worldwide. Harmonization of standards helps avoid conflicting requirements and streamline compliance for multinational organizations enabling the sharing of best practices and lessons learned, thereby accelerating progress towards collective sustainability goals. Exchanging the data via a harmonized data approach gives more opportunities for data sharing and informs interested parties about product performance according to sustainability requirements.

This guideline delivers such a harmonized approach for the chemical industry and opens opportunities for other downstream sectors to select more sustainable products and receive meaningful information along their value chains. It is to be emphasized that the value of a harmonized approach for the definition, characterization and determination of key sustainability metrics is particularly relevant for chemical materials, as they constitute the input to over 95% of all manufacturing goods globally (ICCA, 2019).

Therefore, the primary objective of this guideline is to ensure a consistent, practical, and accurate assessment of cradle-to-gate sustainability impacts for chemical inputs, regardless of their downstream application—whether in automotive, construction, textiles, packaging, personal and home care, pharmaceuticals, raw material extraction, or any other sector.

2.4. Link to Digital Material Passport (DMP) and Digital Product Passport (DPP)

DMPs and DPPs are structured digital records containing detailed product information from chemical production to end-of-life treatment, aiming at enhancing transparency, traceability, and sustainability within the industry. This Guideline document, developed in the frame of project Chem-X, defines the sustainability metrics' portion of the chemical DMP, which is designed to interoperate and enable the fulfillment of upcoming DPPs data requirements for regulated products shown in Figure 1.



* Includes positive list of supply chain due diligence and legal entity specific certificates

Figure 1: Chem-X DMP/DPP relations

This guideline aims to establish harmonized terminology, descriptions, and calculation methods for sustainability metrics in DMPs of chemical materials, regardless of their end-use application. Its purpose is to reduce costs and complexity for chemical sector companies seeking to generate and exchange sustainability data in line with regulated DPP requirements. Given that sustainability data is currently scarce and inconsistent across metrics, industries, regions, and products, this guideline represents a significant step toward enabling an effective and sustainable transformation throughout supply chains.

Beyond the above-mentioned methodological harmonization effort, it is not in the scope of this guideline to define or suggest regulatory must-have data points for upcoming regulated DPPs.

2.5. Methodology and reference to existing standards and guiding documents

This sectorial TfS Guideline within the Chem-X project for chemicals follows the international standards ISO 14040:2006/AMD 1:2020 and ISO 14044:2006/AMD 2:2020 for Life Cycle Assessment. Derived from these generic standards, the TfS PCF guideline v3.0 follows ISO 14067: 2018 for PCF. It also draws from other guidelines such as the GHG Protocol developed in recent years for PCF calculations. For PCF calculations, the Partnership for Carbon Transparency (PACT) Methodology and World Business Council for Sustainable Development (WBCSD) Life Cycle Assessments guidelines were considered as well. The TfS PCF Guideline v3.0 was developed in harmonization with Catena-X and the Global Battery Alliance (GBA).

This new guideline goes beyond PCF calculations, extending coverage to additional impact categories. Many elements from the TfS PCF Guideline v3.0 can also be applied to other impact metrics, as detailed in Chapter 3.

For characterization models and related aspects, the Environmental Footprint (EF) Guideline Version 3.1 issued by the EU Commission (European Commission (EC), 2022) was referenced, as detailed in the chapters dedicated to individual metrics. The EF Guideline is expected to be updated in 2026 with Version 4.0. Once the new version is published, this document will be

reviewed and revised accordingly. In addition to these standards, category-specific guidelines were also considered, such as (ISO 14046, 2014) for water footprint. These category specific guidelines were cited in the respective metric chapters accordingly. While this guideline primarily builds on (EN 15804, 2019) for construction products, which applies similar principles for environmental information as EF guideline. These considerations have informed the Chem-X approach to ensure consistency with established practices across sectors.

General Information box for all chapters

In every subchapter, where relevant, a reference to this information box was introduced.

Selection guidance for characterization factors

Generally, EF 3.1 provides CFs for elementary flows with different geographical granularity. Based on the LCA software and database used, the geographical granularity of available CFs might vary. Specifically for water scarcity, the underlying characterization method AWARE provides localized CFs on watershed level, while EF 3.1 and most LCA software offer less granularity. Following hierarchy shall be followed when choosing CFs (from most granular to global) depending on the availability:

1. localized (e.g. ammonia emissions to a lake in Normandie watershed at water scarcity)
2. country
3. region (e.g. Europe)
4. global

This rationale for selection of available characterization factors is applicable to all sustainability metrics described in this guideline.

2.6. Terminology

This guideline uses precise language to indicate which provisions of the standard are required, which are recommendations, and which are permissible or allowable options that companies may choose to follow. In this guideline, the terms defined by ISO International Standard are used; such as:

- The term “shall” is used throughout this guideline to indicate what is required for an LCI (Life Cycle Inventory).
- The term “should” is used to indicate a recommendation, but not a requirement.
- The term “may” is used to indicate an option that is permissible or allowable.
- The term “required” is used in the guideline to refer to requirements in the standard.
- “Needs,” “can,” and “cannot” may be used to provide guidance on implementing a requirement or to indicate when an action is or is not possible [GHG Protocol Corporate Value Chain (Scope 3) Standard].

Table 1 reports a summary of the terms used and what they indicate in this guideline.

Table 1: Terminology used in this guideline

Term	Indicates
Shall	Requirement
Should	Recommendation
May	Permitted or allowed
Can	Possible (for example, that an organization or individual is able to do something)

In summary, the terms defined by ISO International Standard are used:

- “Shall” indicates a requirement.
- “Should” indicates a recommendation.
- “May” is used to indicate that something is permitted.
- “Can” is used to indicate that something is possible, for example, that an organization or individual is able to do something.

In the ISO/IEC Directives, Part 2, 2021, 3.3.3, a requirement is defined as an “expression, in the content of a document, that conveys objectively verifiable criteria to be fulfilled and from which no deviation is permitted if conformance with the document is to be claimed.”

In the ISO/IEC Directives, Part 2, 2021, 3.3.4, a recommendation is defined as an “expression, in the content of a document, that conveys a suggested possible choice or course of action deemed to be particularly suitable without necessarily mentioning or excluding others.”

3. Relationship and reference to the TfS PCF Guideline

LCIA methodologies are designed to address the scope of several impact categories in a consistent framework. This approach is followed by this Guideline as well, which builds on the TfS PCF Guideline v3.0.

This chapter focuses on the communalities between the determination of PCF and other impact categories guiding the reader to refer to shared concepts to the respective sections covered in the TfS PCF Guideline v3.0. When it comes for example to system boundaries, declared unit, data source provisions, allocations in multi-output systems and several other topics, the approach developed for the Global Warming Potential impact category will apply also to other impacts. Therefore, we provide here the reader with guidance on how to transfer the application of rules specified for PCF to other metrics such as Acidification Potential, Water Footprint, Ozone Depletion Potential, etc.

Table 2 below provides a useful list of corresponding sections in the TfS PCF Guideline v3.0, describing methodological approaches valid also beyond PCF.

Table 2: Sections of the TfS PCF Guideline v3.0 with content applicable also to other impact categories than PCF and described in this Guideline.

Topic	Section in TfS PCF Guideline v3.0
Goal & Scope definition	5.1.1
System boundaries (incl. Geographic scope)	5.1.2
Declared Unit	5.1.3
Temporal scope	5.2.2
Cut-off criteria	5.2.3
Data types and sources	5.2.5
Multi-output process (allocation)	5.2.9
Data Quality and Share of Primary Data	5.2.11
Mass balance & CoC	5.2.10
Electricity	5.2.8

3.1. Goal and Scope: 5.1.1 in the TfS PCF Guideline v3.0

The scope of this guideline covers the so-called “cradle-to-gate” approach to calculate a Lifecycle impact up to the production stage of the company determining and declaring such an impact.

It is stated where the guideline defined specific rules for chemicals that are not reflected in detail in the current standards. The TfS PCF Guideline v3.0 is fully compliant with ISO 14040:2006/AMD 1:2020 and ISO 14044:2006/AMD 2:2020 for Life Cycle Assessment. For PCF calculations ISO 14067:2018 and the GHG Protocol Product Life Cycle Accounting and Reporting standard applies. The TÜV Rheinland as 3rd party certifier checked and validated the compliance of the TfS PCF Guideline v3.0.

It must be noted that a product assessment limited to only GHGs as described in the TfS PCF Guideline v3.0 (TfS, 2024) has the benefit of simplifying the analysis and producing results that can be clearly communicated to stakeholders. However, the limitation of a GHG-only inventory is that potential trade-offs or co-benefits between environmental impacts can be missed. Therefore, the results of a GHG-only inventory should not be used to communicate the overall environmental performance of a product (GHG Protocol Product Standard, 2011). To overcome these limitations, this guideline was prepared to cover more than one environmental impact category and to give users a more complete picture of the environmental impacts of a product.

3.2. System boundaries: 5.1.2 in the TfS PCF Guideline v3.0

The boundary of the guideline is a cradle-to-gate LCA, comprising all processes of extraction, manufacturing, and transportation, until the product leaves the factory gate. Downstream impacts from product use and end-of-life are in general excluded from a cradle-to-gate approach (Figure 5.2 in the TfS PCF Guideline v3.0) and Figure 2 in this document (TfS, 2024). The following activities shall be included in a cradle-to-gate calculation: all product related direct and indirect emissions of the production process, including fossil or biogenic removals, energy consumption from electricity, external heat and steam; fuel consumption like natural gas, biogas, utilities, manufacturing, inbound transportation, site-to-site transportation, treatment of process waste and wastewater treatment and all emissions of raw material consumption including catalysts that are consumed in the reaction (BASF SE, 2021). Further information on included activities is provided in Table 5.1. of the TfS PCF Guideline v3.0.

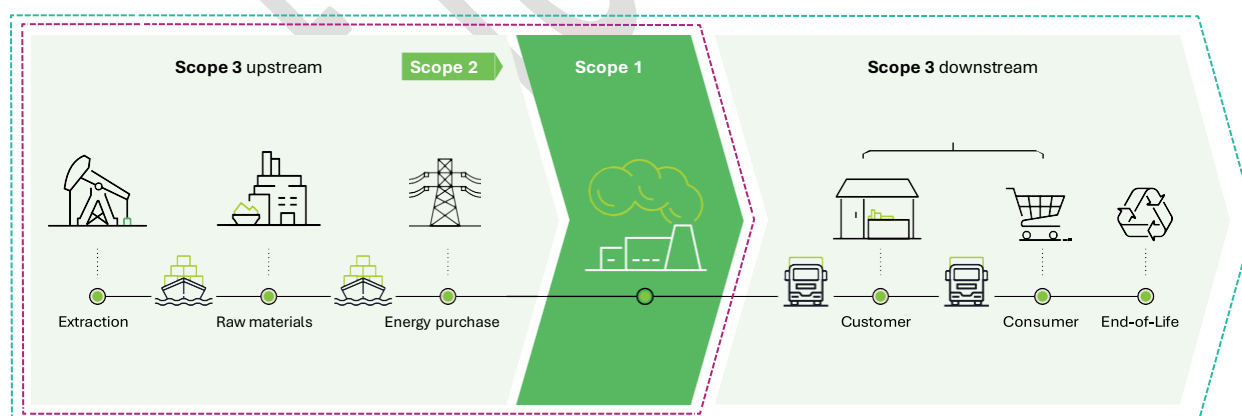


Figure 2: System boundary definition (TfS, 2024)

As the guidance is product-related, the following activities shall not be included within the boundaries of a cradle-to-gate LCA: manufacturing of production equipment, buildings, infrastructure and other capital goods, business travel by personnel, travel to and from work by personnel, and research and development activities because generally they fall under cut-off criteria. However, infrastructure may be included when its relative impact exceeds these cut-off thresholds or is known to be significant for the technology in question. For example, according to

the MLC Sphera online documentation, power plant construction and maintenance in electricity datasets are always included because its associated impacts do not meet the criteria for exclusion. (Together for Sustainability AISBL, 2025)^[22] on requirements to cut off activities.

Outbound transportation of the product is in general excluded in a “cradle-to-gate” impact determination (see Figure 5.2 in the TfS PCF Guideline v3.0). Table 3 below gives an overview of activities and their inclusion in the assessment.

However, if it needs to be considered by customers’ requests, it should be calculated and reported separately (“Distribution stage”). Packaging of the product in question should be included. For many chemicals, the contribution of packaging to the LCA is negligible. This is for example the case for bulk chemicals which are delivered by a supplier to customer manufacturing sites. If packaging is included, it should be visible in the description of the Declared Unit (see 5.1.3 in the TfS PCF Guideline v3.0) and related reporting (see the data field “packaging included” in the data model).

Table 3: Activities to be included and excluded in the system boundaries and optional activities (TfS, 2024)

Included	Excluded	Optional
Production related raw materials (including catalysts and ancillary materials that are consumed) ¹	Services such as engineering or infrastructure services, R&D activities	Packaging of input materials of the product
Utilities consumed	Business travel or employee commuting	Outbound logistics (if included in system boundary, it shall be stated separately)
Energy consumption	Capital and technical goods	
Direct emissions from manufacturing and related on site utilities production/generation	Activities falling under the cut-off requirements (as provided in Chapter 5.2.3)	
Transportation of raw materials and site-to-site transportation		
Treatment or disposal of process wastes and wastewater treatment		

(1) Non-production-related procurement (often called indirect procurement) consists of Purchased Goods and Services that are not integral to the company’s products but are instead used to enable operations. Non-production-related procurement may include capital goods, such as furniture, office equipment, and computers. Source: GHG Protocol Corporate Value Chain Standard.

The system boundary shall be the basis used to determine which unit processes are included within the LCA study. Where Product category rules (PCR) are used, their requirements on the processes to be included supersede those indicated above (see 5.2.4 in the TfS PCF Guideline v3.0).

The criteria, e.g., cut-off criteria (5.2.3 in the TfS PCF Guideline v3.0), used in establishing the system boundary, shall be identified and documented in the data model and the LCA calculation report.

It should be noted that when comparing the environmental performance of products, an LCA with cradle-to-grave boundaries should be used, to ensure impacts throughout the life-cycle of the product are considered.

3.3. Declared Unit: 5.1.3 in the TfS PCF Guideline v3.0

The Declared Unit (DU) describes the quantity of a product that is used as the reference unit in the quantification of the cradle-to-gate LCA. In case of chemical products, the Declared Unit is often defined as 1 kg of unpackaged product.

This TfS guideline deals exclusively with the use of a “Declared Unit” and does not address the use of a “Functional Unit”, as it only covers cradle-to-gate LCA and thus does not include the full product life cycle. Declared unit is further described in ISO 14067 (ISO 14067, 2018).

The LCIA data is expressed in equivalents per Declared Unit. The equivalent unit is defined for every single impact category and can be extracted from every chapter describing the impact categories. Per impact category, the cumulated life cycle impacts shall be linked to the DU.

Standard unit should be LCIA equivalents per kg product preferably. For some specific products like gases (e.g., Hydrogen, LPG) the LCIA might be expressed per unit norm cubic meter of the product. Furthermore, some products are sold, based on a volume unit (like liter), or pieces (e.g.: automotive parts) and in that case the LCIA may be expressed in the respective unit. In these cases, conversion factors (densities with associated conditions) shall be provided by the supplier for conversion to kg which is required in the attributes list in the Data Model. A DU shall be intrinsic to the product in such a way that it could be independently measured and verified. Abstract or equivocal values, such as monetary amounts like Euro, shall not be used.

For processes, the LCIA may be expressed as, but not limited to, LCIA equivalents per ton of distilled product, per ton of treated wastewater or per ton of product in a crystallization process. Some sectors may use other units in the Declared Unit. Regardless of what is used, a sufficient physical transfer shall be communicated to be able to convert these units into kg.

The results of a LCIA linked to the Declared Unit should be reported as LCIA equivalents per Declared Unit with one decimal. However, for very small values (<0.1) it is recommended to report at least one significant figure.

The Declared Unit shall be consistent with the goal and scope of the LCIA study. The primary purpose of a Declared Unit is to provide a reference to which the inputs and outputs are related. Therefore, the Declared Unit shall be clearly defined and measurable. An example of a Declared Unit is typically referring to the physical quantity of a product, for example “1 kg of liquid laundry detergent with 30 percent water content”. The Declared Unit for which the LCIA of a product system is calculated is 1 kg of unpackaged product at factory gate, regardless of its state (solid, liquid, gas), as its specific density is considered (BASF SE, 2021). If packaging is included (see 5.1.2), the Declared Unit is 1 kg of product packaged at the factory gate. 1 kg refers only to the product mass. The packaged product will weigh more than 1 kg.

$$\frac{\text{unit_LCIA}^1 \text{ product (including packaging impact)}}{\text{kg product (excluding the mass of packaging)}}$$

Formula 1: Definition of Declared Unit.

¹ unit_LCIA: unit used in the LCIA calculation, depending on the impact category. For example, Resource use, fossils = MJ; Water use (scarcity) = m³

3.4. Temporal Scope: 5.2.2 in the TfS PCF Guideline v3.0

The time boundary of an LCIA refers to the time period for which the LCIA value is representative was derived from ISO 14067. The following time boundaries apply for the different types of data:

- Primary data (e.g. supplier specific data) used in the calculations should be as recent as practicable and not older than three years. The most recent full year (reporting or calendar year) should be applied as the time boundary for LCIA calculations, if representative of an average year of production. For production years that are not continuous or irregular, production data may be averaged for a longer time period to reduce variability due to revisions, turnaround, or other typical production conditions. When applying average production data in a PCF calculation, no more than the last three years of production (reporting or calendar year) shall be averaged and used in the calculation (BASF SE, 2021) (PACT, 2025)
- Secondary data used for all inputs and outputs should reflect the most recent activity data and/or the latest LCIs (Life Cycle Inventory) available. LCI data (e.g., from databases) used in the calculation of LCIAs shall be as recent as practicable and not older than ten years (BASF SE, 2021). If older, appropriate, more recent proxies should be used instead. The data quality rating will be influenced by the choice of data.
- LCIAs shall have a maximum validity period of up to three years from the reference year of data collection if there have not been major changes to the production process (>20% impact from original LCIA result specific to PCF). It is recommended to use PCF as a guiding element but if there is a clear indication of other indicators differing more than 20% this change should be adopted. Companies may update their calculations on a more regular basis (e.g., annually). TfS decided that after three years or if the production process has changed significantly, LCIA values are no longer considered representative and shall be re-calculated. Once LCIA has been revised, the revised version will replace the original version and be valid for 3 years.
- The time boundary of the LCIA calculation is the reference year. The LCIA reference year and date of calculation/publication shall always be disclosed alongside the different values.

3.5. Cut-off criteria: 5.2.3 in the TfS PCF Guideline v3.0

In general, all processes, flows and activities that are attributable to the product system shall be included in an LCA (see 5.1.2 in the TfS PCF Guideline v3.0) (BASF SE 2021), (ISO 14067, 2018). There is in general no difference among the different impact categories concerning the cut-off criteria. Relevant impacts to the results are the important guidance on decisions if unit processes or inputs cut-off or not. If there are differences in cut-off depending on the impact categories and the cut-off shall be adjusted if needed. For example: If there is a unit process that generates a high level of Acidification but that is not relevant for GWP, the unit process shall not be excluded in the Acidification assessment.

The choice of elements of the physical system to be modelled depends on the goal and scope definition of the study, its intended application and audience, the assumptions made, data and cost constraints, and cut-off criteria. The models used should be described and the assumptions underlying those choices should be identified. The cut-off criteria used within a study shall be clearly understood and described (ISO 14040:2006, 2020)

The LCI data collection process shall aim for completeness. Where quantitative data is available, they shall be included. However, no undue effort should be spent on developing data of negligible significance concerning contributions to the LCIA results. If individual material or energy flows are found to be insignificant for results of a particular unit process, these may be excluded for practical reasons and shall be reported as data exclusions. If materials have a considerable upstream environmental footprint they shall be considered in the LCIA calculation, regardless of their relative contribution to the total mass of material flows. If the contribution is uncertain, an overview calculation should be done, and the results shall be included if significant.

Cut-off criteria specify the amount of material or energy flow or the level of significance of impacting the LCIA results associated with unit processes or the product system that may be excluded from an LCA study (BASF SE, 2021).

Furthermore, cut-offs may become necessary in cases where no data is available, where elementary flows are very small (below quantification limit), or where the level of effort required to close data gaps and to achieve an acceptable result becomes prohibitive.

If no data is available, but elementary flows are significant, data gaps should be closed in accordance with chapters 5.2.6 and 5.2.8. (TfS, 2024).

Several cut-off criteria are used in LCA practice to decide which inputs are to be included in the assessment, such as mass, energy, and environmental significance (BASF SE, 2021).

Requirements for LCIA cut-off criteria

1. All material inputs that have a cumulative total of at least 97% of the total mass inputs to the unit process shall be included. To generate LCIA with higher quality by improving the completeness of the calculation, 100% of total material inputs should be included.
2. All energy inputs that have a cumulative total of at least 97% of total energy inputs to the unit process shall be included. To generate an LCIA with higher quality by improving the completeness of the calculation, 100% of total energy inputs should be included. For most of the input materials, the mass & energy flow reflect the impacts to different impact categories accurately. But exceptions are possible. Where materials are used in a process that is considered or estimated to have a very high contribution to one of the addressed impact categories, the influence on the overall LCIA shall be evaluated and the cut-off kept below a defined threshold of the LCIA results per impact category. Such threshold is set at 3% for the Global Warming Potential impact category; for other impacts in the scope of this Guideline the same threshold shall be applied (except for water scarcity, please refer to the water scarcity section). The applied cut-off value for the given impact category shall be reported in the respective data field of the data model.
3. In cases where the input and influence on the results are unclear, an overall calculation should be made with generic figures to decide if a cut-off can be applied or not (iterative approach) (BASF SE, 2021).
4. Some input material flows (for example catalysts containing metals of the platinum group, uranium, highly toxic materials, materials) that have a considerable high upstream environmental footprint shall be considered in the calculations, regardless of their relative contribution to the total mass of material flows, even if their mass input is $\leq 1\%$ of the total mass. The LCIA calculations should at minimum consider the loss of material (e.g., the loss of catalyst) and assign an impact equal to the virgin material. If known, the efforts of recycling should be considered in addition. Otherwise known efforts, derived from other processes, can be used as a proxy.

3.6. Data types and sources: 5.2.5 in the TfS PCF Guideline v3.0

Data can have different levels of quality. Every LCIA calculation should be of the highest level of quality to be meaningful and applicable. High quality data are, for example emissions data that are verified under a governmental scheme such as the European Union-Emissions Trading SySTEM (EU-ETS) or other schemes. In a chemical reaction, several inputs are needed. Information about the inputs can be derived from different sources. The input from all sources shall be assessed with a quality rating system and data with the highest quality rates shall be used in the calculation of the impacts. For share of primary data and data quality rating, please refer to chapter 5.2.11. in the TfS PCF Guideline v3.0. In most cases, the same set of primary data is used in LCA modelling; however, both the primary data share and the data quality ratings may differ in some cases from one impact category to another. For example, if a practitioner receives PCF data from one supplier and uses acidification data from a database for the same product. Consequently, if that is the case, they should be reported separately for each impact category in the data model.

The most recent databases at point of calculation should be used. Moreover, the database version use shall be transparently indicated in the data model. For the PCF calculation for example, there was a significant change in the datasets in 2023/2024 connected to increased methane emissions from the extraction processes of oil and gas. Therefore, we put a requirement of using database versions as e.g. ecoinvent V3.10, Sphera MLC 2024.1 or Carbon Minds cm.chemicals database Version 2.00, July 2023, or later versions of these databases.

The use of different databases should be avoided as much as possible, to ensure higher quality. If this is not possible, the user shall make clear the databases used, and in which way data from different databases have been mixed and clearly report the Data Quality Rating (DQR) as described in the TfS PCF Guideline v3.0. Overall, the most conservative approach is recommended. The methodology for assessing DQR is further described in Chapter 3.10 of this guideline.

In the TfS PCF Guideline v3.0, Primary and Secondary data definitions are provided. They are valid in the same way for LCIA calculations and shown in Table 4.

Table 4: Data hierarchy for energy and material inputs regarding primary, secondary and proxy data (TfS, 2024)

Approach	Activity data source		Emission factor source	
	Energy ¹	Material	Energy	Material
Best case	In-house/primary		For on-site production: In-house/primary For purchased electricity: Supplier-specific/ Renewable Electricity Certificates and Guarantees of Origin For other purchased energy: Supplier-specific	Supplier-specific (e.g. via Pathfinder Network)
Base case²	In-house/primary		Secondary databases	
Worst case³	In-house/ secondary ³ Proxy data		Proxy data and EEIO databases	

(1) Electricity, heating/cooling, steam.

(2) Prevalent approach in practice.

(3) Financial data.

Data gaps

Data gaps exist when there is no primary or secondary data that is sufficiently representative of the given process in the product's life cycle. For most processes where data are missing, it should be possible to obtain sufficient information to provide a reasonable estimate. Therefore, there should be few, if any, data gaps. The data quality rating will indicate that there are data gaps existing which were filled by proxy data. The section in the TfS PCF Guideline v3.0 gives additional guidance on filling data gaps with proxy data and estimated data. Table 5.2 in the TfS PCF Guideline v3.0 gives a summary and an overview.

Proxy data

Proxy data are data from similar processes that are used as a stand-in for a specific process. Proxy data can be extrapolated, scaled up, or customized to represent the given process. Companies may customize proxy data to resemble the conditions of the process studied more closely in the product's life cycle if enough information exists to do so. Data can be customized to better match geographical, technological, or other metrics of the process. Identifying the critical inputs, outputs, and other metrics should be based on other relevant product inventories or other considerations (e.g., discussions with a stakeholder consultant) when product inventories do not exist.

Examples of proxy data include:

- Using data on polyethylene plastic processes when data on the specific plastic input (e.g., HDPE) is unknown. Depending on the specific assessment, the processes under study and the contribution to the overall sustainability metric, using polyethylene data as a proxy for polypropylene might be sufficient as well.
- Adapting an electricity grid emission or impact factor for one region to another region with a different generation mix.
- Adapting a generic data set of a precursor for one process to another, similar process for Ethylamine or Diethylamine.

- Customizing the process of another product to match the studied process, e.g. by changing the amount of material consumed to match a similar process in the product studied.
- Data from proxy might differ in quality related to the different environmental impacts addressed.

Customizing the environmental impacts of a generic process to match the supplier specific results provided for one environmental category. For example, if a supplier provides PCF data for Ethanol but no other impact category, an industrial average model can be used as a proxy for Ethanol and modified to match the PCF given by the supplier.

Estimated data

When a company cannot collect primary data or integrate meaningful secondary data or proxy data to fill a data gap, companies shall estimate the missing data to determine the significance of its contribution to the LCIA result. If processes are determined to be insignificant based on estimated data, the process may be excluded from the inventory results (cut-off criteria).

Where possible, sensitivity analysis shall be performed. Additionally, DQR shall also be reported transparently.

3.6.1. Data Granularity

Highly granular data significantly enhances the precision and credibility of environmental assessments. They enable more accurate allocation, hotspot identification, and interpretation of impacts across life cycle stages. Best practices emphasize collecting data at the process level, where flows are directly linked to specific operations. However, when such detail is unavailable, structured disaggregation methods should be applied using transparent documentation and justified assumptions.

When detailed mass, energy, or water flow data are not available at the process level, broader datasets (e.g., site-level, department-level, or corporate-level) may be used and systematically disaggregated. Below are practical cases and methodologies applicable across all three flow types.

Case 1: Only Site-Level Data Available

Scenario: A production site includes multiple distinct processes (e.g., Process A and Process B), but only aggregate mass, energy, or water data is available at the site level.

Approach: Disaggregate site-level data to individual processes using relevant allocation criteria. Recommended proxies include (but are not limited to):

- Process-specific intensity data from design specifications or engineering models
- Historical usage patterns or expert input
- Production volumes or throughput

Example: If Process A consumes twice the energy per unit of output compared to Process B, and both produce equal volumes, allocate energy as follows:

- Assign 2 parts energy to Process A

- Assign 1 part energy to Process B

This proportional allocation provides a rational approximation and must be clearly documented, including all assumptions and sources.

Case 2: Flow Estimation Based on Energy or Mass Balance

If direct flow data (mass, energy, or water) is missing, estimates can be derived from:

- Mass or energy balances, which often yield more accurate results (e.g., steam requirements, material conversion rates, heat losses)
- Process-specific benchmarks from literature, industry databases, or technical standards

Example: A beverage facility lacks measured data for water used in bottle rinsing. Industry literature suggests 1.5 liters per bottle rinsed. This can be used as a proxy and scaled based on production data.

Case 3: Shared Utilities or Services

In facilities where flows are shared across multiple units (e.g., central steam generation, compressed air systems, water treatment), allocation should be based on:

- Utility loads per process (e.g., heating or cooling demand, material throughput)
- Engineering estimates of consumption per unit
- Operating time or production intensity

Case 4: Only Corporate-Level Data Available

Scenario: Flow data is only available at the corporate or group level, aggregating multiple sites, products, and geographies. This is common in multinational corporations reporting in sustainability disclosures or environmental databases.

Approach: Allocate corporate-level mass, energy, or water data down to the product system or site of interest using auxiliary data. Recommended allocation bases include:

- Publicly reported site-level environmental intensity indicators (if partially available)
- Production volume of individual facilities
- Sales volume by product line

Considerations: Combine corporate-level water data with production and product-level activity data and clearly disclose the uncertainty and assumptions involved in this top-down allocation.

The examples provided above are intended as guiding suggestions to support consistent and credible disaggregation of mass, energy, and water flows. However, practitioners may encounter unique scenarios not explicitly covered in this guideline. In such cases, applying alternative or more suitable practices is acceptable, provided that all assumptions, data sources, and reasoning are transparently documented. Where possible, sensitivity analysis shall be performed. Additionally, the DQR shall also be reported transparently.

3.7. Electricity and thermal energy: 5.2.8.1 in the TfS PCF Guideline v3.0

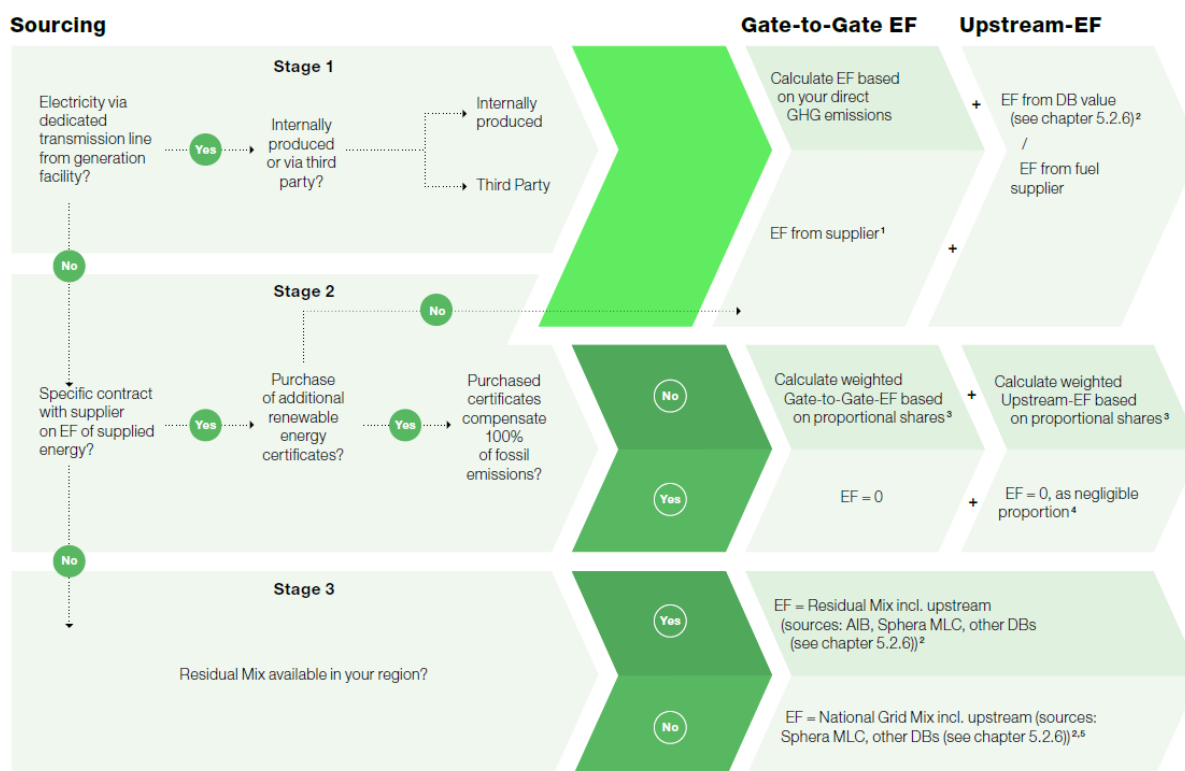
This chapter provides guidance on how to account for the emissions associated with the use of electricity and thermal energy such as steam, heat and cooling.

The emissions associated with the use of energy shall include:

- Upstream emissions from the energy supply system (e.g. the mining and transport of fuel to the energy generator or the growing and processing of biomass for use as a fuel).
- Emissions during the generation of electricity or thermal energy, including losses during transmission and distribution.
- Downstream emissions (e.g. the treatment of waste as ashes arising from the operation of coal fired power plants).

Please follow the decision tree in Figure 3 to determine your options on GHG emissions of procured electricity. Start in the top left corner of stage 1. Exception: If your company has sold energy attribute certificates for received electricity via a contractual instrument to a third party, start at stage 3.

Further details regarding the inclusion of impact from Electricity and Thermal energy use are described in chapter of the TfS PCF Guideline v3.0 Chapter 5.2.8.1 Electricity and thermal energy and is valid for other impact categories including Global Warming Potential.



(1) If the Emission Factor (EF) from supplier is not available, directly move to stage 3.

(2) If no access to Upstream EF data, please apply 20% of the IEA value instead and add it to the Gate-to-Gate EF.

(3) After receiving the individual energy mix from your supplier, multiply the EFs corresponding to their energy sources with their proportional share of the energy mix while also taking the partly compensated fossil emissions by purchased certificates into account (e.g.: energy mix: 20% renewable energy (RE), 80% fossil energy (FE); purchased certificates: an amount to compensate 50% of fossil emissions

$$= EF_{Weighted} = 0.2 \times EF_{RE} + 0.5 \times (0.8 \times EF_{FE}) + 0.5 \times (0.8 \times EF_{FE})$$

(4) If impacts including upstream emissions lie within the cut-off range (s. chapter 5.2.3), apply EF = 0. Otherwise, please use an appropriate DB value: Values from databases consider the full life cycle and also contain emissions from the construction stage (Sphera MLC or other DBs (see chapter 5.2.6)).

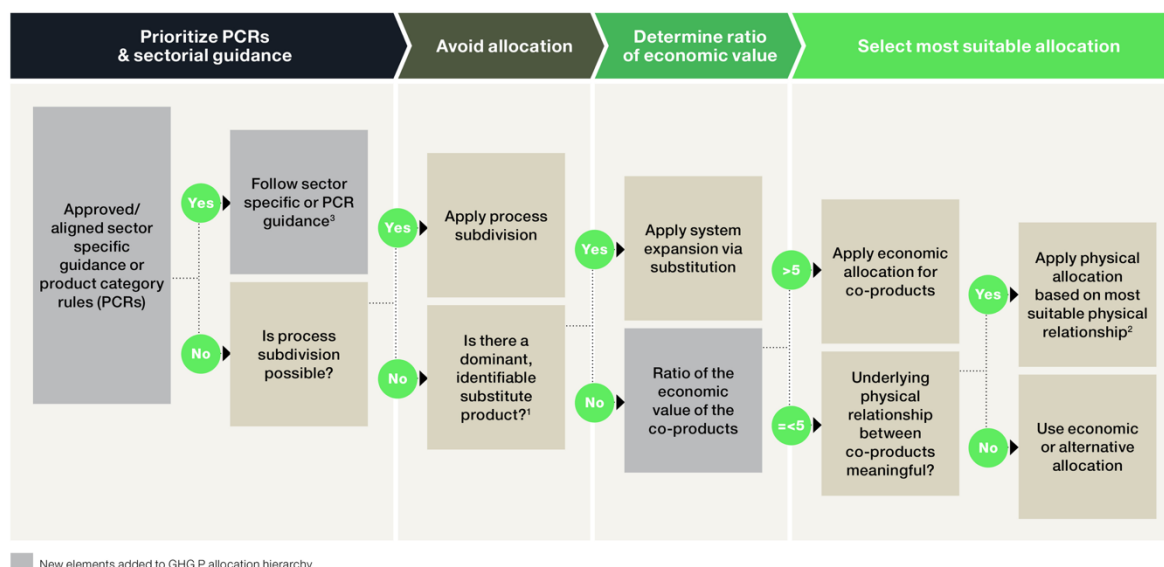
(5) Alternatively, IEA-Data can be implemented if additional Upstream EFs from DBs (Sphera MLC or other DBs (see chapter 5.2.6)) are added.

Figure 3: Decision tree on selection of emission factors for externally sourced electricity (TfS, 2024)

3.8. Multi-output Processes: 5.2.9 in the TfS PCF Guideline v3.0

This chapter is about allocating inputs and impacts in multi-output situations, i.e., when a process delivers more than one product, referred to as co-products. The term co-product also includes energy products such as steam or electricity, or any other product which is defined as co-product and not as waste. Herein *energy* is understood as direct energy e.g., from exothermal reactions (PACT, 2025). Materials that are identified as waste following the decision tree in Figure 5.7 in the TfS PCF Guideline v3.0, Chapter 5.2.8.4, shall be excluded from the attribution of environmental burdens. Impacts from treatment processes shall be linked to the process, where the waste was generated.

Leaning on hierarchies described in the GHG Protocol Product Standard, ISO 14040:2006, ISO 14044: 2006, ISO 14067: 2018, PACT Methodology and the European Commission Environmental Footprint recommendations, the following steps shall be applied to attribute impacts in multi-output situations (see Figure 5.16 in the TfS PCF Guideline v3.0 and Figure 4 below):



(1) System expansion via substitution should only be used if there is a dominant, identifiable displaced product and production path for the displaced product based on sector consensus.
(2) In doubt, mass allocation should be prioritized, but there are instances where other allocation factors may be more suitable (e.g. volume for gases, energy content for energy).
(3) Sector specific guidance or PCRs shall be used if approved and required as Drop-in standards by TFS for Chemical Industry, by Catena-X for other automotive industry supplying sectors or by WBCSD pathfinder for sectors other than those covered by TFS and Catena-X.

Figure 4: Decision tree to show allocation rules and reduce assessment burden downstream (TfS, 2024)

1. The approach described in published and accepted PCR, Industry Association projects, directives as e.g. REDII where available, for corresponding product systems shall be applied (see 5.2.4 Standards used in the TfS PCF Guideline v3.0, along with the list of TfS approved PCRs for chemical-specific product systems published on the landing page²). When more than one PCR exists for a product or product category, priority shall be given to allocation rules as described in chapter 5.2.9.3. in the TfS PCF Guideline v3.0.
2. Multi-output situations shall be avoided by using process subdivision, whenever possible. The common process shall be disaggregated into sub-processes that separately produce the co-products. Process subdivision may be done through submetering specific process lines and/or using engineering models to model the process inputs and outputs (GHG Protocol Product Standard, 2011).
3. If the multi-output situation cannot be avoided by subdivision, a system expansion shall be applied. System expansion refers to expanding the system by including the co-products into the system boundary and communicate LCIA results for the expanded system (PEF, 2012). System expansion and substitution can be a means of avoiding allocation. The product system that is substituted by the co-product is integrated into the product system under study. In practice, the co-products are compared to other substitutable products, and the environmental burdens associated with the substituted product(s) are subtracted from the product system under study (ISO 14040:2006, 2020). System expansion by substitution (further referred to as “substitution”) is only acceptable if the Declared Unit stays as defined in chapter 5.1.3. in the TfS PCF Guideline v3.0. Substitution, as described in chapter 5.2.9.1 in the TfS PCF Guideline v3.0, shall be applied to attribute impact to co-products in multi-output situations if all the following apply:
 - a. The co-products are generated in the process additionally but are not the main products of the process. Main products are defined as products that the process

² <https://www.tfs-initiative.com/pcf-guideline>

- is operated for and optimized to produce. Additionally, the economic values of the main products are generally significantly higher than for the co-products.
- b. The co-product directly replaces an alternative product with a dedicated production process on the market. The production of this alternative product is reduced through provision of the co-product.
 - c. Data about the impact of the alternative production process is available to calculate the LCIA of the alternative product.
 - d. There is consensus for a production path of the displaced product agreed by TfS. TfS maintains and publishes a positive list of processes and product systems on the landing page³.
4. In all other cases companies shall allocate the impact to co-products following the allocation rules described in chapter 5.2.9.3. in the TfS PCF Guideline v3.0. The applied approach to solving multifunctionality shall always be stated and justified.

TfS is aligned with PACT Methodology, Catena-X, GBA on the allocation hierarchy and thus the allocation approach as described in a PCR might be prioritized before system expansion and substitution. Since the PCR is ranked very high, it will overrule other approaches.

3.9. Mass balance & Chain of Custody (CoC): 5.2.10.5 in the TfS PCF Guideline v3.0

Chain of custody is an administrative process by which information about materials is transferred, monitored, and controlled as those materials move through supply chains (ISO 22095, 2020). Mass balance is a chain of custody (CoC) model (ISO 22095, 2020) used in multiple industries where it is not practical to maintain physical segregation of alternative and conventional feedstocks during processing. Mass balance helps enable a transition to a sustainable and circular economy by enabling the efficient co-processing of alternative materials in existing large-scale assets and complex supply chains. The alternative materials are not limited to bio-based feedstocks but could also consist of chemically recycled feedstocks, waste feedstocks, or CO₂-based materials.

Mass balance is especially important to many companies in the chemical industry that are transitioning to the use of waste-based materials and bio-based materials as feedstocks. This transition aims to reduce the usage of virgin fossil-based materials and help solve the global plastic waste dilemma through recycling.

Mass balance ensures that the quantity of output material is balanced with (does not exceed) the input of material and is appropriately adjusted for yields and conversion factors.

Co-processing of alternative and conventional materials results in the production of materials of mixed origin, which are not distinguishable in terms of composition or technical properties. Mass balance allows alternative content to be attributed to individual outputs, creating value from the use of alternative inputs. Large integrated assets cannot be transitioned immediately, and mass balance provides a critical bridge.

Since certain sectors, customers or regulatory frameworks may not support all possible chain-of-custody models and their attribution methods, the economic operator shall transparently

³ <https://www.tfs-initiative.com/pcf-guideline>

communicate about it via the information model. This enables the customer to choose the desired product offering.

The following requirements shall apply for the usage of mass balance chain of custody in determination of LCA calculations:

1. The mass balance shall follow a transparent certification standard, and the conformance to the certification shall be verified by an independent and qualified third party. Different certification systems have different requirements which are in scope of this guideline.
 - a. The certification system shall have clear chain of custody rules, traceability requirements, defined boundaries, guidelines for marketing claims, include safeguards against double-counting, and shall identify the type of sustainable raw material throughout the supply chain. Different certification systems have different requirements which practitioners can follow to be in line with this guideline.
 - b. To attribute environmental characteristic (specified characteristics) of a sustainable input ⁴(feedstock, fuel, energy, etc.) to a product of interest to generate a mass-balanced LCIA, a mass balance certification for the product shall be completed. The certification confirms the total required amount of feedstock, considering all losses.
 This amount of feedstock can be substituted with chosen sustainable feedstocks following the rules of the chain of custody certification schemes (for example, ISCC PLUS, REDcert², UL ECV 2809, RSB Advanced Materials, FSC, RSPO, or equivalent).
 The section in the TfS PCF Guideline v3.0 considers a possible chain of custody certification scheme, the mass-balancing, in detail. The chain of custody certification scheme allows a variety of system boundaries (e.g., process, plant, site, multi-site) and attribution methods.
 Upcoming standards that shall be used are ISO/FDIS 13662 that defines Mass balance requirements in detail and ISO 14077 that describes the calculation of LCA with CoC models as basis.
2. The LCA of the manufacturing process in which the mass balance attribution occurs shall be in conformance with ISO 14044 [ISO 14044: 2006]. The study shall document how the material flow and attributions were calculated. For the LCIA calculation, the system boundaries for the fossil and the mass-balanced product shall follow the standards mentioned in section 5.2.4. in the TfS PCF Guideline v3.0.

All other requirements defined in the TfS PCF Guideline v3.0 shall apply. The examples are generic and can be used in an LCIA context as well.

In the TfS-Chem X “Circularity Guideline” more details related to CoC models can be found.

So far mass-balance credit transfer is not addressed in this guideline.

⁴ e.g. circular, bio or low carbon feedstocks are examples for sustainable feedstocks.

3.10. Process Data Quality and Share of Primary Data: 5.2.11 in the TfS PCF Guideline v3.0

Primary Data Share

To create visibility on the share of primary data in LCIA calculations, the Primary Data Share (PDS) in each dataset shall be determined (and shared) (PACT Methodology). PDS score may differ among the several impact categories, depending on the data input used respectively. The calculation and reporting of a PDS will become mandatory for PCF issued from 2027 onwards, giving companies sufficient time to prepare. So far, for other impact categories it is recommended to do it on a voluntary basis

More details listed in the data exchange format, particularly regarding when this field will become mandatory.

The PDS can be assessed by calculating the proportion (%) of the total impact per impact category in impact equivalents, e.g. H⁺ eq, NMVOC eq etc. that is derived by using primary data in the cradle-to-gate system boundary (see Formula 2).

See glossary for definitions of primary and secondary data.

$$PDS_{DU} = \sum (|IC_i| * PDS_i) / \sum |IC_i|$$

Formula 2: Calculation approach of the PDS (Primary Data Share)

Where:

- DU is the Declared Unit
- PDS_{DU} is the primary data share of LCIA_{DU}, in % (0-100%)
- *i* is any input or output of a process, except the DU
- |IC_{*i*}| is the absolute value of the Impact Contribution of *i* to LCIA_{DU}, in kg LCIA e/DU
- PDS_{*i*} is the Primary Data Share of contributor *i*, in % (0-100%)

Process Data Quality

During the data collection process, companies shall assess the data quality of LCIA contributors (emission factors and/or direct emissions data) by using the data quality indicators (DQIs). The data quality of each LCIA shall be calculated and reported.

If data with higher quality exists in-house than available in secondary databases (for example, in-house emission factors for fuel) and is used for calculations, the adequacy of such in-house data shall be reviewed and reported in a DQR following the criteria outlined in chapter 5.2.11 of the TfS PCF Guideline v3.0 more in detail. Data sourced from verified emission factor databases (see chapter 5.2.6 in the TfS PCF Guideline v3.0) shall be reported in a DQR as well, addressing its representativeness, relevance, and correct application to the product in question as well. The calculation and reporting of a DQR will become mandatory for PCF issued from 2027 onwards, giving companies sufficient time to prepare. For other impact categories it is recommended to do it on a voluntary basis.

Assessing data quality during data collection allows companies to make data quality improvements more efficiently than when data quality is assessed after the collection is complete. Additionally, understanding the quality of the data allows companies to identify key

secondary data sources that should be improved or replaced with primary data for companies to be able to track the impact of emissions reduction plans more accurately.

The requirements of this guideline were harmonized with PACT Methodology, Catena-X and GBA. Three DQIs are required for the assessment of data quality

The process starts by assessing the technological, geographical, and temporal representativeness of emission factors and direct emissions data only for each impact contributing material. Emission factors can be contained in, or derived from, company-specific or secondary datasets, for which the same matrix should be used to assess the quality of this data. Direct emissions data can be derived as explained in chapter 5.2.8.5 (in the TfS PCF Guideline v3.0) and should also use the same matrix proposed for emission factors. The rationale behind this approach is described in the TfS PCF Guideline v3.0.

The quality indicators are summarized in Tables 5.14-5.16 (in the TfS PCF Guideline v3.0). Data quality rating criteria shall follow the approach outlined in Section 5.2.11.2 of the TfS PCF Guideline v3.0. The quality levels of TeR, GeR and TiR are expressed in five categories, from 1 to 5, where 1 is the optimum result in each indicator. The representativeness (technology, geography, and temporal/time-related) characterizes the degree to which the processes and products selected depict the system analyzed.

- **Technological Representativeness (TeR):** the degree to which the data reflects the actual technology(ies) used in the process.
- **Geographical Representativeness (GeR):** the degree to which the data reflects actual geographic location of the processes within the inventory boundary (e.g., country or site).
- **Temporal/Time Representativeness (TiR):** the degree to which the data reflects the actual time (e.g., year) when the process was assessed.

The general calculation of data quality ratings is shown in the following formula:

$$DQR_i = (TeR_i + GeR_i + TiR_i) / 3$$

Formula 3: Calculation approach of the DQR (Data Quality Rating)

DQR of product(s) obtained from a process with one or more input materials:

$$DQR_{DU} = \sum (|IC_i| * DQR_i) / \sum |IC_i|, \text{ for } |IC_i| \geq 0.05 \sum |IC_i|$$

Where:

- DU is the Declared Unit
- DQR_{DU} is the data quality of $LCIA_{DU}$, in range 1-5
- i is any input or output of a process, except the DU
- $|IC_i|$ is the absolute value of the Impact Contribution of i to $LCIA_{DU}$, in kg $LCIA_e/DU$
- DQR_i is the Data Quality of contributor i , in range 1-5

Note: DQR_{DU} is a linear combination of DQR_i . DQR_i is based on the assessment of TeR_i , GeR_i or TiR_i and will yield the respective value of a DQR_i for DU.

The DQR_{DU} shall be calculated for the output of e.g., 1kg or 1t, as defined in the Declared Unit.

Both the primary data share and the data quality ratings may differ from one impact category to the other: consequently, they will be reported separately for each impact category in the data model.

Data quality is handled in many LCA as support in the interpretation phase. Different approaches exist and they are discussed in several publications. Some examples of application and further reading can be found in literature as well (Edelen & Ingwersen, 2016), (Lewandowska, Joachimiak-Lechman, & Kurczewski, 2021) and (Kölsch & Giebeler, 2023).

Not for review

4. GHG emissions / PCF (Global Warming Potential)

For the impact category Global Warming Potential and the rules of determining the product carbon footprint it shall be referred to the TfS PCF Guideline available on the landing page⁵.

According to the TfS PCF Guideline v3.0, the GHGs that shall be accounted for are identified within the GHG Protocol titled “Required Greenhouse Gases in Inventories: Accounting and Reporting Standard Amendment”. The list includes Carbon dioxide (CO₂), Methane (CH₄), Nitrous oxide (N₂O), Hydrofluorocarbons (HFCs), Perfluorinated compounds, Sulphur hexafluoride (SF₆), Nitrogen trifluoride (NF₃), Perfluorocarbons (PFCs), Fluorinated ethers (HFEs), Perfluoropolyethers (e.g. PFPEs), Chlorofluorocarbon (CFCs) and Hydrochlorofluorocarbon (HCFCs). The GHG emissions shall be aggregated as CO₂-equivalents and should not be reported separately for individual gases.

The 100-year GWP characterization factors (GWP100y) according to the Intergovernmental Panel on Climate Change (IPCC) shall be used in the PCF calculations, based on the IPCC’s Sixth Assessment Report (AR6).

These factors include climate carbon response for non-CO₂ gases. If in future there will be updates, TfS will update the guideline accordingly to follow the latest version.

According to ISO 14067, biogenic removals from CO₂ uptake during biomass growth shall be included in the PCF calculation. Additionally, all biogenic emissions (e.g. methane emissions from manure application etc.) and further emissions from relevant processes, such as cultivation, production and harvesting of biomass shall be included in the PCF (ISO 14067, 2018). Furthermore, the biogenic carbon in products, fossil and biogenic GHG emissions and removals shall be reported. GHG emissions and removals from land use should be reported. Biogenic carbon in waste streams shall also be correctly reflected.

Removals of CO₂ into biomass shall be characterized in the PCF calculation as –1 kg CO₂/kg CO₂ when entering the product system, while biogenic CO₂ emissions shall be characterized as +1 kg CO₂e/kg CO₂ of biogenic carbon (ISO 14067, 2018). As referred to in Chapter 5.3.2, the PCF, that considers biogenic emissions and removals, shall be reported as PCF (including biogenic CO₂ removal).

⁵ <https://www.tfs-initiative.com/pcf-guideline>

5. Resource Use, fossils

5.1. General Description

Potential risks and impacts to the environment associated with chemical production and chemical products should be analyzed critically and in detail. One of the indicators selected by the TfS Chem X project was the “Resource Use, fossils”. This impact category was defined in earlier approaches when a characterization factor (CF) was applied as abiotic depletion potential (ADP_{fossil}). That relates to earlier versions of the ADP indicator, where minerals and metals as well as fossil fuels were assessed with a characterization model.

However, several limitations of ADP_{fossil} have been identified leading to the decision not using it anymore in EF 3.1:

- **Resource Availability Uncertainty:** The global reserves and extraction rates of fossil fuels are subject to significant uncertainty and fluctuation. This makes it challenging to provide a reliable, universally applicable depletion indicator.
- **Limited Environmental Relevance:** The environmental impacts associated with fossil fuel use extend beyond resource depletion, including greenhouse gas emissions, air pollution, and ecosystem damage.
- **Lack of Policy Alignment:** Modern environmental policies, especially in the European Union, focus on reducing overall fossil fuel consumption due to climate change concerns, rather than solely on resource scarcity.

Given these limitations, the EF 3.1 methodology has shifted toward directly assessing fossil fuel use, typically measured in terms of energy content (e.g., megajoules of fossil energy used). This category does not apply to a characterization model as in EF 3.1, therefore energy content and energy use are the focus without referring to an environmental characterization model. In this sense, it is more a reporting element and does not address further impacts such as ecological degradation, biodiversity loss, and social impacts in extraction regions. That may be addressed in other impact categories.

The approach does not address other effects associated with resource depletion, is related to EF 3.1 and therefore aligned with upcoming regulatory frameworks (e.g., ESPR).

In this chapter, we describe the resource use of fossil fuels.

When conducting an environmental assessment, “Resource Use, fossils” is assessed within most LCAs and derived mainly from Product Environmental Footprint (PEF). Although many practitioners or experts perceive “Resource Use, fossils” as an economic issue rather than an environmental one.

Upstream methane emissions and other extraction-related losses are reflected both in climate-related impact categories and in the ‘resource use, fossil’ indicator, as incorporated in current LCA databases.

5.1.1. Issues of Concern

Fossil fuels are finite resources. The continued extraction of coal, oil, and gas depletes reserves that have taken millions of years to form. As these resources become scarcer, their extraction

grows more difficult and environmentally damaging, prompting concerns about long-term energy security and sustainability.

The combustion of fossil fuels releases significant amounts of GHGs, notably carbon dioxide, which drives global climate change. This warming effect alters weather patterns, raises sea levels, and threatens biodiversity. Air pollution from burning coal, oil, or natural gas also produces particulate matter, nitrogen oxides, and sulfur dioxide, which can degrade air quality and harm respiratory health.

Moving away from fossil fuels toward cleaner energy sources presents technical, economic, and social hurdles. Many industries, communities, and nations are deeply tied to fossil fuel infrastructure, making the shift to renewables complex and, at times, contentious. The chemical industry is rather unique, as it is currently doubly reliant on fossil raw materials, both for energy use and as a feedstock for the synthesis of the key chemical building blocks upon which chemical manufacturing is based on. In the future, fossil fuels will play a less important role. But the carbon in fossil feedstock might be more relevant for the chemical industry.

5.1.2. Key Components of Potential Impact

The depletion of abiotic resources was defined in different ways: a) decrease in the amount of the resource itself, b) decrease in world reserves of useful energy/exergy, or c) an incremental change in the environmental impact of extraction processes at some point in the future (Hauschild, et al., 2011) (Van Oers L. G., 2016) (Finnveden, 1996) (Heijungs, Guinée, & Huppes, 1997).

Following methodological discussions in EF 3.1, fossil fuels were categorized as a distinct type of resource, not comparable to minerals. Consequently, the method was changed to assess fossil fuels in terms of energy consumption without the application of a characterization model, as opposed to being linked with a specific resource characterization model. Therefore, it is termed as “Resource Use, fossils” instead of abiotic depletion, this term will be used for the remainder of the document.

Fossil fuels are used in industry, making it an important energy source. Therefore, it is considered in the category “Resource Use, fossils”.

5.1.3. Regulatory Compliance

Due to European regulatory schemes (e.g., Green Deal), there is a demand to shift from fossil resources to renewables.

5.1.4. Importance for the Chemical Industry

The chemical industry uses a wide range of fossil fuels. They play a crucial role in the chemical industry as important precursors. They are used as raw materials (feedstocks) to produce a wide range of chemicals, including plastics, fertilizers, pesticides, fibers, and personal care products. The chemical industry is one of the big consumers of fossil fuels and is responsible for roughly 3% of global anthropogenic CO₂ emissions (Our world in data, 2020), that are mainly derived from the use of fossil fuels and motivates the industry to reduce the use of them. In addition, among energy intensive industries, the chemical industry is one of the most challenging to defossilize due to the abundance of cheap fossil fuel-feedstocks. Among energy intensive industries, the chemical industry is one of the most challenging to reduce the use of their fossil fuel-feedstocks.

They are not only used as fuel but also as building blocks of products. In this sense, the term “defossilization” not the best term to address.

Due to European regulatory schemes, such as the European Green Deal, there is a strong demand to shift from fossil resources to renewables. The Green Deal aims for climate neutrality, prioritizing the decarbonization of the energy system and building a power sector largely based on renewable sources. The Renewable Energy Directive sets ambitious targets for increasing the share of renewables in the energy mix. Complementary initiatives like the Fit for 55 package and the REPowerEU Plan further accelerate this transition by reducing fossil fuel dependency and promoting clean energy deployment. These policies are supported by substantial investments, signaling a systemic shift toward renewables.

Even though the impact category “Resource Use, fossil” does not consider the reserves of the different fossil resources, the assessment of “Resource Use, fossil” delivers valuable information for the transition of the chemical industry to a more sustainable use of fossil resources, as they are limited. It is therefore essential to use them in a responsible manner to enable future generations to access these feedstocks when other sources are not available. Renewables feedstocks normally have a much lower “Resource Use, fossil” compared to fossil feedstocks, as their inherent feedstock energy is derived from renewable sources, that do not count for “Resource Use, fossil”.

Unlike other energy-intensive industries, the chemical industry cannot be made fully sustainable directly with renewable electricity and green electricity-based hydrogen (e-hydrogen). Therefore, alternative carbon feedstocks, such as biogenic materials, recycled materials or captured CO₂, must be developed to reduce the use of fossil resources in the production of large volume organic chemicals.

Fossil fuels are essential for various processes, including heating, generating steam, and providing raw materials for chemical production. The environmental impact of fossil fuel extraction and the importance of considering “Resource Use, fossil” in environmental assessments is a key element to be more sustainable in the future.

5.2. Methodology of Characterization

In van Oers & Guinée (2016) and van Oers et al. (2002), resource depletion was considered an environmental problem, while recognizing that views differ regarding this topic. The problem was defined as the decreasing natural availability of abiotic natural resources, including fossil energy resources, elements, and minerals.

The Lower Heating Value (LHV) is a crucial property for energy and fuel calculations, indicating the amount of heat released by a fuel during combustion, without accounting for the latent heat of vaporization of water. PEF 3.1 refers to the PEF Guide, version 3.1 (EC, 2021), which provides standardized factors for energy calculations and environmental assessments.

The authoritative LHV values from PEF 3.1 are available in the official PEF documentation, which should be consulted for precise and regulatory-compliant data. Including uranium in the list of fuels ensures that assessments and comparisons encompass all significant energy sources in modern energy systems.

In order to facilitate improved communication between the two communities in the future, it is recommended to use the terms 'resources' and 'reserves' in a consistent manner. In the next chapter only the chosen EF method is described more in detail, whereas the description of other

impact assessment methods as Exergy, Swiss Ecoscarcity and EDIP 1997 can be found in the in the Appendix 21.2.1.

5.2.1. Chosen Method: EF

Based on comprehensive LCIA method evaluations, the abiotic depletion potential for fossil fuels (ADP fossil fuels) by van Oers et al. (2002) as implemented in the CML method is recommended to assess Resource use of fossil fuels in LCA for chemical industry products and materials. The CML method allows for global applicability across diverse regions and markets. Its widespread adoption by international standards and industry guidelines, such as the EF 3.1 method by the European Commission makes it the preferred choice for harmonization efforts across the chemical sector and beyond (Hauschild, et al., 2011). The scope of this impact category specifically addresses fossil fuels and non-renewable energy carriers, with the CML method (CML, 2016) demonstrating methodological stability as it is based on the LHV of fossil resources without requiring frequent updates. In contrast to related methods using the Higher Heating value such as Cumulative Energy Demand- non renewables (CED-non renewables) (Frischknecht, Wyss, Büsser Knöpfel, Lützkendorf, & Baloutski, 2015), focus on LHV represents the amount of energy that can practically be recovered from fossil fuels in industrial applications.

ADP fossil is not used anymore in the EF 3.1 context, so we will use the new term “Resource use, fossil” in this guideline.

Resource use fossil as an environmental impact category reflects the potential depletion of fossil resources due to their extraction and use, but it is not a physical property of the product itself.

For fossil-based products, the “Resource use fossil” value typically exceeds the product’s LHV, because it accounts not only for the fossil content embedded in the product but also for the upstream fossil resource consumption throughout the pre-chain. However, due to allocation rules applied in multi-output processes, it is possible that the calculated Resource use fossil for a specific product is lower than its LHV. This does not imply an error but reflects the chosen allocation method, which shall be applied uniformly across all impact categories.

In such cases, besides Resource use fossil also the LHV can be reported. A comment should be included to explain why the Resource Use Fossil is lower than the LHV, ensuring transparency and enabling accurate modelling in downstream processes*.

Additionally, for products with partial or full biogenic content, the Resource use fossil may be significantly lower than the LHV, since biogenic inputs do not contribute to fossil resource depletion.

Importantly, the total Resource use fossil across all outputs of a process should reflect the actual fossil resource demand. If allocation results in a lower Resource use fossil for one by-product, it will be correspondingly higher for the other by-product(s), maintaining consistency at the process level*.

How to accurately report:

*Proposed text for a comment in the data exchange format: ‘Note that the “Resource use, fossil” value is lower than the LHV of the product. This may be due to e.g. allocation effects and/or due to biogenic content in the product’.

Formula

Based on all the choices described above, the characterization model can be described. The characterization model is based on the LHV of fossil fuels. The method has been made operational for fossil fuels (actually: the energy content of fossil fuels). The assessment reflects the use of fossil fuels. It shall be expressed in Megajoule (MJ) per kg of product. In accordance with the general structure of the LCIA, the impact category indicator results for the impact category of “Resource use, fossils” is calculated by multiplying LCI results, extractions of fossil fuels (in MJ) by the CFs. It is calculated as outlined in the following formula to calculate the “Resource use, fossils” for all fossil materials and inputs:

$$\text{“Resource use, fossils”} = \sum (I_{i-\text{Resource use, fossil}} \times \text{LHV}_{i-\text{Resource use, fossil}}) \text{ [MJ per kg product]}$$

Formula 4: Equation for “Resource use, fossils” calculation

Where:

- $I_{i-\text{Resource use, fossil}}$ = Input of fossil materials (e.g., Oil, gas, coal, lignite, ...) [kg fossil material/kg product]
- $\text{LHV}_{i-\text{Resource use, fossil}}$ = Lower heating value (LHV) per fossil input [MJ/kg fossil material]

The impact of “Resource use, fossils” is, therefore, expressed in MJ per kg product.

Characterization Factor in EF Method

The LCI flows and the respective CFs for the “Resource use, fossils” category are based on the van Oers et al. (2002) model, extracted from EF 3.1 and are presented in Table 5. In case of missing CFs, these values can be used. Specific CFs shall be addressed and used in LCA studies, because these values can differ depending on the quality of the fuel used as well as their regional specifications. The Table 5 shows an overview of existing average numbers for the assessment of the midpoint category “Resource use, fossil”:

Table 5: Overview of average LCI flows recommended*

Flows	CFs (MJ/kg)
Brown coal (Lignite)	12
Hard coal	25
Crude oil	42
Natural gas	49
Peat	8.4
Uranium**	546,000

*Note: Different CFs values were identified for the LCI flows from EF 3.1 depending on the LCA software used. It is recommended to use the latest EF version proposed by the LCA software provider.

**Uranium is included here because, despite not being a conventional combustible fuel, it is a primary energy source in nuclear power generation. Its energy content is not measured by LHV in the traditional sense, as its energy is released through nuclear fission rather than combustion. However, for the purposes of standardized energy comparisons in environmental assessments and lifecycle analyses, the energy released by uranium through fission can be quantified and is sometimes referenced in terms comparable to heating values. This allows for a more comprehensive comparison across all major energy carriers, ensuring that analyses can account for the vast energy potential of nuclear fuels just as they do for fossil fuels and renewables. It was decided in the Technical advisory board of the EU commission to keep it on the list and to generate a kind of LHV which allows a combination with conventional fossil fuels.

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#)

Downloading the files from EF 3.1 can be done by the steps described in Appendix 15.1. This is relevant for all impact categories with the same procedure as outlined here.

Selection guidance for characterization factors

Generally, EF 3.1 provides CFs for elementary flows with different geographical granularity. Based on the LCA software and database used, the geographical granularity of available CFs might vary. Specifically for water scarcity, the underlying characterization method AWARE provides localized CFs on watershed level, while EF 3.1 and most LCA software offer less granularity. Following hierarchy shall be followed when choosing CFs (from most granular to global) depending on the availability:

1. localized (e.g. watershed at water scarcity)
2. country
3. region (e.g. Europe)
4. global

This rationale for selection of available characterization factors is applicable to all sustainability metrics described in this guideline.

5.2.2. LCI Flows

Table 6 shows a few examples of LCI flows for “Resource use, fossil”.

Table 6: Description of relevant LCI flows concerning Resource use, fossil

LCI Flow	Description of Flow
Brown Coal (Lignite)	Brown coal, or lignite, is a type of soft coal that is low in carbon content and high in moisture. It is primarily used for electricity generation in power plants due to its high-water content and lower energy density compared to harder coals. In the chemical industry, lignite can be converted into synthetic natural gas and other chemicals through gasification processes.
Hard Coal	Hard coal, also known as bituminous coal, has a higher carbon content and energy density than lignite. It is widely used in electricity generation and in the production of coke for steel manufacturing. In the chemical industry, it serves as a feedstock for various chemical processes, including the production of chemicals like methanol and ammonia.
Crude Oil	Crude oil is a liquid fossil fuel composed of hydrocarbons and is a primary source for fuels and petrochemicals. In the chemical industry, crude oil is refined into various products such as gasoline, diesel, and feedstocks for producing plastics, fertilizers, and other chemicals.
Natural Gas	Natural gas is a fossil fuel primarily composed of methane. It is used for heating, electricity generation, and as a feedstock in the chemical industry. Natural gas is crucial for producing ammonia (via the Haber process) and methanol.
Peat	Peat is an accumulation of partially decayed organic matter found in wetlands. It is primarily used as a fuel in some regions and can be processed into biofuels. In the chemical industry, peat can be converted into activated carbon and other chemicals, although its use is less common compared to other fossil fuels.
Uranium	Uranium is a heavy metal used as fuel in nuclear reactors. In the chemical industry, it is primarily involved in the production of nuclear energy.

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#).

5.3. Assessment Examples

Figure 5 provides some assessment examples for Resource use, fossils. Following the Formula 4, all “Resource use, fossils” are calculated. For electricity as an example, the efficiency of a factor 3 was used, meaning that 3 MJ primary energy is needed to generate 1 MJ of electricity. This number can vary significantly depending on energy generation technology. For the transfer to kWh which is often used as well, the factor is 3.6. For steam production an efficiency of 90 % is considered and the energy content of 1 kg steam is considered as 2.5 MJ / kg. This varies as well, depending on the production technology and the pressure of steam.

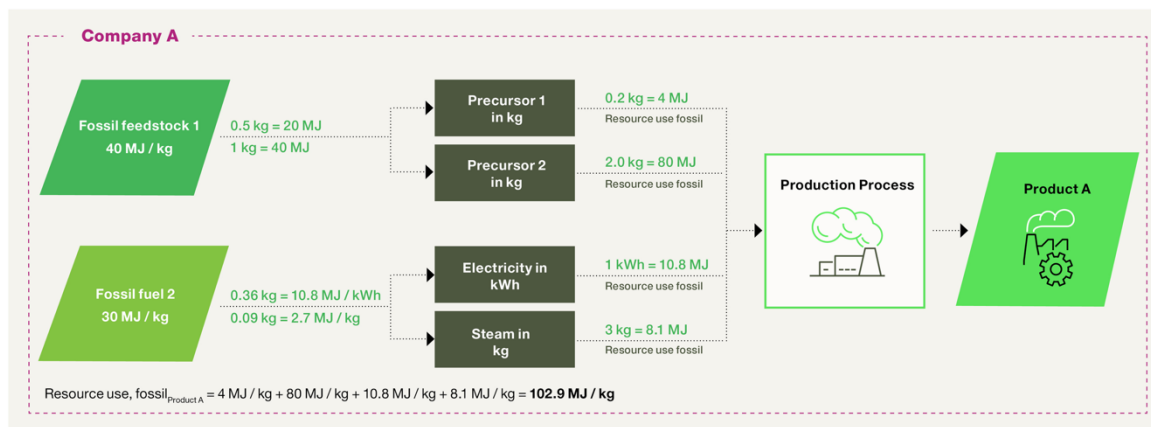


Figure 5: Assessment example for Resource use, fossils



6. Resource use, minerals and metals

6.1. General Description

6.1.1. Issues of Concern

Minerals and metals are fundamental to modern industrial society, forming the basis of infrastructure, technology development, and economic growth. Their use spans construction materials such as steel and cement, as well as critical elements essential for electronics and renewable energy technologies. Their concentrations and accessibility in the Earth's crust vary considerably. Although these formation processes continue, current industrial extraction rates far exceed natural replenishment, rendering these resources effectively non-renewable. Global material extraction has increased more than threefold since 1970, driven by population growth, urbanization, and rising consumption levels (UNEP, 2019). Demand is expected to continue increasing as industrialization and technological innovation accelerate.

Metals such as copper, lithium, and rare earth elements are indispensable for emerging technologies including electric vehicles, wind turbines, and digital devices. Additionally, many mining operations rely on hazardous chemicals, such as cyanide in gold extraction or processes that generate toxic tailings during bauxite refining (UNEP, 2017). This intensifying demand raises concerns about resource depletion, environmental degradation, and social impacts associated with mining activities. Raw materials underpin all economic activity, yet their extraction contributes significantly to greenhouse gas emissions, biodiversity loss, and water stress (EEA, 2024).

Reducing mineral resource depletion therefore constitutes a major technical, social, and economic challenge. The chemical industry depends heavily on these resources for both its infrastructure and its feedstocks. Enhancing resource efficiency, e.g., through the utilization of secondary streams that currently fall below quality specifications, expanded recycling and urban mining, or the development of substitute materials—can help mitigate pressures on abiotic resources (Gabrielli, 2023) (OECD, 2026) (Corder, 2013). Systematic investigation of resource use indicators for minerals and metals is therefore essential. Such indicators quantify material and energy flows and support assessment of environmental burdens across resource life cycles. Improved data availability and methodological consistency are crucial for effective resource management and sustainable policy development (EEA, 2024).

6.1.2. Key Components of Potential Impact

The impact category Resource Use, minerals and metals evaluates the extent to which various metallic and mineral raw materials are extracted during the product life cycle and how this impacts resource depletion. In general, bulk metals, due to their enormous quantities used, as well as rare or critical metals, due to their limited availability and high value, contribute significantly to this category:

- **Iron** is one of the most extensively mined metals worldwide and is generally considered a relatively abundant element. However, the substantial volumes consumed still result in a significant contribution to the overall impact category.
- **Aluminium** is the second most abundant metal in technical applications and widely used. Due to the large production volume, it is also significant to Resource Use, minerals and metals.

- **Copper** is an essential metal for instance for electrical engineering but less abundant than iron. Nevertheless, electrification and renewable energies lead to increasing demand.
- **Precious and special metals like gold, silver, platinum** score highly on resource scarcity indicators due to their rarity, limited substitutability, and finite reserves.
- **Battery raw materials as lithium, cobalt and nickel** have become increasingly important due to the rapid expansion of lithium-ion battery applications. Their extraction has increased significantly, and these metals are less abundant than widely used metals such as iron and aluminium. As a result, they now contribute substantially to the impact category Resource Use, minerals and metals.

A full list of contributors can be found in chapter 6.2.2

6.1.3. Regulatory Compliance

The depletion of minerals and metals is subject to several interconnected international and regional regulations. The EU Critical Raw Materials Act is the most comprehensive EU-level instrument directly addressing the sustainable use of minerals and metals. It establishes strategic targets for domestic extraction and recycling of critical raw materials, explicitly recognizing secondary raw materials as a strategic alternative to primary extraction and incentivizing their recovery from waste streams (EU, 2024). The EU Batteries Regulation (EU, 2023) introduces binding recycled content targets for lithium, cobalt, nickel, and lead, phased in from 2030, and mandates supply chain due diligence addressing environmental risks at the mining stage. For chemical companies producing battery materials, this regulation creates direct compliance obligations for which the assessment of Resource Use, minerals and metals is crucial. The United Nations Convention on the Law of the Sea (UNCLOS) deep seabed regime, administered by the International Seabed Authority, governs extraction of polymetallic nodules, cobalt-rich crusts, and seafloor massive sulfides beyond national jurisdiction, with the objective of preventing marine ecosystem harm (UN, 1982). Its relevance for the extraction of metals such as cobalt, nickel, and manganese might increase further in the future. The Minamata Convention is a global treaty primarily targeting health risks connected to mercury pollution while carrying indirect relevance for co-extracted metals like gold, lead, copper or zinc (UNEP, 2024). It underscores the principle that mineral depletion and metal pollution are intrinsically linked. Across these frameworks, a common requirement emerges: the need for primary data to track the depletion of minerals and metals along the value chain.

6.1.4. Importance for the Chemical Industry

The chemical industry is intensely relying on various minerals and metals. Across its diverse sub-sectors from basic chemicals and polymers to specialty chemicals, catalysts, and battery materials, minerals and metals serve as indispensable raw materials, catalysts, and functional additives. This structural dependency makes the impact category Resource use, minerals and metals particularly relevant for chemical companies. Use of metal-based catalysts as key process enablers represents a significant source of mineral depletion in chemical production. Transition metals such as Platinum group metals are widely used as catalysts in chemical synthesis and refining. Despite often being used in relatively small quantities and recyclability, their scarcity can make them notable contributors to this impact category. Mineral-based raw materials and additives constitute a further relevant area. Inorganic pigments and mineral fillers such as titanium dioxide, zinc compounds, or sulfates are used across coatings, plastics, and

specialty chemical formulations. Each of these materials carries a measurable depletion contribution that can accumulate significantly across large production volumes. Quantifying the resource use of minerals and metals is a useful tool for identifying material hotspots and guiding more resource-efficient decision-making across the chemical value chain.

Circularity strategies such as recycling, reuse and the use of secondary raw materials help preserve those resources by reducing the need for virgin extraction.

6.2. Methodology of characterization

The impact category “Resource use, minerals and metals” is based on the Abiotic Depletion Potential (ADP) for elements originally developed by van Oers et al. (2002) and further discussed by van Oers and Guinée (2016). Both references defined resource depletion as decreasing availability of abiotic natural resources, including fossil energy resources, elements, and minerals, while at the same time recognizing that views may differ regarding this topic. The impact category discussed in this chapter quantifies the potential depletion of mineral resources. In this framework, antimony (Sb) is used as a reference substance for normalization purposes, and results are therefore expressed in kg Sb-equivalent. This choice enables aggregation and comparison across different mineral and metal resources without implying physical consumption or criticality of antimony itself.

To improve future communication, we recommend using the terms “resources” (natural stocks) and “reserves” (economically recoverable subset) consistently. A detailed description of the chosen method is provided in the next chapter.

6.2.1. Chosen method: EF

Based on comprehensive LCIA method evaluations and alignment with EU guidance, the recommended method to assess Resource use, minerals and metals is the EF 3.1 midpoint indicator implemented as ADP (elements). It is expressed in kg Sb-eq (EC, 2021) and uses characterization factors derived from the use to availability ratio considering ultimate reserves (Van Oers L. G., 2020). This method is maintained within the EF reference packages and updated by the European Commission’s JRC; users shall apply the official EF 3.1 CF set for consistency and comparability across studies.

The category builds on the ADP framework developed at CML/Leiden (CML 2002 and subsequently revised 2016+, 2019/2020) to incorporate updated ultimate reserves and production data. EF adopts the elements (non-fossil) branch, separate from fossil energy carriers, to reflect mineral/metal scarcity through a normalized proxy (kg Sb-eq) (European Commission, JRC, 2023).

The indicator covers primary extraction of minerals and metals (e.g., Fe, Al, Cu, Ni, Co, Li, Pt-group metals, rare earths). It excludes fossil resource energy carriers (covered by Resource use, fossil) and biotic resources.

Formula

“Resource use, minerals and metals” [kg Sb-eq] = $\sum_i (m_{i, \text{extracted element}} [\text{kg}] \times CF_i [\text{kg Sb-eq per kg}])$

Formula 5: Equation for “Resource use, minerals and metals” calculation

Where:

- $m_{i, \text{extracted element}}$ = mass of element i extracted from nature (elementary flow, “in ground”).
- CF_{i-} = EF 3.1 characterization factor for element i (Sb as reference)

The impact indicator is expressed in kg **Sb-eq per declared unit (1 kg or product)**. This differs from Resource use, fossil, which is expressed in MJ based on LHV.

Characterization factors in EF method

The LCI flows and the respective CFs for the “Resource use, minerals and metals” category are based on the van Oers et al. (2002) model, extracted from EF 3.1. Selected characterization factors for impact category Resource use, minerals and metals are presented in Table 7. In case of missing CFs, these values can be used.

Table 7: Overview of selected average LCI flows recommended

Flows	CFs (kg Sb-eq. per kg)
Aluminium see Bauxite at EF 3.1	1.09E-09
Antimony	1.00E+00
Cadmium	1.57E-01
Cobalt	1.57E-05
Copper	1.37E-03
Gold	5.20E+01
Indium	6.89E-03
Iron	5.24E-08
Lithium	1.15E-05
Nickel	6.53E-05
Palladium	5.71E-01
Phosphorus	5.52E-06
Platinum	2.22E+00
Silver	1.18E+00
Titanium	2.79E-08

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#)

Downloading the files from EF 3.1 can be done by the steps described in Appendix 15.1. This is relevant for all impact categories with the same procedure as outlined here.

Selection guidance for characterization factors

In general, EF 3.1 provides characterization factors (CFs) for elementary flows of individual elements. In contrast, inorganic compounds and aggregates, such as chlorides, sulfates, nitrates, and carbonates, are assigned a characterization factor of 0.00E+00 kg Sb-eq. per kg.

In this respect, EF 3.1 deviates from the recommendations of the CML 2001 methodology. The implications of this approach can be illustrated using sodium chloride (NaCl) as an example (Table 8). According to CML (2016), the characterization factor for NaCl is derived from the weighted contributions of its constituent elements, sodium and chlorine. In EF 3.1, however, the compound itself is assigned to be a characterization factor of zero, while characterization factors are only available for the individual elemental flows.

Table 8: Resource use, minerals and metals for sodium chloride (rocksalt)

Substance/element	NaCl	Na	Cl ₂
Mass in kg/kg NaCl	1.00	0.39	0.61
CF acc. to CML (CML, 2016) in kg Sb-eq./kg	1.65E-05*	5.50E-08	2.71E-05
CF acc. to EF 3.1 in kg Sb-eq./kg	0.00E+00	5.50E-08	2.71E-05

* = $5.50\text{E-}08 \text{ kg Sb-eq./kg} \cdot 0.39 \text{ kg} + 2.71\text{E-}05 \text{ kg Sb-eq./kg} \cdot 0.61 \text{ kg}$
 = $1.65\text{E-}05 \text{ kg Sb-eq./ 1 kg NaCl}$

Nevertheless, life cycle assessment software may report non-zero results for the impact category Resource use, minerals and metals. These values typically originate from upstream co-extraction processes rather than from the assessed substance itself. For example, the extraction of copper is frequently associated with the recovery of precious metals such as gold, silver, and platinum. Consequently, copper sulfate may not have a CF for resource use, minerals and metals, while significant contributions to this impact category can arise from the extraction of associated metals from the same geological deposit.

Given the chemical industry's strong dependence on mineral resources, assigning a CF of 0.00E+00 kg Sb-eq. per kg to many mineral compounds may lead to misleading interpretations regarding the availability of abiotic resources. In particular, a value of zero may be perceived as indicating an abundant resource with no depletion risk, although this does not necessarily reflect the actual resource situation. In the NaCl example, the use of zero in a Chloro-Alkaline Electrolysis results in a zero Resource use, minerals and metals consumption whereas the CML approach clearly indicates consumption. In cases where chemicals are compared in LCA to other materials like e.g. Copper, the Resource use, minerals and metals can be zero, whereas the chemicals alternative has an impact to the Resource use, minerals and metals probably by using a catalyst. Therefore, alternative assessment methods presented in Appendix Chapter 21.3 can be used.

6.2.2. LCI Flows

Table 9: Description of selected relevant LCI flows concerning Resource use, minerals and metals

LCI Flow	Description of Flow
Aluminium	Aluminium is a lightweight metal used for corrosion-resistant equipment, reactors, and packaging. Often used in catalysts and as aluminium compounds in water treatment.
Antimony	Antimony is mainly used in flame retardants and alloys. In the chemical sector, antimony compounds act as catalysts for PET (polyethylene terephthalate) production.
Cadmium	Cadmium is applied in specialty alloys, pigments, and stabilizers. Cadmium compounds are also used in electrochemistry and coatings, though use is declining due to toxicity.
Cobalt	Cobalt is important for catalysts (e.g., in oxidation reactions), battery materials, and high-strength alloys. Essential in petrochemical and polymer production processes.
Copper	Copper is used for electrical equipment, heat exchangers, and corrosion-resistant components. Copper compounds serve as catalysts and biocides.
Iron	Iron is a basic construction material for chemical plants (steel reactors, pipelines). Iron salts are used in water treatment and as catalysts in chemical synthesis.
Lithium	Key component in lithium-ion batteries and used in high-purity lithium salts for polymers, ceramics, and specialty chemicals.
Nickel	Nickel is used for corrosion-resistant alloys and catalytic hydrogenation processes. Nickel catalysts are essential in petrochemical and fine-chemical production.
Palladium	Palladium as precious metal catalyst is widely used in hydrogenation, dehydrogenation, and cross-coupling reactions (e.g., Suzuki reactions). Important in pharmaceuticals and petrochemistry.
Phosphorus	Phosphorus is used in fertilizers, flame retardants, detergents, and metal treatment. Phosphorus compounds play a key role in organic synthesis.
Platinum	Platinum as high-performance catalyst for oxidation, hydrogenation, and fuel-cell reactions. Common in petroleum refining and specialty chemical production.
Silver	Silver is known for excellent electrical and thermal conductivity. Used in catalysts for ethylene oxide production, coatings, and specialty electronics.
Titanium	Titanium is mainly used as titanium dioxide for pigments, coatings, and plastics. Metallic titanium is used for corrosion-resistant equipment in chemical plants.

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#).

6.3. Assessment Examples

A simplified example for Resource Use, minerals and metals is the production of 1 kg of a hydrogenation catalyst, where 200 g nickel and 5 g palladium is required. Even though much less palladium is used, it contributes most of the resource impact because precious metals have very high CFs.

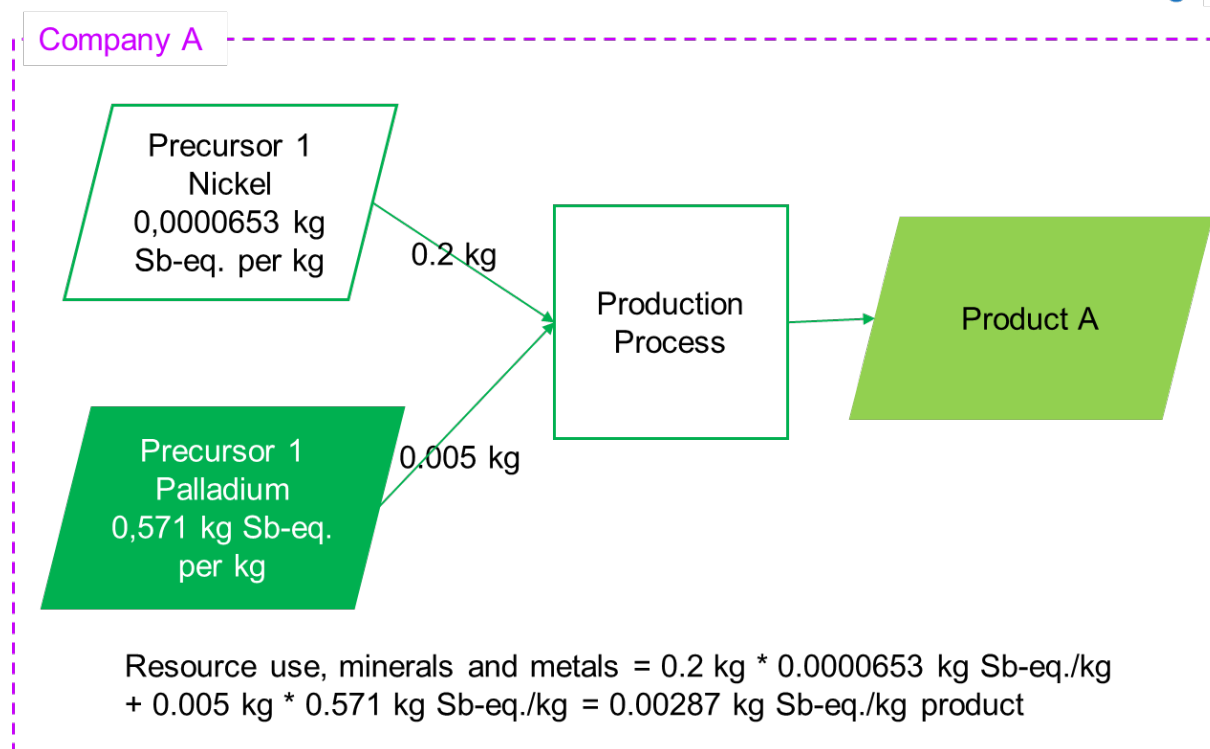


Figure 6: Resource use, minerals and metals calculation of hydrogenation catalyst

7. Water Scarcity

7.1. General Description

Water is an indispensable resource for life and a critical input for numerous industrial processes, including chemical production. The sustainable management of water resources has become a significant concern, considering the increasing demand and the impact of water scarcity on the environment and society. Water scarcity is an important impact category in LCA and is being increasingly included in environmental assessments

Comparable to the Product Carbon Footprint which is an LCA study focusing on only one environmental impact, a water footprint (ISO 14046, 2014) is defined as metric(s) that quantifies the potential environmental impacts related to water within LCA. If water-related potential environmental impacts have not been comprehensively assessed, then the term “water footprint” can only be applied with a qualifier. A qualifier is one or several additional terms used in conjunction with the term “water footprint” to describe the impact category/categories studied in the water footprint assessment, e.g. “water scarcity footprint”, “water eutrophication footprint”, “non-comprehensive water footprint”⁶. This chapter delves into the concept of water scarcity within the framework of LCA and its application in the chemical industry. Water scarcity as described in this guideline is considered a non-comprehensive water footprint.

7.1.1. Issues of Concern

According to ISO 14046 water scarcity is defined as the extent to which demand for water compares to the replenishment of water in an area, e.g. a drainage basin, without considering the water quality.

According to Joint Research Centre (JRC), water scarcity assesses water use impacts by considering both consumption and regional water stress levels (JRC, 2018). The Figure 7 shows the relation between Water use, Consumptive Water and Water Scarcity. The water scarcity can therefore be calculated by multiplying the inventory data of water consumption with the CF of the country. Relevant CFs are defined by different LCIA methodologies.

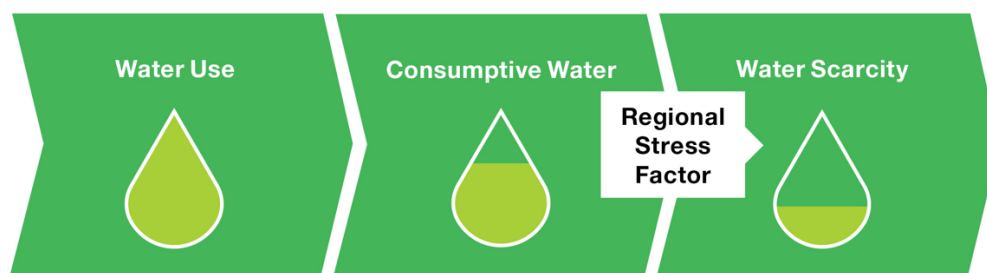


Figure 7: Definition of water scarcity footprint

⁶ The principle of comprehensiveness implies to consider all environmentally relevant attributes or aspects of natural environment, human health and resources related to water, including water availability and water degradation.

According to ISO 14046:2014, Consumptive Water Use refers to the volume of freshwater withdrawn and not returned to the same watershed. Water consumption can be because of evaporation, transpiration, integration into a product, or release into a different drainage basin or the sea. Change in evaporation caused by land-use change is considered water consumption (e.g. reservoir).

The environmental impact of water consumption largely depends on the availability of water in a given country where the process is located. Using water in areas with plentiful resources typically has different consequences than in countries facing water scarcity. These differences are captured through water stress indicators from countries where water is used in the life cycle of a product. This assessment method focuses exclusively on the quantity of water used.

7.1.2. Key Components of Potential Impact

Water scarcity can have significant effects on ecosystems (destruction of aquatic habitats and effects on biodiversity), human health (malnutrition and infectious diseases) and natural resources (depletion of water reserves for future generations).

Integrating water scarcity into environmental assessments is crucial for promoting sustainable water management practices. It allows for a comprehensive understanding of how water resources are utilized and helps in the development of policies and strategies that balance water use with conservation. This can include initiatives such as efficient irrigation techniques, water recycling programs, and the promotion of water-saving technologies.

Water scarcity issues in many countries or regions are getting very important nowadays. Changes in precipitation patterns, increased evaporation rates, and the frequency of extreme weather events can all influence water availability.

When water is diverted from rivers, lakes, or aquifers for consumptive purposes, the reduced water availability can impact aquatic habitats, alter water temperature, and affect the quality of the remaining water. These changes can threaten the survival of fish and other aquatic organisms, disrupt breeding and feeding patterns, and lead to the degradation of wetlands and riparian zones (EC, 2025).

7.1.3. Regulatory Compliance

Water scarcity represents critical global challenges in sustainable resource management, prompting the European Union and other jurisdictions to establish regulatory frameworks aimed at preserving freshwater availability and promoting responsible water use. The Water Framework Directive (EU, 2015) provides a comprehensive basis for water resource protection, requiring Member States to assess and manage water quantity alongside quality, and to ensure sustainable abstraction and use of water bodies to achieve “good status”. In parallel, the Groundwater Directive (EU, 2006) complements these efforts by regulating groundwater abstraction and preventing overexploitation, thereby safeguarding long-term water availability.

To address agricultural pressures on water resources, the Common Agricultural Policy (CAP) incorporates water-related conditionalities and incentives for efficient irrigation practices, drought-resilient cropping systems, and water-saving technologies. These measures align with broader EU goals for climate adaptation and resource efficiency.

Globally, water scarcity has driven policy responses such as the U.S. WaterSMART Program, which promotes water conservation and reuse in drought-prone regions, and the UN Sustainable

Development Goal 6, which calls for universal access to clean water and sustainable water management. These initiatives reflect growing recognition of water footprint as a key environmental indicator in LCA, especially in countries facing hydrological stress.

7.1.4. Importance for the Chemical Industry

The chemical industry uses significant amounts of water, with applications ranging from chemical synthesis to cooling and cleaning. The sector's water use is broadly categorized in Table 10. More information can be found in CORDIS - EU research results (EC, 2016).

Not for review

Table 10: Water usage categories within chemical industries

Category	Description	Example
Chemical Synthesis	Water is a crucial reactant and solvent in many chemical processes. It facilitates reactions, dissolves reactants, and helps in the separation and purification of products.	In the production of ammonia through the Haber process, water is used to generate hydrogen via steam reforming natural gas.
Heating and Cooling Systems	Cooling and heating are vital for maintaining operational safety and efficiency in chemical plants.	Water is used in cooling towers, as heat exchangers, and in other cooling systems to dissipate heat generated during exothermic reactions and mechanical operations.
Cleaning and Maintenance	Water is essential for cleaning equipment, maintaining hygiene standards, and preventing contamination between production batches.	High-purity water is often required to meet stringent quality standards.
Waste Treatment	The chemical industry generates various effluents that require treatment before discharge or reuse.	Water is used in the treatment processes, including dilution, neutralization, and biological treatment.
Steam generation and condensation	Steam in the chemical industry refers to steam that is produced on-site or off-site, which is then used for heating, power generation, or driving equipment.	Typically, freshwater is used to produce steam. A closed circuit helps to recover steam condensate. However, any loss of steam condensate should be replaced with fresh water.
Evaporation	Some chemical processes produce water vapor, which is water evaporated from the process. In addition, evaporation can be used for cooling. Evaporated water is usually not directly emitted back to the water body / basin where the water initially comes from	While using the spray drying process, for example by producing dispersible polymer powder, water vapor occurs which sometimes evaporates without further use.
Water in products	The chemical industry also produces aqueous based products via emulsion-based polymerization. The water contained in products as raw material usually is consumptive water.	Aqueous dispersion, solutions,

Note: The table contains non-exhaustive list of examples for water scarcity and therefore might not cover all categories relevant for the water scarcity application.

7.2. Methodology of characterization

This section outlines the approach used to characterize water use impacts in accordance with international standards and best practices. It begins with relevant ISO guidance, followed by the rationale for selecting the Environmental Footprint (EF) method as the primary LCIA methodology for water footprint. Finally, it explains how the EF method is applied in practice to quantify the water footprint.

7.2.1. Chosen method: EF

ISO 14046:2014 outlines the principles, requirements, and guidelines for conducting a water footprint assessment within the framework of environmental LCA. ISO 14046 uses ISO 14040:2006 and ISO 14044:2006 as normative references and applies all general principles of these standards

The ISO standard addresses both consumptive water use, and water-related impacts, such as water scarcity. It emphasizes the local context of water availability and scarcity, recognizing that the same quantity of water use can lead to different impacts depending on the location.

Although ISO 14046 does not prescribe a specific LCIA method for water-related impacts, it provides a conceptual framework for applying scientifically validated models. These models typically use data on water availability and withdrawals to quantify water scarcity level, which is usually done with the geographical resolution on water basin and country level.

To support alignment with international best practices and ensure regionally sensitive assessments, the AWARE (Available WATER REmaining) method was developed in accordance with ISO 14046 (Boulay, Bare, & Benini, 2018). It also serves as the basis for the water scarcity indicator used in the EF method developed by the European Commission. While water scarcity category in EF is derived from AWARE, it includes modifications to the original CFs to improve the differentiation of countries and to align with the European Union's policy goals and data quality standards.

Choosing the EF method over the standalone AWARE approach supports greater consistency with other environmental impact categories assessed under the EF framework and facilitates broader acceptance and comparability of results. Given its widespread application in product-level environmental assessments and alignment with both ISO standards and European guidance, EF provides a robust and harmonized basis for evaluating water scarcity impacts in life cycle assessments.

These models are based on the pre-selected methods reported in the ILCD Handbook (Hauschild, et al., 2011).

Furthermore, it's the only available compilation of characterization methods covering the whole breadth of 16 impact categories, and which is subject to a scientifically maintained cross consistency check (through JRC).

In the Environmental Footprint (EF) method, Water Scarcity is represented as Water Use. This should not be mixed with simple water consumption that ignores local water stress levels.

The EF 3.1 indicator follows ISO 14046 standards and measures how water use in a specific country may limit availability for other users—both people and ecosystems. It reflects the potential impact of water scarcity at the midpoint level.

Formula

The EF method calculates Water Scarcity impact using the following formula:

$$\text{Water Scarcity [m}^3 \text{ world eq.]} = \text{Consumptive Water Use [m}^3] \times \text{EF water scarcity CF [m}^3 \text{ world eq./m}^3]$$

Formula 6: Equation for “Water Scarcity” calculation

Where:

- Consumptive Water ⁷Use refers to the volume of freshwater withdrawn and not returned to the same watershed (e.g., via evaporation, incorporation into products, or transfer to other basins or the sea).
- EF 3.1 CFs are applied based on the geographic origin (Country level) of water use.

The resulting unit, m³ world equivalent, facilitates comparison across different countries and systems.

Remark: water that is generated in a chemical reaction contribute negatively to consumptive use and reduces the consumptive water use of a process if this water is captured and transferred to a watershed.

Characterization Factor in EF Method

In the EF method, each country is assigned a CF that reflects its relative water scarcity, normalized against the global average. A CF of 1 represents the global average water scarcity level. In practice, CFs range from 0 (no scarcity) to well above 1, even reaching values near 100 in extremely stressed countries. These CFs are determined using hydrological models such as WaterGAP3 and account for water availability, sectoral demand, and environmental flow needs.

Official EF 3.1 CFs are maintained by the European Platform on Life Cycle Assessment (EPLCA) and are available as part of the EF LCIA method documentation:

- EF 3.1 reference package spreadsheet can be downloaded from <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html>
- CFs can be assessed by geographically defined countries, ensuring as much as possible accurate assessments.
- Practitioners can integrate CFs directly or use them via LCA software platforms that support the EF method.

It should be noted that water scarcity can vary significantly within a country. Companies can choose a more specific CF if the source of this CF is referenced. Although this is a slight deviation from the EF method, it is important to allow increased specificity where available.

⁷ In some sources, this may be referred to as blue water consumption. However, we adopt the ISO terminology for consistency with international standards

If the region where the emission occurs is known, use the regionalized factors. For regionalized figures see guidance on page 17.

Selection Guidance

In the spreadsheet “Cradle to Grave Template with EI 3.10 Emission Factors”, tab “lciamethods_CF”, CFs are provided for specific water flows and countries. Notably, the same specific values may appear as either positive or negative, depending on whether the water flow represents an input or output for that country. This approach ensures that the water mass balance is maintained across the modeled product system.

To correctly select and apply the appropriate CFs in each calculation, the following considerations are important:

- For practitioners using standard background databases available on the market as sources of secondary data, CFs are typically pre-selected and applied within the datasets. However, these background databases may carry uncertainties regarding the country and flow-specific granularity of CF application. In the absence of primary data, such limitations are acknowledged, and these datasets are treated as the best available solution.
- For practitioners modeling foreground processes, it is essential to know the country associated with each individual inflow and outflow of water.
- If all water flows pertain to the same country, net consumptive water use can be calculated and multiplied by the positive CF provided by the EF method for that country.
- However, if the origin and/or destination of water flows differ across countries, it is critical to apply the correct CF based on both the flow name and corresponding country. This ensures an accurate water balance and appropriate characterization of water use across the product system.

7.2.2. LCI Flows

Calculating water scarcity is a critical aspect of understanding and managing water usage in various processes and products. LCI flows play a pivotal role in this calculation, as they provide the necessary data on the inputs and outputs associated with water use.

To assess water scarcity impacts, LCI data should ideally be collected with spatial resolution, preferably at the watershed or basin level. However, in alignment with the EF method, which applies country-level CFs, this document focuses on the collection of annual, country-specific water use data. This approach is deemed as adequate to achieve scale in the water scarcity assessment at current levels of data availability.

If water is qualified as freshwater, it typically contains less than 1 000 mg/l of dissolved solids and is generally accepted as suitable for withdrawal and conventional treatment to produce potable water. If the water quality is changed from freshwater to brackish water (1 000 mg/l to 30 000 mg/l) or to seawater (concentration of dissolved solids greater than or equal to 30 000 mg/l), this is considered as consumptive water use.

In Table 11 the key LCI flows needed for the calculation of a water footprint, along with precise examples, are shown:

Table 11: Checklist of Water Flows for Consumptive Use Assessment (Aligned with EF method – country-level resolution)

Water Use Element	Examples	Data Required	Contributes to Consumptive Use? ⁸
Water input from environment ^{6, 7}	River, lake, groundwater withdrawal	Source type, country, volume	No
Water from water supply system	Municipal supply	Supplier, country of withdrawal, volume	No
Water incorporated into product ^{9,10}	Water contained in final product	Estimated or measured volume	Yes
Evaporation	Boiling, drying, cooling towers	Estimated volume	Yes
Water lost via drift or leaks	Open systems, faulty pipes	Estimated volume	Yes
Water transformed, chemically bound or contained	Chemical reactions (consumed or produced), incorporated in waste	Volume, transformation description	Yes
Return to same country*	Discharge to surface or sewer	Volume, water quality, receiving country	No
Return to a different country	Discharge across borders (e.g., via pipeline)	Volume, receiving country	Yes
External wastewater treatment	Sent off-site for treatment	Volume, treatment type, discharge country	Possibly, depends on final quality ⁶
Onsite recycled/reused water	Cooling systems, process loops	Volume reused	No
Stormwater harvested	Rainwater used in processes	Volume used, purpose	No
Incidental water uses	Firefighting or spills		Possibly ¹¹

⁸ Water generated during chemical reactions in a process reduces overall consumptive use (negative consumptive use), as it adds to the available water rather than depleting it.

⁹ if fully returned in usable quality

7.2.3. Data Granularity

Water Balance and Cut-off Criteria

To ensure data consistency and completeness, a water balance check should be performed across the system boundaries. The relative difference between total water inputs and outputs should not exceed 5% in absolute value, which is considered acceptable based on best practice in water footprinting. Flows below this threshold are considered negligible and are excluded only if they have no significant influence on the overall results. All exclusions should be transparently documented and justified to maintain methodological robustness.

As a best practice, conservative assumptions and adjustments may be applied to water flow data to correct imbalances (>5%) and ensure a closed water balance (section 6.2.4.1.1).

Corrective Considerations for Surplus Water Outputs

In cases where the water balance shows more water output than input, a discrepancy may exist that warrants further investigation. While such imbalances may arise from measurement errors or data gaps, they can also result from physical or chemical phenomena that are not always captured in initial flow inventories. The following corrective approaches outline common causes and recommended methods for resolution.

Case 1: Water Formation Through Chemical Reactions

In certain processes, water is generated as a byproduct of chemical reactions (e.g., condensation reactions, neutralizations, or combustion). This additional water may appear in the output flows (e.g., wastewater, steam, or emissions), leading to an apparent surplus relative to measured inputs.

Recommended Action: Perform a stoichiometric analysis of the relevant chemical reactions to quantify the amount of water produced. If the calculated water formation aligns with the imbalance, it is considered a valid explanation. The result should be documented and included as an internal source of water in the inventory.

Case 2: Water Content in Raw Materials

Some input materials may contain inherent moisture (e.g., wet biomass, slurries, agricultural products) that are not initially accounted for as a separate water input. This moisture can be

¹⁰ Note on water quality:

- If return water is degraded to the point that it is no longer usable, it is functionally lost and should be counted as consumptive.
- If water undergoes adequate on-site or off-site treatment before discharge, it is considered returned in usable form and thus non-consumptive.
- If water is discharged with pollutants exceeding regulatory or ecological thresholds, it may be considered fully consumptive (in practice, partial consumptiveness is generally not accounted for in LCA databases).

¹¹ Incidental water uses, such as firefighting or spills, are excluded from LCI unless they are frequent, systemic, and materially significant at the product level.

released during processing and counted as part of water output (e.g., in evaporated or discharged streams).

Recommended Action: Review the moisture content of raw material inputs and estimate the corresponding water mass using material specifications or literature data. Adjust the water input inventory accordingly to account for this internal water source.

Case 3: Rainwater Entering Water Output Flows

In some cases, rainwater may unintentionally be included in measured water outputs, particularly in outdoor or open-system facilities where stormwater enters wastewater drains, surface runoff collection systems, or treatment infrastructure. This can result in apparent excess output water volumes relative to the reported input water, thus distorting the water balance.

This is particularly relevant in methodologies such as the EU PEF, where rainwater is not characterized with any water scarcity impact factor. Including rainwater in output flows without adjusting the inventory can lead to misinterpretation of results, specifically:

- Artificially high output volumes that appear to "offset" consumptive water use.
- Incorrect attribution of negative water scarcity impacts (credits).
- **Recommended Action:** Identify if the water output streams include rainwater contributions.
- Estimate the volume of rainwater using local precipitation data, catchment area dimensions, and runoff coefficients.
- Deduct the calculated rainwater volume from the water output inventory.

Example: If a facility discharges 5,000 m³ of water annually and 500 m³ is estimated to originate from rainwater collected on impermeable surfaces, only 4,500 m³ should be reported as water output for water scarcity impact modeling.

Corrective Considerations for Surplus Water Inputs

In situations where the water balance indicates a higher total water input than output, this suggests that certain water losses or transformations have not been fully captured in the system inventory. These imbalances must be addressed to ensure consistency and to avoid underestimating water consumption or misleadingly low water scarcity impacts. The following are common causes and corrective measures for surplus water inputs.

Case 1: Unaccounted Water Evaporation or Transpiration

Water losses due to evaporation (e.g., from cooling towers, open tanks, cleaning processes) or transpiration (e.g., from agricultural crops) may not always be measured directly and can lead to an apparent deficit in water outputs. These flows are considered consumptive uses and must be accounted for in the output inventory to maintain an accurate water balance.

Recommended Action: If there is more input water than output water, consider scaling up the average water output, such as evaporated water and/or wastewater, in proportion to your average water outputs.

- Identify processes where evaporation or transpiration likely occurs.
- Add the estimated water vapor as an elementary flow to air in the water output inventory.

In a chemical plant, 1,000 m³ of water is input, and only 850 m³ is accounted for in discharge and product incorporation. The missing 150 m³ is likely lost through evaporation in the unit process. This volume should be added as water vapor output to air, closing the water balance and ensuring accurate accounting of consumptive use.

Case 2: Water Incorporated into Byproducts or Waste Streams

In some cases, water may leave the system via byproducts, residues, or waste that was not originally considered part of the product system. If water content of these streams is not well defined by the water inventory, they can result in unaccounted water losses.

Recommended Action:

- Review whether any moisture-containing byproducts (e.g., sludges, organic waste, co-products) are leaving the system unaccounted for.
- Estimate water content using material specifications or standard moisture content values.
- Adjust the output inventory to reflect this water flow.

Water Loss Estimation

Water losses through evaporation commonly occur in cooling and heating systems, including cooling towers and steam generation processes (section 6.1.4). Due to the inherent difficulty in accurately measuring water vapor emissions, precise quantification is often challenging. In situations where actual evaporation rates are unknown or unavailable, it is considered best practice to apply estimated default values to account for evaporative water losses, ensuring consistency and conservatism in the water balance. However, these default evaporation rates are suggested, but the LCA practitioner is not limited to use if better estimates are available.

Table 12: Default water loss estimation when primary data is missing. Estimations are based on expert judgement.

Input flow	Default consumption rate
Water for steam production, closed system	5% of input value
Cooling water (approx. 20°C), (Closed circuit with cooling tower)	2% of input value
Cooling water (approx. 5°C), (closed circuit without cooling tower)	1% of input value
Process water	7% of input value
Cleaning water	30% of input value

Cleaning Water: stream of water used to clean equipment, reactors, pipelines, containers, and production areas.

Process Water: is the water used directly in chemical manufacturing operations to enable, carry out, or influence chemical reactions and process conditions.

Cooling Water: is water used to remove excess heat from chemical processes, equipment, or utilities in order to maintain safe operating temperatures, ensure process stability, and protect equipment integrity. It does not participate in the chemical reaction itself; instead, it serves as part of the thermal management system.

Water for Steam Production: is water that is treated and supplied generate steam used as a thermal utility in chemical manufacturing.

7.3. Assessment Examples

This example shows how to estimate the water scarcity impact of producing 1 ton of solvent at a chemical plant in Spain (gate-to-gate¹² system boundary).

Water balance from site inventory:

Table 13: Example water scarcity

Input	
Water flow	Volume [m ³]
Cooling tower	5.0
Process water	3.0
Boiler water for steam	2.0
Cleaning water	1.0
Output	
Cooling water returned to network	4.0
Process water returned to river	2.8
Steam condensate to network	1.8
Cleaning water returned to river	0.9
Evaporation	0.9
Water lost via drift or leaks	0.4
Water bound in product	0.2

9.5 m³

Water balance:

Total water inputs = $5.0 \text{ m}^3 + 3.0 \text{ m}^3 + 2.0 \text{ m}^3 + 1.0 \text{ m}^3 = 11.0 \text{ m}^3$

Total water outputs = $4.0 \text{ m}^3 + 2.8 \text{ m}^3 + 1.8 \text{ m}^3 + 0.9 \text{ m}^3 + 0.9 \text{ m}^3 + 0.4 \text{ m}^3 + 0.2 \text{ m}^3 = 11.0 \text{ m}^3$

¹² The calculation is performed gate to gate to facilitate the understanding of practitioners. Therefore, the same procedure should be performed for the supplied material and energy (suppliers water consumption) and being summed up with this gate-to-gate calculation to entail the cradle to gate calculation needed for the product level water scarcity.

Step 1: Calculate Consumptive Water

Consumptive water = Total water inputs – Total water returned to environment (except the sea) =
 $11.0 \text{ m}^3 - 9.5 \text{ m}^3 = 1.5 \text{ m}^3$

Step 2: Obtain EF CF

From EF 3.1 environmental footprint reference packages, obtain CF for Spain:

CF = $77.7 \text{ m}^3 \text{ world eq./m}^3$

Step 3: Calculate Water scarcity

Water scarcity Impact = consumptive water use x CF = $1.5 \text{ m}^3 \times 77.7 \text{ m}^3 \text{ world eq./m}^3 = 116.6 \text{ m}^3 \text{ world eq. per ton solvent.}$

Not for review

8. Acidification Potential

8.1. General Description

8.1.1. Issue of Concern

Acidification refers to the process by which acidic substances are introduced into the environment, leading to a decrease in pH levels. This phenomenon is primarily caused by the emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3), which can result from various chemical processes, industrial activities (e.g., fuel and coal combustion) as well as agricultural activities (e.g., through fertilizers) (Gade, Hauschild, & Laurent, 2021). When these compounds are released into the atmosphere, they can react with water vapor to form sulfuric acid, nitric acid, and other acidic compounds, leading to acid rain and other forms of acid deposition. Acidification potential (AP) refers to the compounds that are precursors to acid rain. Acidification occurs with substances varying in their acid formation potential. This guideline emphasizes terrestrial acidification as it represents the initial stage of preceding ocean acidification.

Acidification has a wide range of negative effects on both natural and human environments, and it is regarded as a regional effect. It is caused by the release of protons in terrestrial or aquatic ecosystems. The acidifying substances are only contributing to acidification if the anion is leached out from the system. Organic acids predominantly are mineralized and do not leach to the system; accordingly, they are not regarded as contributors to acidification. In certain areas, acidification leads to increased mobility of heavy metals and aluminium. Acid rain, resulting from airborne acidifying substances, can affect ecosystems hundreds of kilometers from original emission sources. Acidic deposition on land, either direct or via acidic precipitation, initiates significant changes in soil chemistry. Primary effects include a decrease in soil pH, altered bioavailability of essential plant nutrients (like calcium and magnesium), or enhanced leaching of critical nutrients. Premature shedding of leaves and needles, disruption of photosynthesis, impaired plant growth and development, and reduced overall ecosystem health and resilience are only some negative aspects of acidification (Zhang, et al., 2023). A shift in soil pH might also cause leaching of ecotoxic minerals and metals, e.g., Aluminium (III) or heavy metal ions, ultimately leading to a decrease of biodiversity and bio-productivity in affected areas. While this also affects agricultural plant growth, acidification has negative implications for food safety as well (Chen, Lan, Bai, Grace, & Bai, 2013). Besides affecting plant growth (Shi, et al., 2021), acid rain can also corrode buildings, monuments, and other infrastructure, leading to economic losses (Pawłowski, 1997). The hydrological transport of acidifying compounds creates significant impacts on aquatic environments, e.g., due to lowering the pH in water bodies (Baker & Christensen, 1991). So, acidification can harm fish and other aquatic organisms by disrupting their reproductive processes and causing physiological stress (Gade, Hauschild, & Laurent, 2021) (Baker & Christensen, 1991). Furthermore, it can negatively impact human health, particularly respiratory health, due to increased exposure to harmful pollutants (UNECE, 2012) (EEA, 2024).

Considering that the economic benefits of improved air and water quality outweigh the costs of reductions measures, there is ample reason to reduce N emissions, both from agriculture and from traffic and industrial sources (de Vries, 2021). High NO_2 concentrations can lengthen and worsen common viral infections and cause severe damage to the lungs (Spannhake, et al., 2002) as well as asthma (Achakulwisut, Brauer, Hystad, & Anenberg, 2019).

The release of acidifying substances may represent a significant environmental concern requiring the inclusion in comprehensive environmental assessments within the framework of digital product passports. Systematic evaluation of AP delivers multiple benefits. These include identification of emission hotspots throughout product lifecycles, which supports the development of targeted soil and plant protection strategies.

8.1.2. Key Components of Potential Impact

The substances normally considered as contributors to acidification are: sulfur dioxide (SO_2), sulfur trioxide (SO_3), nitrogen oxides (NO_x), hydrogen chloride (HCl), nitric acid (HNO_3), sulfuric acid (H_2SO_4), phosphoric acid (H_3PO_4) (note: the anion does not leach and the contribution to acidification is in practice equal to zero), hydrogen fluoride (HF), hydrogen sulfide (H_2S) and ammonia (NH_3). Although the list of acidification contributors is long, not all of them are considered in LCIA methods. Usually SO_x , NO_x and NH_3 are considered as the main contributors to the formation of acid rain. HCl , for example, while being an acid, does not typically contribute to the same atmospheric processes that lead to acidification as these other compounds do.

8.1.3. Regulatory Compliance

There are no existing specific regulations dealing with acidification pollutants, but with general air pollutants as The National Emissions reduction Commitments (NEC) Directive (2016/2284/EU) (European Union (EU), 2024), which sets 2020 and 2030 emission reduction commitments for five main air pollutants. (European Union (EU), 2024) namely NO_x , Non-Methane Volatile Organic Compounds (NMVOCs), NH_3 , SO_2 and $\text{PM}_{2.5}$. The directive transposes the reduction commitments for 2020 agreed by the EU and its Member States under the revised Gothenburg Protocol (UNECE, 2012) for the Convention on Long-range Transboundary Air Pollution (LRTAP Convention). The more ambitious reduction commitments agreed for 2030 are designed to reduce the health impacts of air pollution by half compared with 2005. Further, it requires Member States to draw up National Air Pollution Control Programs that should contribute to the successful implementation of air quality plans established under the EU's Air Quality Directive (EEA, 2024).

It is particularly critical to deliver on the 2030 targets related to air pollution under the zero-pollution action plan (European Commission (EC), 2021) to reduce the number of premature deaths caused by air pollution by 55% and to reduce the area of EU ecosystems where air pollution threatens biodiversity by 25%, in both cases compared to 2005 levels. To achieve these targets, it will be vital that EU Member States meet their respective emission reduction commitments set for 2020-2029 and for 2030 onwards under the NEC Directive. The biggest challenge for the period 2020-2029 is reducing ammonia emissions: 10 Member States need to cut their 2021 emission levels to fulfil their 2020-2029 reduction commitments. The agriculture sector is the principal source, responsible for 93% of total ammonia emissions. Since 2005, ammonia emissions have only slightly decreased in many Member States and in some cases have increased (European Environment Agency (EEA), 2025). Regarding NH_3 -emissions, five Member States already met their 2030 emission reduction commitments in 2021. 13 Member States need reductions under 10% and 8 need emissions to fall by between 10% and 30%. Regarding NO_x emissions, four Member States met their emission reduction commitments for 2030. However, 23 Member States will need to reduce emissions, of which 1 Member State will need to reduce them by more than 50%, 6 Member States by more than 30% and 15 Member States need a reduction of up to 30% (Figure 8) (European Environment Agency (EEA), 2025).

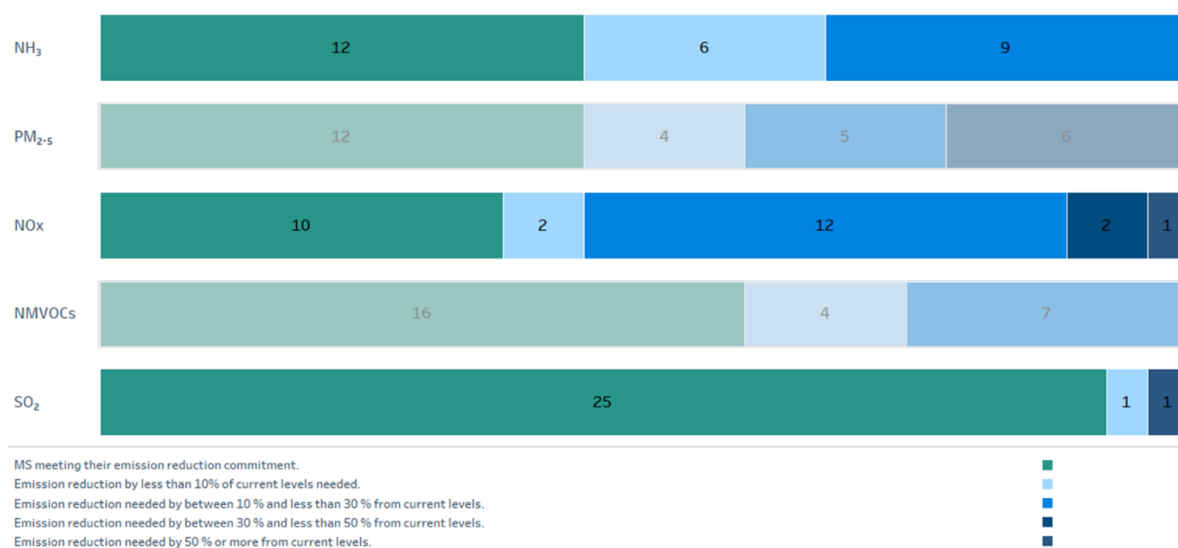


Figure 8: Number of Member States that had met their national emission reduction commitments for the five main pollutants for 2030 (European Environment Agency (EEA), 2025).

The updated Directive on industrial and livestock rearing emissions is in force, revising the former Industrial Emissions Directive (European Environment Agency (EEA), 2025). In line with the zero pollution ambition of the European Green Deal (European Commission (EC), 2019), the revised Directive will result in less emissions from large industrial installations. Under the Industrial Emissions Portal Regulation (IEPR), industrial operators for these sites are required to report on significant emissions and the use of resources (European Commission (EC), 2026). The EU aims to improve transparency in data reporting by collecting and disseminating information on the amounts of industrial pollutant releases, off-site transfers of waste and pollutants in wastewater, the consumption of energy, water and key raw materials. This modernized law will help guide industrial investments necessary for Europe's transition towards a cleaner, carbon-neutral, more circular, and competitive economy. By 2050, the implementation of the revised Directive is expected to reduce emissions of key air pollutants (PM_{2.5}, SO₂, NO_x and NMVOC) by up to 40% compared to 2020 levels. It is the first EU environmental law to enshrine the right of people to seek compensation for damage to their health caused by illegal pollution (European Commission (EC), 2024).

In the United States, the Clean Air Act (CAA) provides the legal framework for addressing air pollution, including acid rain. The Acid Rain Program, established under Title IV of the CAA, requires significant reductions in sulfur dioxide and nitrogen oxides emissions from power plants and other industrial sources. (Lattanzio, 2022)

8.1.4. Importance for the Chemical Industry

The chemical industry, being an energy intensive sector, is one big emitter of SO₂ and NO_x (Figure 9) (European Environment Agency (EEA), 2025) that react in the atmosphere producing acid rain.

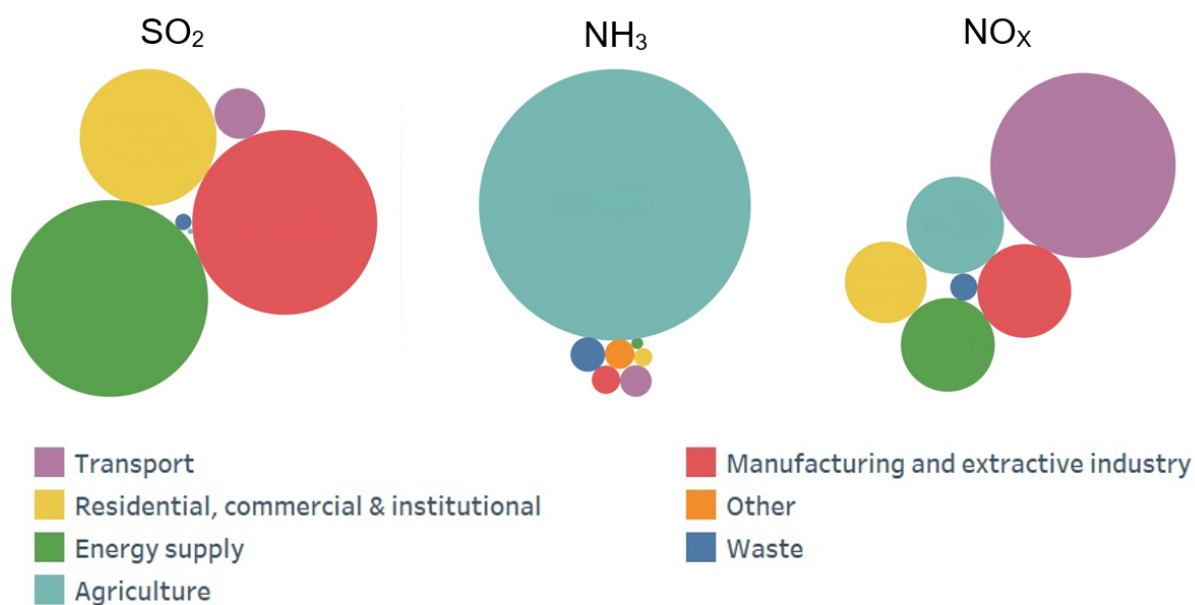


Figure 9: Sectors and activities contributing to emissions of the five regulated air pollutants in EU Member States in 2023 (European Environment Agency (EEA), 2025)).

The chemical industry supports company and product related transparency on emissions and related impacts while having its own mitigation targets in place. Product related impacts on acidification are not only dependent on safe production and processing but also on safe transport, use, and end-of-life handling. Understanding and controlling acidification is essential for reducing acid rain formation and complying with environmental regulations. Chem-X developed a sustainability data model with an acidification information data model to be useable in a digital material passport.

Acidification is a significant environmental issue in the chemical industry, and there are several applications where it is particularly relevant. These processes can be categorized as follows in Table 14.

Table 14: Processes directly or indirectly related to acidification relevant in the chemical industry (not exhaustive list)

Processes	Example
Production of Sulfuric Acid	Sulfuric acid is widely used in the chemical industry for various applications, including fertilizer production, mineral processing, and chemical synthesis. The production process can lead to acidification due to the release of sulfur dioxide (SO ₂) and other acidic compounds
Nitric Acid Manufacturing	Nitric acid is another important chemical used in fertilizers, explosives, and other industrial processes. Its production involves the oxidation of ammonia, which can result in the emission of nitrogen oxides (NO _x) that contribute to acidification.
Petrochemical Industry	The refining of petroleum and the production of petrochemicals can lead to acidification through the release of sulfur compounds and other acidic pollutants.
Metal Plating and Surface Treatment	Processes such as electroplating and surface treatment often use acidic solutions, which can lead to acidification if not properly managed.
Waste Treatment and Disposal	The treatment and disposal of industrial waste, especially hazardous waste, can result in acidification if acidic substances are not neutralized before disposal.

8.2. Methodology of Characterization

The prevailing LCIA characterization models emphasize terrestrial acidification, as it often occurs prior to aquatic acidification when inland water is acidified after the attenuation of the acid neutralization capacity of its watershed (Hauschild, et al., 2011). Several LCIA methods can be used to assess the terrestrial acidification potential (tAP) in LCA. These LCIA methods can differ due to their underlying characterization model, considered elementary flows or other aspects (Hauschild, et al., 2011). Brief descriptions of existing LCIA methods and their considered AP characterization models are given below for the chosen EF method and for the other LCIA methods see the Appendix 21.5.1. These models are based on the pre-selected methods reported in the ILCD Handbook (Hauschild, et al., 2011), while methods not compatible with LCA and outdated methods are excluded (Jungbluth, 2025).

8.2.1. Chosen Method: EF

Based on the LCIA method comparisons (see Appendix 11.4.1 21.5.1), the LCIA method EF 3.1 (or any updated version) is recommended to assess AP in LCA for products / materials especially intended for the European market. As recommended by the ILCD Handbook (Hauschild, et al., 2011), EF 3.1. uses the Accumulated Exceedance (AE) method (Seppälä, Posch, Johansson, & Hettelingh, 2006) as default method for midpoint evaluation of acidification as currently used in the EF Method. The AE method provides country-specific CFs for acidification and terrestrial eutrophication in Europe (Seppälä, Posch, Johansson, & Hettelingh, 2006). It uses the European Monitoring Centre for Air Pollution (EMEP) model along with a critical load database to determine atmospheric transport and deposition to land and major water bodies. AP is expressed as

Accumulated Exceedance, with an implicit dose-response curve of 1. An updated publication (Posch, et al., 2008) revised the AE factors using the 2006 EMEP Eulerian model, which includes deposition data across various land cover types and the latest critical load database (Hettelingh, et al., 2007) covering approximately 1.2 million ecosystems. The AE model is utilized in the EF LCIA method for assessing the Product Environmental Footprint (PEF), which includes guidelines for modeling this impact category (Hauschild, et al., 2011).

The EF method, developed by the European Commission, provides a comprehensive framework for evaluating the environmental performance of products throughout their life cycle. In terms of acidification, the EF method includes specific guidelines for modelling and assessing this impact category. The method uses CFs to translate emissions into potential acidification impacts, considering various substances such as SO₂, NO_x, and NH₃.

Formula

The following formula shows how to calculate the AP:

$$\text{Acidification Potential} = \sum(E_{i-AP} \times CF_{i-AP}) \text{ [mole of H}^+ \text{ eq. per kg]}$$

Formula 7: Equation for Acidification Potential calculation

Where:

- E_{i-AP} = Emission of the relevant substance for acidification (e.g., SO₂, NO_x, NH₃)
- CF_{i-AP} = Characterization factor for the respective acidifying substance

Where: E_{i-AP} and CF_{i-AP} are, respectively, the mass and the CF_{i-AP} of the acidifying substance. The impact of AP is, therefore, expressed in mole of H⁺ eq. per kg.

Characterization factors in EF method

In Table 15, the average CFs for Acidification, which help to quantify the extent to which each emission contributes to acidification, are presented. The impact of acidification is often expressed in SO₂ equivalents (SO₂-eq), meaning that different acidifying substances are converted based on their effect relative to sulfur dioxide (SO₂), which is used as the standard reference. Some LCA methodologies, such as the Environmental Footprint (EF) method, express acidification in moles of atomic hydrogen (mol H⁺ eq).

If the region where the emission occurs is known, use the regionalized factors. For regionalized figures, see guidance on page 17.

Table 15: EF 3.1 Acidification average characterization factors, expressed in mole of H⁺ eq. per kg emissions to air (EF 3.1)

Flow	CF [mole of H ⁺ eq. per kg]
Ammonia	3.02
Nitrogen dioxide	0.74
Nitrogen monoxide	1.13
Nitrogen oxides	0.74
Sulphur dioxide	1.31
Sulphur oxide	1.31
Sulphur trioxide	1.05

Link to download the CFs for Acidification can be found under the following link: [EF 3.1](#).

The approach fulfils scientific-based standards, and it has been well received by stakeholders. The method includes atmospheric and soil fate factors that are sensitive to the emission scenario, and it distinguishes between the loading of sensitive and non-sensitive areas. This method generates Average Default CFs, or a consistent set of CFs for each continent, if complemented by regional/continental models that are consistent with each other and expert estimates of soil sensitive areas (Hauschild, et al., 2011). The EF approach ensures consistency and comparability across different products and industries, enabling stakeholders to identify and implement effective mitigation strategies.

Selection Guidance

Generally, EF 3.1 provides regionalized CFs for the AP relevant elementary flows. However, depending on the database used (e.g., ecoinvent, Sphera MLC, CarbonMinds), the AP is only assessed using averages provided by EF (like the water footprint with AWARE methodology, see Chapter 6.2.10). Averages should be used to increase consistency. The goal for the future should remain to switch from average to more regionalized CFs.

8.2.2. LCI Flows

Table 16 shows a few examples of LCI flows for acidifying substances.

Table 16: Description of relevant LCI flows concerning Acidification.

LCI Flow	Description of Flow
Ammonia	Ammonia (NH_3) is primarily produced through agricultural activities, particularly from livestock waste and the application of nitrogenous fertilizers. It can also be emitted during the combustion of fossil fuels and biomass.
Nitrogen Dioxide	Nitrogen dioxide (NO_2) is generated from combustion processes, particularly in vehicles and power plants. It is formed from nitrogen oxides (NO_x) during high-temperature combustion.
Nitrogen Monoxide	Nitrogen monoxide (NO), also known as nitric oxide, is produced during combustion processes, especially in internal combustion engines and industrial processes. It is one of the primary nitrogen oxides emitted.
Nitrogen Oxides	Nitrogen oxides (NO_x) are a group of gases that includes both nitrogen monoxide (NO) and nitrogen dioxide (NO_2). They are emitted from vehicle exhaust, industrial processes, and power generation, primarily during combustion.
Sulphur Dioxide	Sulphur dioxide (SO_2) is mainly produced from the burning of fossil fuels, particularly coal and oil, in power plants and industrial facilities. It can also be emitted from volcanic eruptions.
Sulphur Oxide	Sulphur oxides refer to a group of gases that includes both sulphur dioxide (SO_2) and sulphur trioxide (SO_3). They are primarily generated by the combustion of sulphur-containing fuels and industrial processes.
Sulphur Trioxide	Sulphur trioxide (SO_3) is produced during the oxidation of sulphur dioxide (SO_2) in the atmosphere or during industrial processes, particularly in the manufacture of sulfuric acid.

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#).

8.3. Assessment Examples

Example: Fertilizer Production

Consider the production of ammonium nitrate fertilizers, which involves the reaction of ammonia (NH_3) with nitric acid (HNO_3). This process releases significant amounts of nitrogen oxides (NO_x) and ammonia, both of which contribute to acidification. To assess the Terrestrial Acidification Potential within LCA, the following steps are taken:

- Inventory Analysis: Data is collected at each stage of the fertilizer production process, including the extraction of raw materials, synthesis of ammonia, production of nitric acid,

and the final reaction to form ammonium nitrate. Emissions are measured and recorded, focusing on NO_x and NH_3 released during these processes.

- **Impact Assessment:** Using characterization models like EF 3.1, the AP of the emissions are calculated. CFs for NO_x and NH_3 are applied to quantify their contribution to acidification, expressed in mole of H^+ eq. per kg. See simplified calculation example in Table 17.
- **Mitigation:** The results of the impact assessment highlight the stages with the highest AP. To mitigate these impacts, the company might implement Selective Catalytic Reduction systems to reduce NO_x emissions, optimize the ammonia synthesis process to minimize NH_3 release, and explore alternative raw materials or production methods. Additionally, research into more sustainable fertilizer formulations, such as controlled-release fertilizers, can reduce acidifying emissions.

Table 17: Simplified example for the calculation of the Acidification Potential to produce a fertilizer.

	Emission flows [g/t]	CF	Result [H ⁺ eq./t]
NH ₃ Production			
NH ₃ emission	14	3.02	42.28
NO _x emission	2,200	0.74	1,628
SO ₂ emission	1,800	1.31	2,358
Nitric acid process			
NH ₃ emission	20	3.02	60.40
NO _x emission	500	0.74	370
SO ₂ emission	1	1.31	1.31
Ammonium nitrate process			
NH ₃ emission	30	3.02	90.60
NO _x emission	100	0.74	74
SO ₂ emission	10	1.31	13.10
Total			
NH ₃ emission			193
NO _x emission			2,072
SO ₂ emission			2,372
			4,637

9. Ozone Depletion Potential

9.1. General Description

9.1.1. Issues of Concern

The ozone layer acts as Earth's sunscreen, filtering out ultraviolet (UV) radiation that can cause skin cancer, cataracts, and other health problems, as well as damage aquatic ecosystems and terrestrial plant life. Without this protective layer, life on Earth would be exposed to significantly higher levels of UV radiation, leading to severe ecological and health consequences. Any significant depletion of this protective layer can lead to increased UV exposure, resulting in adverse effects on human health and negative impacts on ecosystems and agriculture. In this context, the ozone depletion potential (ODP) is a critical environmental impact category assessed in LCA, as it measures the potential of various substances to destroy ozone and consequently deplete the ozone layer. The ODP of a substance is a metric for determining the relative strength of that chemical's ability to destroy ozone (WMO, 2022).

Ozone (O_3) is formed when oxygen molecules (O_2) are split by UV light into individual oxygen atoms, which then combine with O_2 to form O_3 . This process occurs naturally and is balanced by the natural breakdown of ozone molecules shown in Figure 10. However, human activities have introduced substances that disrupt this balance, leading to ozone depletion. Besides ozone-depleting substances (ODS)¹³, the subsequent release of reactive halogen gases, especially chlorine and bromine, after breaking down by UV light in the stratosphere has a big impact on ODP (WMO, 2022). These released atoms then react with ozone, causing it to break down into oxygen molecules, thus thinning the ozone layer. Although, any substance that can destroy ozone in the stratosphere (NO, OH, Cl, or Br) is an ODS, in the Montreal Protocol only volatile compounds containing Cl or Br are classified as ODSs (UNEP, 2020).

Figure 11 illustrates the explanations from (Oever, et al., 2024) and of (Baird & Cann, Chapter 1 Stratospheric chemistry: the ozone layer., 2012; Baird & Cann, Chapter 2 the ozone holes, 2012; European Commission (EC), 1991; European Commission (EC), 1991; Baird & Cann, Chapter 1 Stratospheric chemistry: the ozone layer., 2012; Glibert & Burford, 2017)

¹³ Ozone-depleting substance (ODS) refers to gases containing either chlorine or bromine that are released to the atmosphere because of human activity and are controlled under Annexes A, B, C, or E of the Montreal Protocol. These include, among other CFCs, CCl_4 , CH_3CCl_3 , halons, CH_3Br and HCFCs. These ODSs typically have sufficiently long atmospheric lifetimes to reach the stratosphere after being emitted at the surface. Methyl bromide is the shortest-lived of the controlled substances and has natural and anthropogenic sources. Other substances contribute chlorine and bromine to the atmosphere but are not controlled under the Montreal Protocol for various reasons. (WMO, 2022)

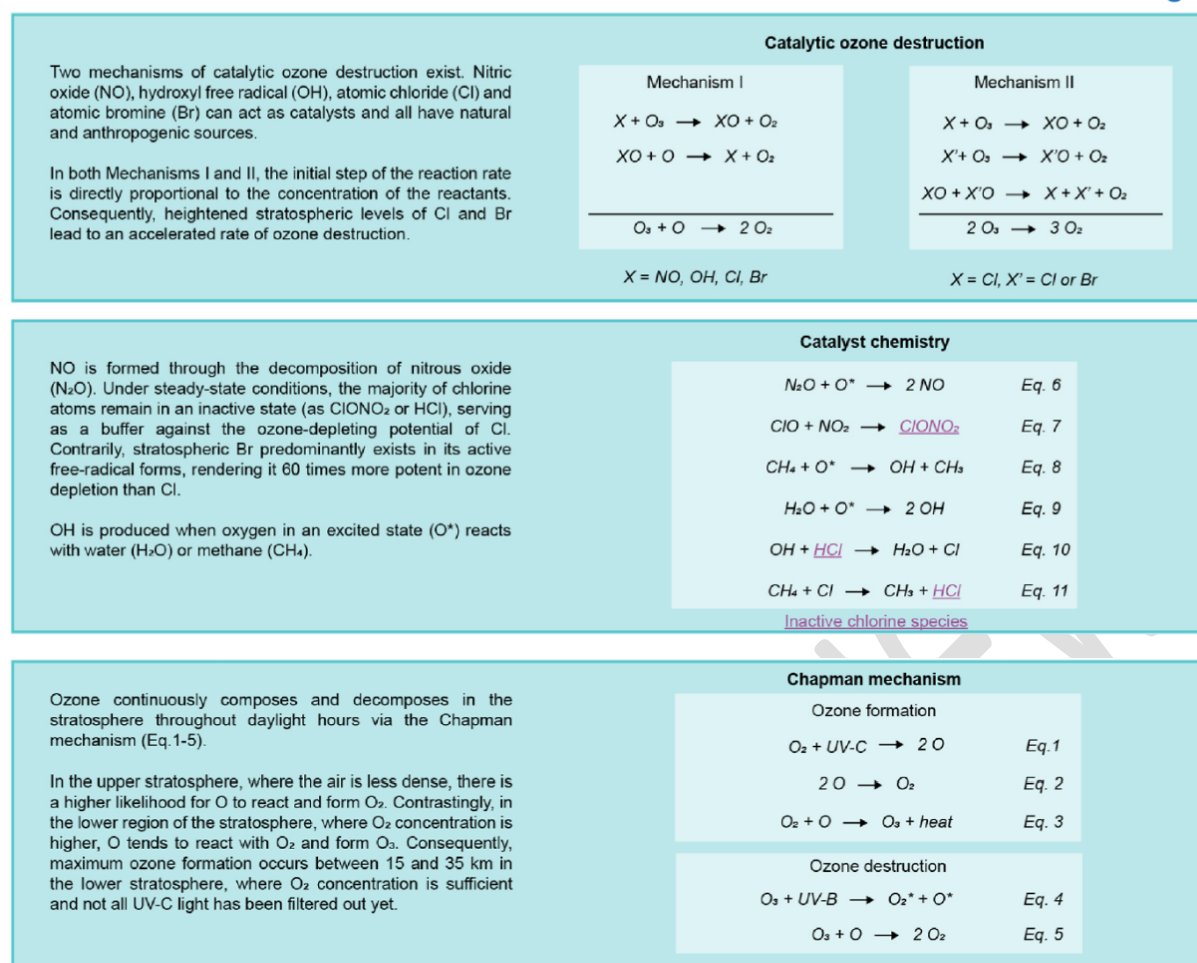


Figure 10: Summary of stratospheric ozone chemistry (Oever, et al., 2024).

In Figure 11, substances having a positive effect on the ozone layer (marked with a plus-sign) and ODS (marked with a minus-sign) are illustrated, including other impacts resulting from ODP (GHG = greenhouse gas, VSLS = very short-lived substance). Moreover, the arrows show if the substances are generally considered in (LCIA) methods. The Figure shows effects on the Ozone Layer, with Illustrations by Francesco Gavardi (Oever, et al., 2024).

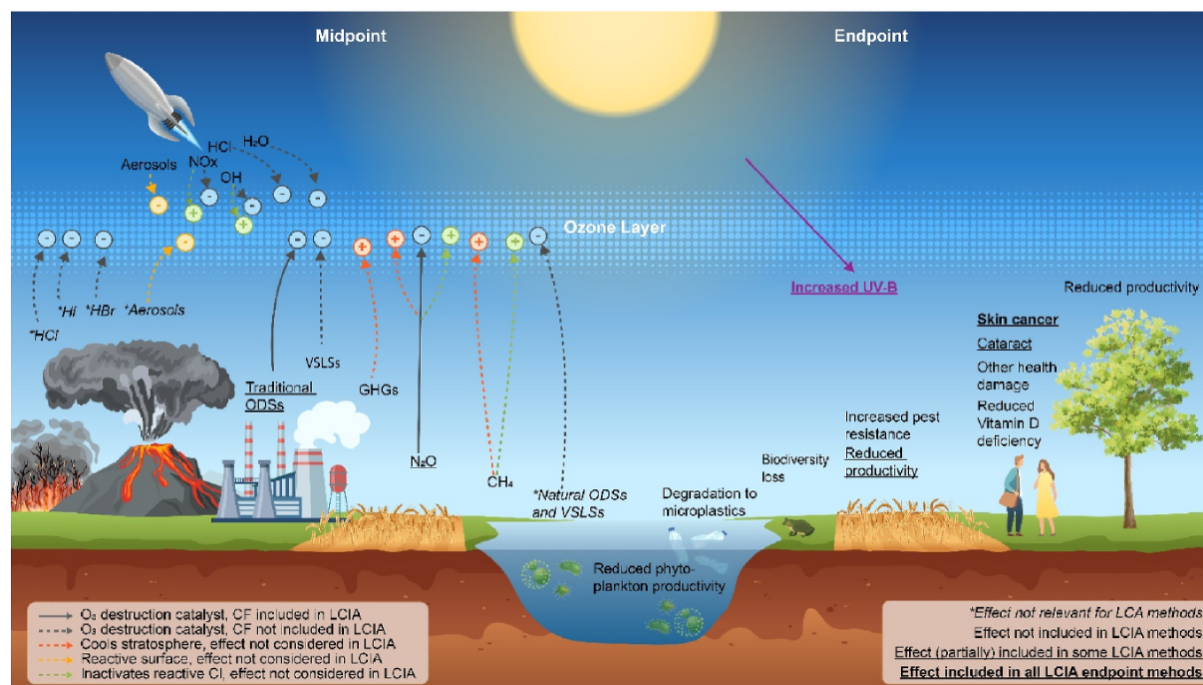


Figure 11: Summary of limitations and challenges related to midpoint and endpoint characterization (Oever, et al., 2024).

ODP is seen as the second-least important impact category for human health in specific LCIA methods (Bassi et al., 2023; Fazio, et al., 2018; Sala & Cerutti, 2018), due to the existing reports proving a recovering of the ozone layer (WMO, 2022). However, potential ozone layer threats caused by new technologies in the space sector must be considered (Oever, et al., 2024). Additionally ODP remains important for other sectors as the agricultural sector due to fertilizer-related N₂O emission and the chemical industry, as data gaps between ODS consumption reports and atmospheric measurements point to potential leakage issues from ODS serving as precursors or intermediates (WMO, 2022). The importance of ODP for the chemical industry is described in more detail in the next chapter.

9.1.2. Key Components of Potential Impact

Some of the ODS are the following:

- Chlorofluorocarbons (CFCs)
- Halons (e.g., bromine-containing halons)
- Methyl-bromide (CH₃Br)
- Carbon Tetrachloride (CCl₄)
- Methyl Chloroform (CH₃CCl₃)
- Hydrochlorofluorocarbons (HCFCs)

These substances were commonly used in refrigeration, air conditioning, foam blowing, and as solvents until their harmful effects on the ozone layer were discovered. ODS can be also found in

aerosol products, portable fire extinguishers, insulation boards, panels, pipe covers, and pre-polymers (UNEP, 2020).

9.1.3. Regulatory Compliance

Recognizing the significance of ODP has led to international efforts to control and eliminate the use of high-ODP substances. The most notable of these efforts is the Montreal Protocol, an international treaty signed in 1987 aimed at phasing out the production and consumption of ozone-depleting substances. The Montreal Protocol has been successful in reducing the emission of ODS, and it has been amended several times to include more substances and accelerate phase-out schedules.

Over the years, many other national and international regulations have been developed to limit ODP substances. Compliance with these regulations is essential for the industry to avoid penalties and trade restrictions. Accurate LCA, including ODP metrics, helps companies adhere to these regulations and demonstrate their commitment to environmental protection. (Andersen, Sherman, Carvalho, & Gonzalez, 2018).

The Montreal Protocol has led to significant reductions in the concentrations of high-ODP substances in the atmosphere. This has contributed to the gradual recovery of the ozone layer, with projections suggesting that the ozone layer could return to pre-1980 levels by the middle of the 21st century, if current regulations are maintained (Andersen, Sherman, Carvalho, & Gonzalez, 2018)).

9.1.4. Importance for the Chemical Industry

The chemical industry has been a contributor to ozone depletion through the production of synthetic ODS. The discovery of the Antarctic ozone hole in the 1980s prompted global concern, leading to the adoption of the Montreal Protocol in 1987, which mandated the phase-out of ODS. In response, industry has evolved significantly, developing safer alternatives. Regulations and national legislation have significantly restricted the production and use of high ODS, but calculating ODP of chemical substances remains crucial for the chemical industry as it directly influences environmental sustainability, regulatory compliance, innovation and market advantage. The chemical industry plays a pivotal role in environmental sustainability. Understanding ODP is vital for gauging the environmental impact of various chemicals and for formulating strategies to preserve and restore the ozone layer (WMO, 2022).

The chemical industry uses products or applications potentially affecting the ozone layer, which are categorized and presented in Table 18.

Table 18: Categories directly or indirectly related to Ozone depletion relevant for the chemical industry

Category	Example
Refrigeration and Air Conditioning	CFCs and HCFCs have been extensively used as refrigerants in cooling systems.
Aerosols	CFCs were commonly used as propellants in aerosol sprays.
Foam Blowing Agents	CFCs and HCFCs have been used in the production of foam insulation and packaging materials.
Fire Suppression Systems	Halons have been used in fire extinguishers and fire suppression systems.
Solvents	CFCs and other ODS have been used as solvents in cleaning and degreasing applications.

9.2. Methodology of Characterization

Several LCIA methods can be used to assess the ODP in LCA. Brief descriptions of existing LCIA methods and their considered characterization models are given below for the chosen EF method and for the other LCIA methods see the Appendix chapter 21.6.1.

9.2.1. Chosen Method: EF

Based on the LCIA method comparisons presented in the chapter above, the LCIA method EF 3.1 (or any updated version) is recommended to assess ODP in LCA for products / materials. Besides the reason that EF 3.1 is the recommended LCIA method by the European Union, EF 3.1 is up to now the only LCIA method, compared to all the others, that is based on the WMO (2014) publication. It is expected that the ODP impact category will further be maintained by the EU and consequently the new version of (WMO, 2022) will be updated, too.

Formula

The ODP is a metric used to quantify the relative ability of a chemical to destroy stratospheric ozone. It is defined as the ratio between the change in global ozone resulting from a given mass of the substance and the change produced by the same mass of CFC-11 (CFCl_3), which serves as the reference compound. (WMO, 2022)

To allow comparison of the potential impacts of different gases on the ozone layer, emissions are multiplied by their respective ODP characterization factors and expressed as ODP-normalized emissions.

Formula 8 (adapted from (Oever, et al., 2024)) to calculate the ODP is as follows:

$$\text{Ozone Depletion Potential} = \sum (E_{i-ODP} \times CF_{i-ODP}) \text{ [kg CFC-11-eq. per kg]}$$

Formula 8: Equation for Ozone Depletion Potential calculation

Where:

- E_{i-ODP} = Emission of the relevant ozone depleting substance (e.g., CFC-11, Halons, Carbon Tetrachloride (CCl_4))
- CF_{i-ODP} = Characterization factor for the respective ozone depleting substance

Where: E_{i-ODP} and CF_{i-ODP} , are, respectively, the mass and the CF_{i-ODP} of the ozone depleting substance. The impact of ODP is, therefore, expressed in kg CFC-11-eq. per kg.

Characterization Factors in EF Method

The ODP factors for a selection of substances are listed in Table 19. The reference substance for ODP calculation is trichlorofluoromethane (CFC-11), which has an ODP of 1.0. Other substances are compared to CFC-11 to determine their ODP values: substances with an ODP greater than 1.0 have a higher potential to destroy ozone molecules than CFC-11, while those with values below 1.0 are less harmful by comparison.

Table 19: Selected ODP characterization factors for some substances (retrieved from EF 3.1)

Substance	Characterization Factor (CFC-11 eq.)
CFC-11	1.0
Halons	3-10
Carbon Tetrachloride (CCl_4)	1.2
Methyl Chloroform (CH_3CCl_3)	0.8
HCFC-22	0.055
HCFC-123	0.02

Links to download the CFs for Ozone Depletion can be found under the following link: [EF 3.1](#).

Selection Guidance

As this is a global impact category, no selection is needed.

9.2.2. LCI Flows

Table 20 shows a few examples of LCI flows for ODP.

Table 20: Description of relevant LCI flows concerning Ozone Depletion

Flow	Description of Flow
CFC-11	CFC-11 (trichlorofluoromethane) is primarily produced as a refrigerant and aerosol propellant. It was widely used in foam-blowing agents and as a solvent in industrial applications. Its production has been largely phased out due to its ozone-depleting potential.
Halons	Halons are a group of brominated compounds used mainly in fire extinguishers. They are produced during the manufacturing of specific fire suppression systems and have significant ozone-depleting effects.
Carbon Tetrachloride (CCl ₄)	Carbon tetrachloride is produced as a solvent and in the manufacture of other chemicals. It was historically used in dry cleaning and as a refrigerant, but its production has been reduced due to its harmful environmental impact, particularly in ozone depletion.
Methyl Chloroform (CH ₃ CCl ₃)	Methyl chloroform was primarily used as an industrial solvent for degreasing and cleaning. Its production has decreased significantly due to its classification as an ozone-depleting substance.
HCFC-22	HCFC-22 (hydrochlorofluorocarbon) is used as a refrigerant in air conditioning and refrigeration systems. It is produced as a transitional replacement for CFCs, but its use is being phased out due to its potential to harm the ozone layer.
HCFC-123	HCFC-123 is primarily used as a refrigerant in commercial air conditioning systems. It is produced as a replacement for CFCs and is less harmful to the ozone layer, but it is still being phased out under international agreements.

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#).

9.3. Assessment examples

Case Study: The Transition from CFCs to HFCs in Refrigeration

A significant example of the importance of ODP in the chemical industry is the transition from CFCs to HFCs in the refrigeration industry (IRP, 2026). CFCs, once widely used as refrigerants, were found to have a high ODP and were major contributors to ozone depletion. In response to the Montreal Protocol, companies invested in research and development to find alternatives with lower ODP (Adams, 2025; Bhatti, Kumar, Reetu, & Singh, 2023).

One successful outcome of this effort is the adoption of HFCs, which have significantly lower ODP. A notable problem is the transition by the company to new systems, which has developed new refrigeration systems using HFCs. These systems not only comply with international regulations but also offer improved energy efficiency and reduced environmental impact. This transition not only helped to preserve the ozone layer but also demonstrated the chemical industry's capability to innovate and adapt in response to environmental challenges.

Chemical industry example

A simplified example of the general calculation process for chemicals is shown in Figure 12. The mass flows derived from a bill of materials shall be linked with the relevant LCI and the ODP flows in the LCI to generate the LCI for the process. Linked to the CFs (see Table 16) the single ODP flows can be calculated and aggregated to the CFC-11eq total result.

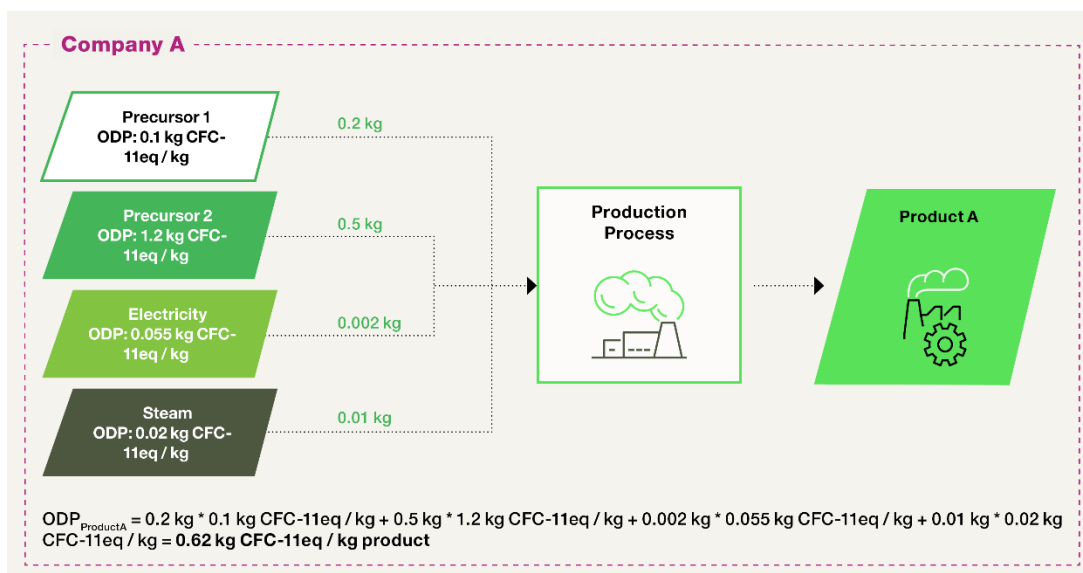


Figure 12: Simplified example of an ODP calculation for a chemical process with ODP mass emission flows.

10. Photochemical Ozone Creation Potential

10.1. General Description

10.1.1. Issue of Concern

Photochemical Ozone Creation Potential (POCP) describes the ability of a chemical compound to form ground-level ozone in the presence of sunlight and nitrogen oxides (NO_x). POCP is commonly used to evaluate the relative ability of various organic compounds to create photochemical smog. High POCP values indicate that a compound significantly contributes to ozone formation.

Tropospheric ozone is a secondary pollutant and is not directly emitted. The formation occurs locally through photochemical reactions initiated by solar radiation, which cause the oxidation of NMVOCs in the presence of nitrogen oxides (NO_x) (Preiss, 2015). NMVOCs are released using solvents, domestic activities and natural sources, such as forests. Figure 12 shows an example of activities emitting Volatile Organic Compounds (VOCs) and NO_x as the main contributors to ozone formation (Donzelli & Suarez-Varela, 2024). This document focuses primarily on NMVOCs due to their direct role in ozone formation. Figure 13 illustrates the human activities that mostly contribute to VOC and NO_x emissions, highlighting that coal combustion and diesel vehicles emissions have the biggest impact. The graphic Figure 13 illustrates the human activities that mostly contribute to VOC and NO_x emissions, highlighting that coal combustion and diesel vehicles emissions have the biggest impact.

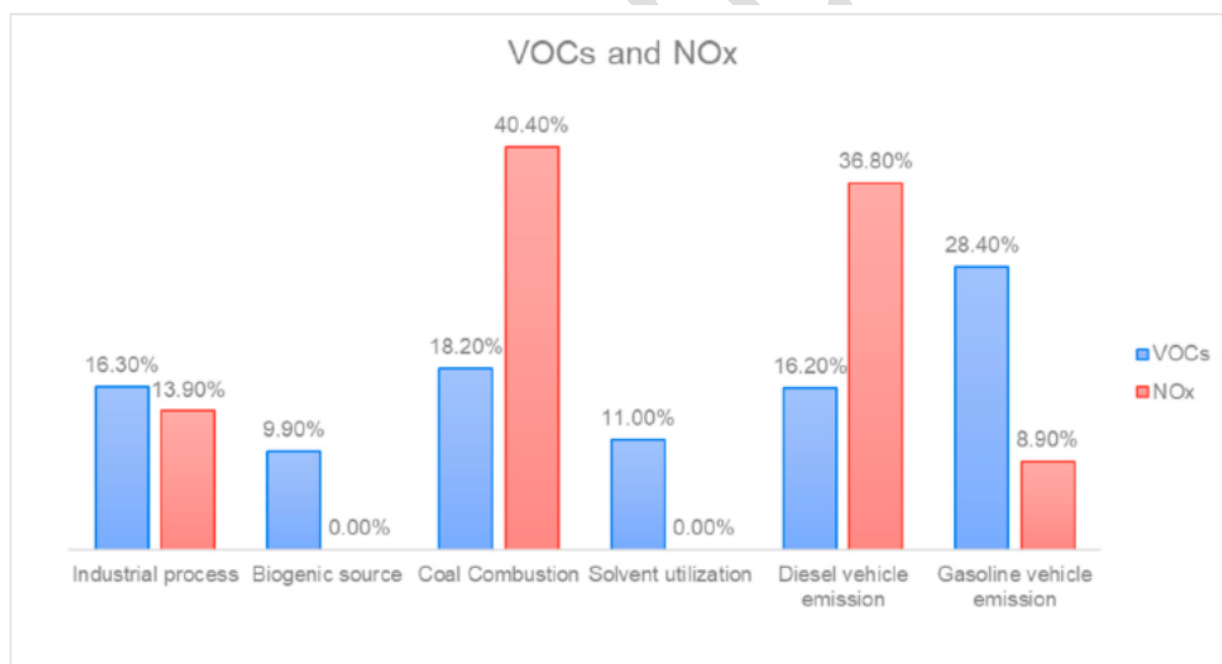


Figure 13: Representation of the six main sources of VOCs and NO_x in a typical industrial city in China (Donzelli & Suarez-Varela, 2024).

The interaction between NMVOCs and NO_x is non-linear and strongly depends on meteorological factors and the background concentration of these compounds. This process is typical of sunny and warm days and is one of the main causes of ground-level ozone pollution (Preiss, 2015). This negatively affects air quality and generates major consequences on:

- Human health: Ozone irritates the respiratory system, worsens conditions such as asthma and increases the risk of premature mortality, especially among vulnerable populations (Donzelli & Suarez-Varela, 2024).
- Ecosystems (flora & fauna): Ozone reduces photosynthesis, damages leaves, and decreases crop yields. This leads to biodiversity loss and compromises ecosystem services, ultimately impacting human well-being and food security (Emberson, Effects of ozone on agriculture, forests and grass lands, 2020).
- Materials: Ozone accelerates the deterioration of materials exposed to air, including rubber, plastics, and surface coatings. While often not part of LCIA, this degradation can lead to substantial economic costs due to increased maintenance needs and shortened product lifespans (Preiss, 2015)

Assessing the POCP of a product is a crucial aspect of LCA. It enables the identification of the environmental impacts (i.e., on air quality and human health) and supports strategies for mitigation (Holland, H., Khan, & Shallcross, 2025). Additionally, since POCP is partly driven by anthropogenic activities (i.e., transportation, industrial processes, energy production), it is closely monitored by policymakers aiming to reduce its impact (Donzelli & Suarez-Varela, 2024).

10.1.2. Key Compounds of Potential Impact

High concentration of ozone is formed due to release of NO_x (comprising of nitric acid (HNO_3) and nitrogen dioxide (NO_2)) and VOCs because of incomplete combustion. The reactivity of VOCs plays a crucial role in ozone formation. Recent studies have shown that reactive VOCs tend to decrease with altitude due to oxidation, while oxygenated VOCs accumulate at higher altitudes, influencing ozone production rates differently across atmospheric layers. Additionally, the balance between VOCs and NO_x concentrations governs the efficiency and rate of ozone formation, with variations leading to different photochemical regimes. While VOCs and NO_x are the primary precursors, other compounds such as carbon monoxide (CO), methane (CH_4) and Peroxyacetyl Nitrate (PAN) also contribute towards the formation of ozone.

Understanding the roles and interactions of these compounds is essential for developing effective strategies to mitigate ground-level ozone pollution and its associated health and environmental impacts.

10.1.3. Regulatory Compliance

POCP is also an important topic for regulatory Compliance. Governments and environmental agencies have established strict regulations to control VOC emissions and reduce ground-level ozone. The chemical industry must monitor and manage POCP to comply with these regulations and avoid penalties (Kim, et al., 2023).

- In the United States, the Clean Air Act and the National Ambient Air Quality Standards (NAAQS) regulate ozone precursors. Facilities must develop State Implementation Plans (SIPs) and apply Best Available Control Technology (BACT) to limit emissions (U.S. Environmental Protection Agency [EPA]).
- In the EU, the Industrial Emissions Directive 2010/75/EU (European Union (EU), 2010) establishes emission limit values for VOCs. Additionally, the VOC Solvents Emissions Directive 1999/13/EC (European Union (EU), 1999), now incorporated into the Industrial Emissions Directive (IED), specifically regulates emissions from solvent use. Complementing these source-control measures, EU legislation has also addressed the impacts of VOCs through their role in ozone formation: the earlier Council Directive

92/72/EEC on air pollution by ozone introduced a harmonized system for ozone monitoring, thresholds for health and vegetation protection, and public information duties. This framework has since been replaced by Directive 2002/3/EC (European Union (EU), 2002) and is now consolidated under the Ambient Air Quality Directive (European Union (EU), 2008), which sets binding standards for ozone and other pollutants across Member States. Compliance with these directives is critical for industries such as chemicals, paints, coatings, and pharmaceuticals (European Parliament Research Service, 2021).

- Under the UNECE Gothenburg Protocol (to the Convention on Long-range Transboundary Air Pollution), signatory countries commit to reducing emissions of ozone precursors, including NO_x and VOCs, to mitigate cross-border smog and ground-level ozone formation (UNECE).
- In China, the Air Pollution Prevention and Control Law requires industries to reduce VOC emissions through strict standards, substitution of low-VOC materials, and the installation of treatment technologies. Compliance is monitored by the Ministry of Ecology and Environment (MEE) through real-time emission reporting and inspections, with penalties for exceedances. These measures, reinforced under China's 13th and 14th Five-Year Plans, aim to curb ground-level ozone formation and reduce the health and environmental impacts of photochemical smog (Envilience ASIA, 2019).

10.1.4. Importance for the Chemical Industry

Chemical processes such as the production of organic compounds, polymers, and pharmaceuticals are major sources of VOC emissions, releasing approximately 40,000 tons into the atmosphere annually (Joint Research Centre (JRC): EU Science Hub, 2021). From production to processing, storage, and transportation, chemical plants emit VOCs that react with NO_x in the atmosphere to produce photochemical smog (Sanjh, 2023). Understanding and controlling POCP is essential for reducing ozone formation and complying with environmental regulations. Table 21 lists examples of the chemical industry where POCP is an important aspect.

Table 21: This is a non-exhaustive list of process steps that should be considered for data collection on POCP.

Process steps	Example
Raw Material Extraction	The extraction and processing of raw materials can release VOCs and NO _x , contributing to POCP.
Production and processing	Many industrial processes, such as distillation, cracking, and polymerization, emit VOCs.
Storage and Transportation	Storing raw materials and finished products in tanks can release VOCs, especially if they are not properly sealed.
Waste Management	Waste containing organic compounds can release VOCs if not properly treated.
Disposal & Recycling	Disposal and recycling processes can release VOCs and NO _x , influencing the POCP assessment.

10.2. Methodology of Characterization

Several methodologies can be employed to assess POCP in LCA. The choice of methodology depends on the goal and scope of the study, the available data, and the specific requirements of the assessment. Brief descriptions of existing LCIA methods and their considered characterization models are given below for the chosen EF method and for the other LCIA methods see the Appendix chapter 21.6.1.

10.2.1. Chosen method: EF

Hauschild (2011) recommends Recipe as the default method at both the midpoint and endpoint level as it considers spatially differentiation based on the impact assessment methods existing in 2010. Recommendations to include natural ecosystem within the scope and to expand the CFs beyond Europe have been adapted with the update of ReCiPe method in 2016. In general, the model can be applied in other regions as well. This led to the consideration of POCP for both terrestrial ecosystem and human health (Huijbregts, Steinmann, & Elshout, ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, 2017). Although ReCiPe 2016 offers a highly detailed quantification model and is widely regarded as the most comprehensive method for assessing POCP, we recommend using the EF method version 3.1. This recommendation is based on the need for consistency with other sustainability metrics presented in this guideline and alignment with the PEF reporting requirements.

Formula

Within the EF 3.1 method, the LOTOS-EUROS model is applied to calculate the POCP value. LOTOS-EUROS is a combination of Long-Term Ozone Simulation and European Operational Smog and calculates the CFs for human health damage caused by emitted substance x in Europe (Segers, et al., 2025). The CFs is composed of three different factors: dimensionless intake factor ($IF_{pop, x}$), effect factor (EF_k in kg^{-1}) and damage factor (DF_k in yr) (Van Zelm R. , et al., 2008).

$$CF_x = \sum_i \left(IF_{pop,x,i} \sum_e (EF_{e,k,i} DF_{e,k}) \right)$$

Formula 9: Equation for “Characterization factor for compound x”

POCP values from (Preiss, 2015) and (Derwent R. G., Jenkin, Saunders, & Pilling, 1998) and from updated work (Derwent R. , Jenkin, Passant, & Pilling, 2007) can be coupled with generic NMVOC CFs to calculate specific impacts per compound class:

$$CF_x = \frac{POCP_x}{POCP_{NMVOC}} \cdot CF_{NMVOC}$$

Formula 10: Equation for “Photochemical Ozone Creation Potential” calculation

Where:

- CF_x : characterization factor for compound x
- CF_{NMVOC} : midpoint CF for aggregated NMVOC emissions (e.g., in kg O₃ eq/kg)
- $POCP_x$: POCP of compound x
- $POCP_{NMVOC}$: average POCP across the NMVOC profile

Characterization Factors in EF Method

Table 22 below shows the POCP characterization factors (in kg NMVOC-eq. per kg) from EF 3.1 method. There are two relevant categories for POCP, 1) human health and 2) ecosystems. The relevant scope for this document and for sustainability metric is Human Health.

If the region where the emission occurs is known, use the regionalized factors. For regionalized figures see guidance on page 17.

Table 22: Overview of selected NMVOC characterization factors

Compound	CFs (kg NMVOC-eq. per kg) for Human Health
Ethylene	1,69
Propylene glycol	0,772
1-Butene	1,82
trans-2-Butene	1,91
cis-2-Butene	1,94
trans-2-Pentene	1,89
Butadiene	1,44
Isoprene	1,84
p-Xylene	1,71
m-Xylene	1,87
o-Xylene	1,78
Toluene	1,08
Benzene	0,368
Pentane	0,667
Hexane	0,814
Heptane	0,834
Propane	0,297
Ethane	0,208
Acetaldehyde	1,08
Formaldehyde	0,877
Acetone	0,159
Methane	0,010
NO _x	1

The list of chemicals in the above Table 22 is non-exhaustive. To access the full list of characterization factors for POCP, please use the following link: [EF 3.1](#)

Selection guidance

Generally, EF 3.1 provides regionalized CFs for the POCP relevant elementary flows. However, depending on the database used (e.g., ecoinvent, Sphera MLC, CarbonMinds), the POCP is only assessed using averages provided by EF (like the water footprint with AWARE methodology, see

Chapter Water use). Averages shall be used to increase consistency. The goal for the future should remain to switch from average to more regionalized CFs.

10.2.2. LCI Flows

Table 23 shows a few examples of LCI flows for POCP. For the full table see [EF 3.1](#).

Table 23: Overview of LCI flows

Compound	Description
Ethylene	Produced from crude oil or natural gas. The feedstock (naphtha or ethane) undergoes steam cracking at high temperature, breaking large hydrocarbons into smaller molecules, yielding ethylene as a primary product.
Propylene glycol	Derived from crude oil or natural gas. Propane is converted to propylene, which is oxidized to propylene oxide. Hydrolysis of propylene oxide gives propylene glycol.
Toluene	Formed mainly from crude oil naphtha during catalytic reforming or recovered from coal tar distillation. Separation and refining yield toluene.
Benzene	Obtained from crude oil naphtha through catalytic reforming, or from pyrolysis gasoline (a byproduct of steam cracking). Extraction and purification yield benzene.
NO_x	Generated from air (N ₂ + O ₂) during high-temperature combustion in crackers, reformers, and furnaces. These conditions cause nitrogen and oxygen to combine into NO _x gases.

10.3. Assessment examples

Case Study:

A company conducted an analysis of its production processes to identify the main sources of VOC emissions and assess their POCP values using the EF method. Toluene (POCP EF: 1.08 kg NMVOC-eq/kg) was found to be the primary contributor to ground-level ozone formation.

The goal was to find an alternative that would reduce ozone formation without compromising product quality. Two options were evaluated:

- Methyl Ethyl Ketone (MEK): MEK has a POCP EF of 0.63. Advantages are good solubility as well as fast evaporation, but it requires 1.2 kg/kg for equivalent performance.
- Propylene Glycol Monomethyl Ether (PGME): PGME has a POCP EF of 0.60. It shows excellent solubility and moderate evaporation, but it requires 1.4 kg/kg for equivalent performance.

In this case study (see Figure 14), it is assumed that the solvent is completely evaporated, meaning that 100% of the solvent mass is emitted to air. The calculated POCP values therefore mainly represent the solvent's own contribution, based on its emission factor and the amount required for equivalent performance. In addition, a small "additional POCP emission" term

(0.01–0.02 kg NMVOC-eq/kg) was included in the following calculations to account for other process-related NMVOC emissions such as handling, cleaning, or storage losses. These are not part of the solvent itself and therefore are not double-counted. The variation of this additional term between the scenarios reflects the differences in solvent volatility and quantity handled (e.g., 1.2 kg MEK vs. 1.4 kg PGME). This ensures that all relevant emissions are considered while keeping the calculation transparent and scientifically consistent.

Impacts were calculated according to the POCP guidelines:

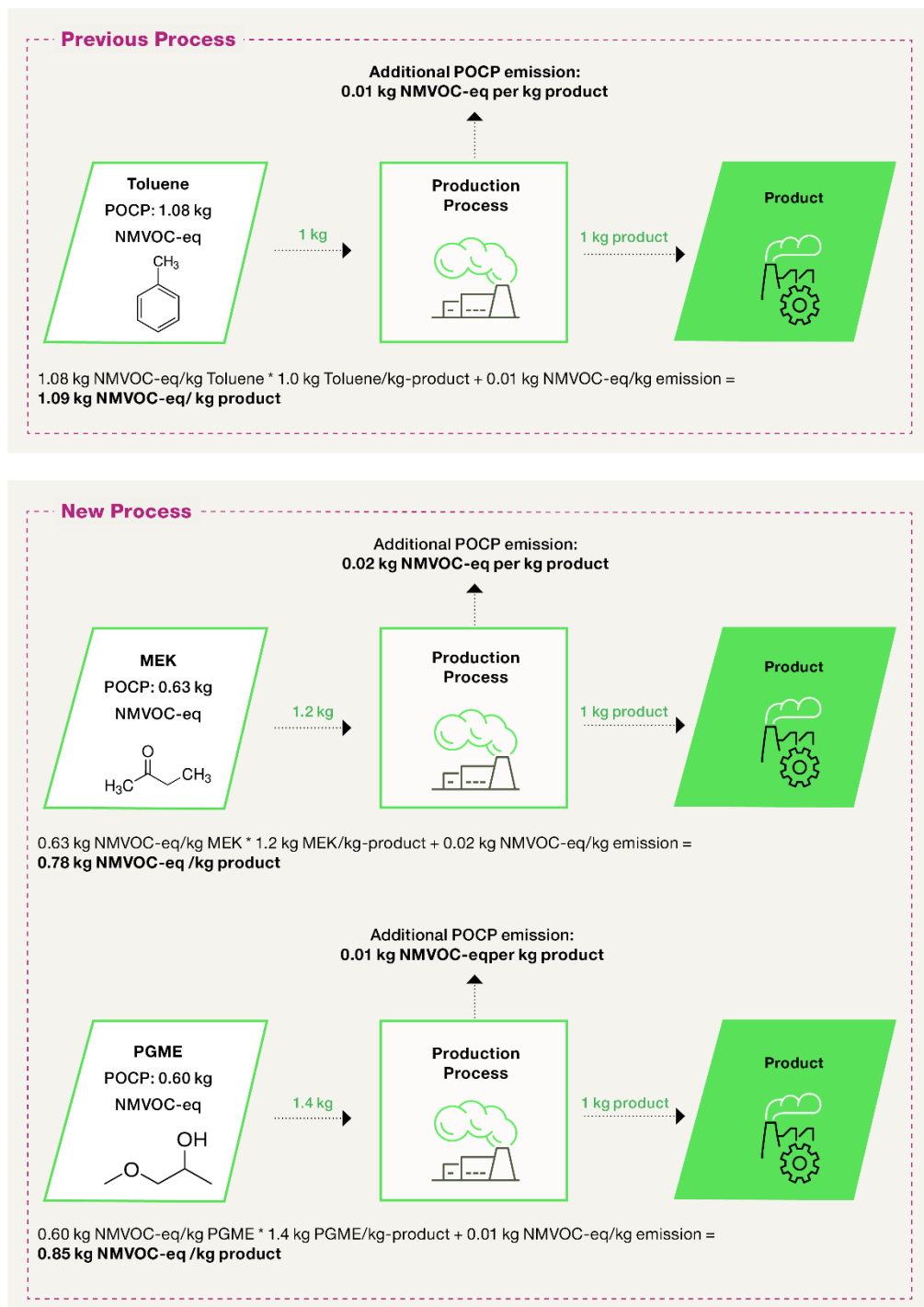


Figure 14: Comparison of previous and new process addressing POCP impacts

Switching to MEK reduced ozone formation and improved environmental compliance. VOC emissions dropped, product quality remained high, and stakeholder trust increased.

Not for review

11. Eutrophication

11.1. General Description

11.1.1. Issues of Concern

Eutrophication is a significant environmental issue characterized by the excessive supply of nutrients, particularly nitrogen (N) and phosphorus (P), to ecosystems through synthetic fertilizers and increased nitrogenous emissions (Henderson, 2015). Human activities have contributed to the increased cycling of N and P throughout the biosphere. This poses significant risk to the health of terrestrial, freshwater and marine ecosystems, as well as the economic and life-support services they provide (Rockström, et al., 2009).

The process of eutrophication begins when nutrient loading exceeds natural rates, stimulating primary production. Terrestrial eutrophication is caused by deposition of airborne nutrient-rich emissions, mainly associated with airborne nitrogen compounds such as nitrogen oxides and ammonia, since airborne phosphorus emissions are insignificant. In terrestrial ecosystems, increased nutrient inputs can alter plant composition and productivity, which can change crop yields and affect food production. In freshwater systems, phosphorus is typically the limiting nutrient, meaning that its addition can lead to significant changes in species composition and biomass. Marine ecosystems are usually nitrogen-limited, and their response to nutrient inputs can vary widely (Henderson, 2015). Both freshwater and marine systems often experience harmful algal blooms and oxygen depletion due to nutrient over-enrichment.

Harmful algal blooms arise from the rapid or exponential proliferation of algae and cyanobacteria, typically resulting from an excess of available nutrients. These algal blooms can lead to various shifts in species composition and other significant negative impacts to fish, wildlife, pets, and humans (Glibert & Burford, 2017; Paerl & Otten, 2014). Additional impacts are observed e.g. for human health and drinking water systems as well (U.S. Environmental Protection Agency (EPA), 2015; Millennium Ecosystem Assessment, 2005).

While some degree of eutrophication occurs naturally, human activities - such as fertilizer application, atmospheric deposition, and agricultural practices - have significantly accelerated nutrient cycling, disrupting the natural balance and leading to more severe ecological impacts (Bouwman, Beusen, & G., 2009). Figure 15 illustrates the relationship between nutrient input, transport, removal, and transformation as N and P cycle through the biosphere.

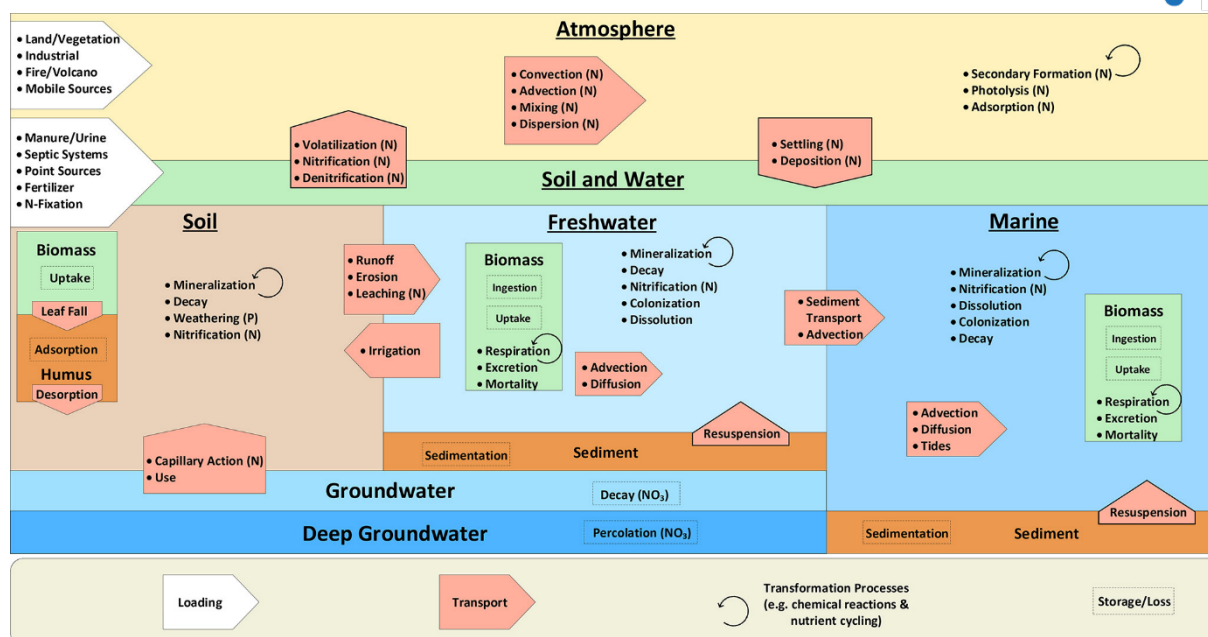


Figure 15 : Fate and transport considerations relevant for eutrophication modelling (Morelli, et al., 2018).

11.1.2. Key Components of Potential Impact

In aquatic systems, eutrophication is driven mainly by phosphorus in freshwater and nitrogen in marine environments. Terrestrial eutrophication results from nitrogen deposition via air emissions such as ammonia (NH_3) and nitrogen oxides (NO_x), affecting soil nutrient balance and plant species composition. Another major contributor to terrestrial eutrophication is the accumulation of nutrients in soils caused using agricultural fertilizers.

Key contributors from the chemical industry include the following emissions:

- **Ammonia (NH_3):** Deposits nitrogen onto soils from industrial emissions, disrupting plant communities.
- **Nitrogen oxides (NO_x):** Emitted from combustion and chemical processes, including wastes contributing to both terrestrial and marine eutrophication.
- **Nitrate (NO_3^-):** Released via wastewater and fertilizer runoff, driving freshwater eutrophication.
- **Phosphates (PO_4^{3-}):** Municipal effluents and wastes promoting algal blooms in freshwater.
- **Organic nitrogen compounds:** Degrade into reactive nitrogen, enriching ecosystems and altering microbial and plant dynamics.

11.1.3. Regulatory Compliance

Eutrophication of surface water bodies represents a major global water quality challenge, prompting the European Union to establish a robust regulatory framework aimed at mitigating nutrient pollution. Water Framework Directive (European Union (EU), 2000) sets comprehensive standards for water quality management and mandates comprehensive assessment of the ecological status of all surface waters, promoting sustainable practices and regulating nutrient inputs to achieve "good status" (European Union (EU), 2000). Complementarily, the Nitrates Directive (Directive 91/271/EEC) (European Union (EU), 2000) focuses on reducing agricultural nitrate pollution, promoting good agricultural practices, and designating Nitrate Vulnerable

Zones for targeted nutrient management and requires the implementation of action programs that include measures such as crop rotation, cover cropping, and optimized fertilizer application (European Commission (EC), 1991).

The impacts of eutrophication on freshwater and coastal ecosystems have prompted global political initiatives to address these issues. In the United States, the Coastal Zone Management Act and the Clean Water Act (US CWA, 1972) were enacted to tackle urban and industrial pollution, with the aim of reducing point sources of phosphorus emissions. Similarly, the Urban Wastewater Treatment Directive (Directive 91/676/EEC) was established in the European Union (European Commission (EC), 1991) to achieve similar objectives (Nikolaidis, et al., 2024).

Additionally, the United Nations has established the Sustainable Development Goals (SDGs) (United Nations (UN), 2026) with a particular focus on Goal 6. This goal emphasizes the importance of ensuring the availability and sustainable management of water and sanitation for all. It is directly linked to the need for nutrient management to combat eutrophication. Globally, organizations such as the United Nations Food and Agriculture Organization (FAO) promote guidelines for sustainable agricultural practices that aim to minimize nutrient pollution and enhance soil health.

Assessing and mitigating eutrophication not only ensures compliance with existing regulations, but also protects environmental quality, supports long-term food security and enhances community well-being by safeguarding water resources that are vital for both communities and industries sectors.

11.1.4. Importance for the Chemical Industry

Eutrophication is relevant for the chemical industry because it is often linked to the release of nutrients—particularly nitrogen and phosphorus—from industrial processes, wastewater, and agricultural runoff.

Chemical manufacturers are responsible for managing these emissions. The industry is directly involved in developing solutions such as advanced water treatment technologies and nutrient recovery systems, highlighting its responsibility and opportunity to mitigate eutrophication and protect aquatic ecosystems. Excessive nutrient discharges can lead to stricter environmental regulations, increased treatment costs, and reputational risks for chemical manufacturers.

Compliance with these regulations is crucial for sectors such as agriculture, wastewater management, and manufacturing, all of which can contribute significantly to nutrient loading. Moreover, the increasing use of bio-based feedstock within the chemical industry to produce bio-based chemicals increases the dependency on the agricultural production systems. This increases the industry's indirect contribution to the LCIA category eutrophication potential.

11.2. Methodology of characterization

11.2.1. Chosen method: EF

Several midpoint LCIA methods exist to assess terrestrial, freshwater, and marine eutrophication. Early approaches such as CML applied simple mass-based characterizations (kg N-eq. or kg P-eq.) and did not explicitly consider fate processes or ecosystem sensitivity. ReCiPe (Goedkoop, et al., 2009) provides midpoint indicators for freshwater (phosphorus-limited) and

marine (nitrogen-limited) eutrophication but does not define terrestrial eutrophication as a standalone midpoint category; terrestrial effects are instead addressed indirectly through acidification (Hauschild, et al., 2011). (While Impact World+ (Bulle C. , et al., 2019) provides spatially differentiated characterization factors that may better capture regional environmental variability, it has not undergone evaluation according to the ILCD-recommended framework. Consequently, the EF methodology was adopted to maintain methodological consistency and ensure comparability across studies.

The ILCD Handbook concluded that available approaches either lacked sufficient environmental relevance for European ecosystems or were not suitable for regulatory applications. It therefore recommended the Accumulative Exceedance (AE) method for terrestrial eutrophication, which relates emissions of reactive nitrogen (NO_x, NH₃, and nitrogen to soil) to exceedances of ecosystem-specific critical loads (Hauschild, et al., 2011). This recommendation forms the basis for the EF method, which provides a coherent and harmonized framework for all eutrophication midpoint indicators.

Within the EF method, eutrophication is addressed through three midpoint indicators, applying different modelling approaches where scientifically justified:

- Terrestrial eutrophication is assessed using a critical-load-based approach, linking atmospheric nitrogen emissions to exceedances of ecosystem tolerance levels. Due to strong spatial variability in ecosystem sensitivity, this indicator applies to country-specific characterization factors. However, EF3.1 offers regionalized characterization factors in addition.
- Freshwater eutrophication is assessed using a phosphorus-limited, fate-based approach, reflecting the dominant role of phosphorus in freshwater eutrophication processes. Characterization factors are not geographically differentiated at midpoint level.
- Marine eutrophication is assessed using a nitrogen-limited approach that accounts for the transfer of nutrients from freshwater to marine systems, reflecting the role of inland waters as pathways for nitrogen emissions. Characterization factors are not spatially differentiated at midpoint level.

For DMP-related applications, the EF characterization method (Zampori & Pant, 2019) is applied as a single, harmonized LCIA framework across all eutrophication categories. Where geography-specific characterization factors are available (terrestrial eutrophication), they are applied; where they are not (freshwater and marine eutrophication), EF default characterization factors are used, in line with EF guidance and official documentation. This approach ensures consistency, transparency, and comparability while acknowledging methodological limitations.

Formula, Terrestrial

For the calculation of terrestrial, marine and freshwater eutrophication, the formulas are presented below. The following calculation procedure is recommended:

1. Collect relevant inventory flows
2. Match flows to [EF 3.1](#) CFs
3. Multiply emissions by CFs

4. Aggregate to obtain the specific Eutrophication result

For DMP and EF-aligned assessments, the recommended LCIA model implemented in the EF method is the AE-method. It calculates the terrestrial eutrophication potential in mol N-eq., reflecting exceedance of critical nitrogen loads in ecosystems.

The calculation is as follows:

$$\text{Eutrophication, terrestrial (mol N-eq.)} = \sum E_{i-\text{Eutrophication},t} \times CF_{i-\text{Eutrophication},t}$$

Formula 11: Equation for “Eutrophication, terrestrial” calculation

Where:

- $E_{i-\text{Eutrophication},t}$ = Emission of the relevant substance for Eutrophication, terrestrial (kg emitted)
- $CF_{i-\text{Eutrophication},t}$ = Characterization factor for the respective eutrophying substance (mol N-eq. per kg emission).

Characterization Factors in EF Method, Terrestrial

Table 24 presents the regionalized CFs for terrestrial eutrophication, which help to quantify the extent to which each emission or nutrient contributes to this impact category. Terrestrial eutrophication impact is measured in mol N-eq., converting various substances to their nitrogen-equivalent effect.

If the region where the emission occurs is known, use the regionalized factors. For regionalized figures see guidance on page 17.

Table 24: EF 3.1 Eutrophication, terrestrial regionalized characterization factors, expressed in mol N-eq. per kg emissions to air (EF3.1)

Flow	CF [mol N-eq. per kg]
Ammonia (global)	13.47
Ammonia (France)	10.8 (see example in chapter 10.3)
Ammonium	12.72
Nitrate	3.16
Nitrite	4.26
Nitrogen Dioxide	4.26
Nitrogen Monoxide	6.53
Nitrogen Oxides	4.26

To access the full list of characterization factors for Eutrophication, terrestrial, please use the following link: [EF 3.1](#).

Formula, Marine

The EF 3.1 method for “Eutrophication, marine” uses the unit kg N-eq. to measure the impact, representing the amount of emitted nutrients that reach a marine ecosystem. The impact is calculated by multiplying the emission of nitrogen and its relevant compounds by a CF that quantifies the potential to cause “Eutrophication, marine”.

The calculation is as follows:

$$\text{Eutrophication, marine (kg N-eq.)} = \sum E_{i-\text{Eutrophication},m} \times CF_{i-\text{Eutrophication},m}$$

Formula 12: Equation for “Eutrophication, marine” calculation

Where:

- $E_{i-\text{Eutrophication},m}$ = Emission of the relevant substance for Eutrophication, marine (e.g., nitrate; kg emitted)
- $CF_{i-\text{Eutrophication},m}$ = Characterization factor for the respective eutrophying substance (kg N-eq. per kg emission).

Characterization Factors in EF Method, Marine

Table 25 presents the average CFs for marine eutrophication, which helps to quantify the extent to which each emission or nutrient contributes this impact category. The impact of marine eutrophication is expressed in kg N-eq., wherein various eutrophying substances are converted based on their effect relative to nitrogen, which is used as the standard reference.

If the region where the emission occurs is known, use the regionalized factors. For regionalized figures see guidance on page 17.

Table 25: EF 3.1 Eutrophication, marine average characterization factors, expressed in kg N-eq. per kg emissions to air and water (EF3.1)

Flow	Emission to	CF [kg N-eq. per kg]
Ammonia	Air ¹	0.092
	Water ²	0.824
Ammonium	Air ¹	0.087
	Water ²	0.778
Nitrate	Air ¹	0.028
	Water ²	0.226
Nitrite	Air ¹	0.304
Nitrogen Dioxide	Water ²	0.389

Nitrogen Monoxide	Air ¹	0.596
Nitrogen Oxides	Water ²	0.389
Nitrogen, total (excluding N ₂)	Air ¹	1.000
¹ unspecified, lower stratosphere and upper troposphere, unspecified long-term, urban air close to ground, non-urban air or from high stacks ² fresh water, unspecified, unspecified long-term, sea water		

To access the full list of characterization factors for Eutrophication, marine, please use the following link: [EF 3.1](#).

Formula, Freshwater

The EF 3.1 formula for Eutrophication, freshwater is a calculation that measures the degree to which emitted nutrients reach freshwater ecosystems, using phosphorus as the limiting factor. The impact is expressed in kilograms of phosphorus equivalent (kg P-eq.) and is calculated by multiplying the emission of phosphorus and its relevant compounds by a CF that quantifies the potential to cause freshwater eutrophication.

The calculation is as follows:

$$\text{Eutrophication, freshwater (kg P-eq.)} = \sum E_{i-\text{Eutrophication},f} \times CF_{i-\text{Eutrophication},f}$$

Formula 13: Equation for "Eutrophication, freshwater" calculation

Where:

- $E_{i-\text{Eutrophication},f}$ = Emission of the relevant substance for Eutrophication, freshwater (e.g., phosphate; kg emitted)
- $CF_{i-\text{Eutrophication},f}$ = Characterization factor for the respective eutrophying substance (kg P-eq. per kg emission).

Characterization Factors in EF Method, Freshwater

Table 26 [Table](#) presents the average CFs for freshwater eutrophication, quantifying each emission or nutrient's contribution to this impact. The impact of freshwater eutrophication is expressed in P- eq., wherein different eutrophying substances are converted based on their effect relative to phosphorus, which is used as the standard reference.

If the region where the emission occurs is known, use the regionalized factors. For regionalized figures see guidance on page 17.

Table 26: EF 3.1 Eutrophication, freshwater average characterization factors, expressed in kg P-eq. per kg emissions (EF3.1), also including secondary emissions to soil

Flow	Emission to	CF [kg P-eq. per kg]
Phosphate	Soil ¹	0.016
	Water ²	0.330
Phosphoric acid	Soil ¹	0.016

	Water ²	0.320
Phosphorus	Soil ¹	0.050
	Water ²	1.000
Phosphorus, total	Soil ¹	0.050
	Water ²	1.000

¹ unspecified, agricultural, non-agricultural (secondary emission)

² unspecified long-term, sea water, fresh water, water unspecified (primary emission)

To access the full list of characterization factors for Eutrophication, freshwater, please use the following link: [EF 3.1.](#)

Selection guidance

Generally, EF 3.1 provides CFs for elementary flows with different geographical granularity. Based on the LCA software and database used, the geographical granularity of available CFs might vary.

For Eutrophication, marine and freshwater there are only global averages available (see [EF 3.1.](#)). For Eutrophication, terrestrial there are in some cases country-specific CFs available (see [EF 3.1.](#)).

11.2.2. LCI flows

Commonly, a few examples of relevant flows regarding Eutrophication can be found in Table 27.

Table 27: Description of relevant LCI flows concerning Eutrophication

LCI flow	Description of flow
Terrestrial and marine-specific	
Ammonia, Ammonium emissions to air	- Haber-Bosch and fertilizer production plants release ammonia during manufacturing - Terrestrial ammonia discharges due to excessive fertilizer usage in agricultural processes
Nitrogen oxide (NO _x , NO, NO ₂) emissions to air	- Burning of fossil fuel industrial boilers, furnaces, and other high-temperature processes - Release of nitrogen oxides in nitric acid and adipic acid production
Nitrate emissions	Fertilizer production plants e.g., for ammonium nitrate release nitrate emissions during manufacturing
Freshwater-specific	
Phosphate, Phosphorus, phosphoric acid	- Release of phosphorous containing emissions in phosphoric acid production, fertilizer production and detergent manufacturing - Agricultural run-off containing phosphorous emissions due to excessive fertilizer usage

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#).

11.3. Assessment examples

This following example illustrates how the eutrophication is calculated for a product system called “fertilizer production”.

Example: Fertilizer Production

A company is producing a common fertilizer containing phosphate and nitrate salts in France. During production and wastewater treatment, emissions into the environment occur (Figure 16). To calculate the eutrophication potentials (freshwater, marine and terrestrial) the calculation is done as follows:

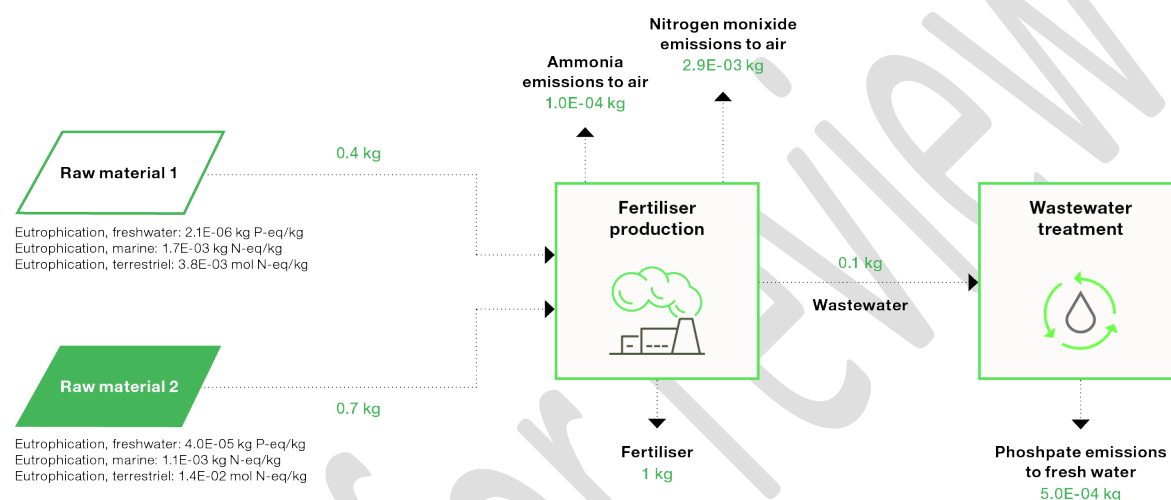


Figure 16: Exemplary calculation of eutrophication impacts of fertilizer production.

With the CFs from EF3.1 as listed in Table 25, 26 and 27, the three eutrophication potentials can be calculated as follows:

Eutrophication, terrestrial = eutrophication, terrestrial (RM1) + eutrophication, terrestrial (RM2) + eutrophication, terrestrial (production, wastewater treatment)

Formula 14: Equation for “Eutrophication, terrestrial” calculation

$$\begin{aligned} \text{Eutrophication, terr} &= 0.4 \frac{\text{kg}_{\text{RM1}}}{\text{kg}_{\text{fert}}} * 3.8 \cdot 10^{-3} \frac{\text{mol}_{\text{Neq}}}{\text{kg}_{\text{RM1}}} + 0.7 \frac{\text{kg}_{\text{RM2}}}{\text{kg}_{\text{fert}}} * 1.4 \cdot 10^{-2} \frac{\text{mol}_{\text{Neq}}}{\text{kg}_{\text{RM2}}} + 1 \cdot 10^{-4} \frac{\text{kg}_{\text{Ammonia}}}{\text{kg}_{\text{fert}}} * 10.8 \frac{\text{mol}_{\text{Neq}}}{\text{kg}_{\text{Ammonia}}} \\ &\quad + 2.9 \cdot 10^{-3} \frac{\text{kg}_{\text{NO}}}{\text{kg}_{\text{fert}}} * 6.53 \frac{\text{mol}_{\text{Neq}}}{\text{kg}_{\text{NO}}} \\ \text{Eutrophication, terrestrial} &= 3.1 \cdot 10^{-2} \frac{\text{mol}_{\text{Neq}}}{\text{kg}_{\text{fert}}} \end{aligned}$$

Formula 15: Equation for “Eutrophication, marine” calculation

Eutrophication, marine = eutrophication, marine (RM1) + eutrophication, marine (RM2) + eutrophication, marine (production, wastewater treatment)

$$\begin{aligned} \text{Eutrophication, marine} &= 0.4 \frac{kg_{RM1}}{kg_{fert}} * 1.7 \cdot 10^{-3} \frac{kg_{Neq}}{kg_{RM1}} + 0.7 \frac{kg_{RM2}}{kg_{fert}} * 1.1 \cdot 10^{-3} \frac{kg_{Neq}}{kg_{RM2}} + 1 \cdot 10^{-4} \frac{kg_{Ammonia}}{kg_{fert}} * 0.092 \frac{kg_{Neq}}{kg_{Ammonia}} + \\ &\quad 2.9 \cdot 10^{-3} \frac{kg_{NO}}{kg_{fert}} * 0.596 \frac{kg_{Neq}}{kg_{NO}} \\ \text{Eutrophication, marine} &= 3.2 \cdot 10^{-3} \frac{kg_{Neq}}{kg_{fert}} \end{aligned}$$

Formula 16: Equation for “Eutrophication, freshwater” calculation

Eutrophication, freshwater = eutrophication, freshwater (RM1) + eutrophication, freshwater (RM2) + eutrophication, freshwater (production, wastewater treatment)

$$\begin{aligned} \text{Eutrophication, freshwater} &= 0.4 \frac{kg_{RM1}}{kg_{fert}} * 2.1 \cdot 10^{-6} \frac{kg_{Peq}}{kg_{RM1}} + 0.7 \frac{kg_{RM2}}{kg_{fert}} * 4 \cdot 10^{-5} \frac{kg_{Peq}}{kg_{RM2}} + 5 \cdot 10^{-4} \frac{kg_{P_{emissions}}}{kg_{fert}} * 0.33 \frac{kg_{Peq}}{kg_{P_{emissions}}} \\ \text{Eutrophication, freshwater} &= 1.9 \cdot 10^{-4} \frac{kg_{Peq}}{kg_{fert}} \end{aligned}$$

12. Particulate Matter

12.1. General Description

12.1.1. Issues of Concern

Particulate matter (PM) consists of solid or liquid particles suspended in the air and is commonly categorized by size, such as PM_{10} (coarse particles), $PM_{2.5}$ (fine particles) and ultrafine particles ($<0.1 \mu m$) (U.S. Environmental Protection Agency (EPA), 2025). These particles originate from combustion processes, industrial activities, mechanical abrasion, and secondary atmospheric formation through chemical reactions of precursor gases. Sources can be as well natural, such as dust storms and wildfires, or anthropogenic, including industrial processes, transportation, residential heating, and agriculture. The analysis in this chapter is restricted to PM_{10} and $PM_{2.5}$ due to the greater availability and reliability of data for these particle size fractions.

PM influences multiple environmental domains, including ecosystems, materials, and the built environment. However, in impact assessment frameworks aligned with EF and ILCD recommendations (Zampori & Pant, 2019; Hauschild, et al., 2011), the primary concern is the impact of PM on human health, as this represents the most scientifically quantifiable impact. Fine particles, with $PM_{2.5}$ and its precursors, contributes to adverse health outcomes through inhalation exposure, leading to increased risks of respiratory and cardiovascular diseases.

Although secondary effects such as reduced visibility, material degradation, and ecological disturbances are recognized, these outcomes are not typically used as the basis for quantifying PM-related impacts within standardized assessment methodologies. Instead, characterization focuses on human exposure pathways, intake fractions, dose response relationships and resulting damage to health (European Commission (EC), Joint Research Centre, Institute for Environment and Sustainability, 2011).

Activities such as combustion of fossil fuels, agricultural burning, industrial processes, and wildfires strongly influence atmospheric PM concentrations. When PM accumulates in the atmosphere, it can alter radiative balance and modify local environmental conditions. Nevertheless, from a methodological standpoint, these broader environmental alterations remain secondary to the measurable and scientifically validated health effects, which form the foundation for particulate matter characterization in internationally harmonized impact assessment methods (U.S. Environmental Protection Agency (EPA), 2025).

Because of its ability to travel long distances, affect human health, degrade ecosystems, and contribute to climate change, PM is a key focus in environmental monitoring and air quality management. Accurate characterization methods are essential for understanding its distribution, behavior, and potential impacts (U.S. Environmental Protection Agency (EPA), 2025).

Human Health Impacts

Fine particles, especially $PM_{2.5}$, can penetrate deep into the respiratory tract and reach the bloodstream. Exposure is associated with respiratory diseases, cardiovascular disorders, and increased mortality risk. Because these effects are well-characterized and quantifiable, human health represents the primary focus for particulate matter within impact assessment frameworks.

Environmental Effects

Deposition of particles on soil and water bodies can alter physicochemical conditions and affect ecological functioning. PM also reduces visibility through light scattering and contributes to the formation of atmospheric haze. Surface deposition may impair vegetation by coating leaves and reducing photosynthetic efficiency.

Climate Interactions

Different particle types influence the earth's radiative balance in opposing ways. Light-absorbing aerosols such as black carbon contribute to atmospheric warming, whereas reflective particles such as sulfates exert a cooling effect. PM also plays a role in cloud nucleation processes, affecting cloud formation, lifetime, and precipitation patterns.

Material and Cultural Heritage Damage

PM contributes to the soiling, discoloration, and chemical degradation of building materials, monuments, and cultural heritage assets, particularly through interactions with moisture and acidic components.

Given these wide-ranging impacts, particulate matter remains a key pollutant of concern across environmental policy, atmospheric sciences, and human health protection frameworks (U.S. Environmental Protection Agency (EPA), 2025).

12.1.2. Key Components of Potential Impact

The substances mostly considered as contributors to particulate matter impacts in LCA include but are not limited:

- Primary particulate matter
- Dust (PM₁₀, PM_{2.5}) from mechanical processes, handling of solids, grinding, drying, and abrasive operations
- Metal-containing particles (e.g. alumina, unspecified metal dusts) (Fantke, et al., 2016).
- Combustion-derived particles such as black carbon and organic carbon (EEA, 2024).
- Secondary particulate matter precursors
- Sulfur dioxide (SO₂) and sulfur trioxide (SO₃), which form sulfate aerosols (Roy & Sardar, 2015).
- Nitrogen oxides (NO_x), which contribute to nitrate aerosol formation (Lao, Li, & Yan, 2024).
- Ammonia (NH₃), which reacts with sulfuric and nitric acids to form ammonium sulfate and ammonium nitrate particles (Patil, Voris, Kane, & Northrop, 2025).
- Selected VOCs, which contribute indirectly to secondary PM formation through atmospheric oxidation pathways (Wang, et al., 2022).

Although a wide range of substances may contribute to PM formation, SO₂, NO_x, and NH₃ are generally considered the dominant precursors in LCIA methodologies, due to their well-

established role in secondary particle formation and their inclusion in harmonized characterization models.

12.1.3. Regulatory Compliance

Particulate matter regulation plays a critical role in ensuring air quality and protecting public health. Regulatory compliance requires organizations to monitor emissions, implement control technologies, and adhere to standards established by governing bodies (Nazarenko, Pal, & Ariya, 2021). While global standard for PM has not been defined, some countries/regions have established their own regulatory frameworks. A high-level overview is provided in Table 28.

Table 28: Overview of regulatory bodies and sources

Regulatory Body	Source
European Union (EU)	Directive 2008/50/EC on ambient air quality (European Union (EU), 2008)
United States Environmental Protection Agency (USA)	NAAQS (National Ambient Air Quality Standards) form the legal compliance regime for ambient air quality in the U.S. (U.S. Environmental Protection Agency (EPA), 2025)
Ministry of Ecology and Environment (China)	China differentiates between “protected/natural” zones (Class I) and urban/industrial zones (Class II) in its air-quality standards. (Ministry of Ecology and Environment of the People’s Republic of China, 2012)

The World Health Organization (WHO) plays an advisory but highly influential role in global air-quality governance. Their guideline is designed as a reference tool for decision-makers at the international, national or local level (World Health Organisation (WHO), 2021).

12.1.4. Importance for the Chemical Industry

PM is a critical performance indicator for the chemical industry due to its significant impacts on human health, the environment, and regulatory compliance. Chemical manufacturing activities, including combustion processes, material handling, and secondary particle formation from gaseous precursors such as SO₂, NO_x, and VOCs, contribute to emissions of PM₁₀ and PM_{2.5} (Wang, et al., 2022). Monitoring PM as a key performance indicator (KPI) enables chemical companies to track emission performance, ensure compliance, and identify opportunities for process optimization and emission reduction. Furthermore, integrating PM indicators into life cycle assessment and sustainability reporting supports risk management, improves transparency, and aligns the chemical industry with broader environmental and public health objectives.

In many chemical manufacturing processes, particulates are either a desired product or an unwanted byproduct. For example, in processes like crystallization or precipitation, control of particle size and distribution is critical in achieving the desired product quality. Uncontrolled particulate formation and release to the environment can cause negative impacts to ecosystems and human health.

The chemical industry is subject to stringent environmental regulations regarding emissions of particles into the air and water. Excessive release of particulates can contribute to air pollution, harm ecosystems, posing significant risks to public health. Monitoring and controlling PM emissions helps companies comply with environmental standards and avoid legal penalties, while also supporting corporate sustainability goals.

Exposure to airborne particulates can present health risks to workers, including respiratory issues, skin irritation, and long-term diseases such as silicosis or cancer, depending on particle composition. Implementing dust control measures, proper ventilation, and personal protective equipment is crucial for safeguarding employee health and maintaining a safe work environment.

Below are reported some chemical production processes related to PM.

- **Cement and Lime Manufacturing:** Although often classified as mineral industries, many chemical plants produce cement and lime as part of broader operations. Crushing, grinding, and kiln processes emit both coarse and fine particulates (U.S. Environmental Protection Agency (EPA), 1987; de Souza Zorzenão, et al., 2024).
- **Sulfuric Acid Plants:** The production of sulfuric acid releases sulfur dioxide (SO_2), which is a key precursor for secondary PM. Additional dust can arise during ore handling and roasting (Roy & Sardar, 2015).
- **Chlor-alkali Industry:** Processes involving salt handling, electrolysis, and product separation can generate PM emissions, especially in older facilities with less advanced abatement technologies (Brinkmann, Giner Santonja, Schorcht, Roudier, & Delgado Sancho, 2014).
- **Petrochemical Production:** Flaring, catalyst regeneration, and various combustion processes associated with the production of ethylene, propylene, and other chemicals can emit both primary particulates and gaseous precursors such as NO_x and SO_2 (Tavella, da Silva Júnior, Santos, Miraglia, & Pereira Filho, 2025).
- **Pigment and Dye Manufacturing:** Operations such as grinding, drying, and blending of solid dyes and pigments are sources of PM emissions (Kavitha, Govindhan, & Premkumar, 2025).
- **Pharmaceutical Manufacturing:** Tablet pressing, coating, and powder handling in pharmaceutical production can release fine dust, impacting indoor and outdoor air quality (Champmartin & Clerc, 2014).

12.2. Methodology of characterization

12.2.1. Chosen method: EF

Various LCIA characterization models are available to assess the human health impacts of PM using either midpoint or endpoint approaches. For midpoint assessment, the RiskPoll model is applied, with $\text{PM}_{2.5}$ used as the indicator (European Commission (EC), Joint Research Centre, Institute for Environment and Sustainability, 2011). Endpoint assessment is based on adapted Disability-Adjusted Life Year (DALY) calculation derived from midpoint results (Van Zelm R. , et al., 2008; Pope, et al., 2002). The midpoint impact category focuses on disease incidences associated with exposure to both primary and secondary particulate matter. In contrast, the endpoint approach captures long-term human health effects and expresses them in terms of DALYs. Consistent with all other methods used throughout the document, a midpoint approach

is also selected for this impact category. The Product Environmental Footprint (PEF), as defined in EF 3.1, is therefore the recommended methodology for assessing particulate matter impacts as well.

The EF-approach leverages the latest scientific consensus and advanced modeling techniques, which allow for more precise and reliable quantification of particulate matter impacts. By using updated characterization factors and exposure models, the use of the EF-model reduces uncertainty and delivers results that are trusted by both scientists and regulators.

Within the EF framework, impacts are quantified in units of deaths per kilogram of emitted substance, accounting for secondary particle formation through a combined application of the joined approach of United Nations Environment Programme (UNEP) and the Life Cycle Initiative (United Nations Environment Programme, SETAC Life Cycle Initiative, 2016) and the RiskPoll models (Fantke, et al., 2016) therein. The following section describes the underlying impact pathways and provides an overview of the different methodological approaches and indicators used for particulate matter impact assessment.

In Chem-X the Product Environmental Footprint (PEF) recommended method of „disease incidence" is used (Fantke, et al., 2016).

The EF method, developed under the European Commission's Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) initiatives, is a harmonized LCIA approach designed for consistency across sectors. For PM impacts, EF focuses on human health effects due to exposure to PM emissions.

EF 3.1 addresses both direct and indirect effects of particulate matter:

- Direct emissions (primary PM) from tailpipes, smokestacks, and construction sites.
- Indirect (secondary PM) formation from chemical precursors in the atmosphere.

These particles contribute to a range of health impacts, including aggravated asthma, heart attacks, decreased lung function, and premature death, especially in vulnerable populations such as children and the elderly (European Commission (EC), 2021).

Formula

The process follows the next steps to prepare the calculation of the impacts:

- **Identify emissions:** Collect all relevant PM emission data from your product's life cycle. These are the "flows" of substances into the environment.
- **Apply characterization factors:** Multiply the amount of each substance (e.g., PM_{2.5}, PM₁₀) by its specific CF from the EF 3.1 method.

The calculation is as follows and shown in Formula 17:

Characterization

Aggregation of the results: The total characterized value for PM is the sum of the characterized values for all relevant substances.

$$\text{Particulate Matter (Disease Incidence)} = \sum E_{i-\text{Particulate Matter}} \times CF_{i-\text{Particulate Matter}}$$

Formula 17: Equation for "Particulate Matter" calculation

Where:

- $E_{i-\text{Particulate Matter}}$ = Emission of the relevant substance for Particulate Matter, e.g. Ammonia via transformation per kg emission
- $CF_{i-\text{Particulate Matter}}$ = Characterization factor for the respective particulate matter (Disease Incidence per kg emission).

Characterization Factors in EF Method

In the EF methodology, the focus is typically on PM₁₀ (particles with a diameter of 10 micrometers or less) and PM_{2.5} (particles with a diameter of 2.5 micrometers or less) as these are small enough to be inhaled and cause respiratory and cardiovascular issues in humans. In some cases, ultrafine particles (smaller than 0.1 micrometers) are also considered due to their ability to penetrate deep into the lung tissue and bloodstream. These particles originate from various sources, including combustion processes, industrial activities, and natural phenomena such as dust storms and wildfires (Hauschild, et al., 2011). PM₁₀ and PM_{2.5} will be the focal point in this analysis due to the better data availability and availability of characterization factors for these particle sizes.

EF 3.1 (Hauschild, et al., 2011; Fantke, et al., 2016) employs advanced characterization models to translate emissions of various precursor substances into potential health impacts. These models consider:

- **Emission Source and Location:** The effect of particulate matter depends greatly on whether it is released into urban, rural or remote areas.
- **Chemical Composition:** Not all particulates are equally harmful. The model considers the toxicity and reactivity of different compounds, such as black carbon, organic carbon, sulfate, and nitrate particles.
- **Transformation Pathways:** Some emissions, like nitrogen oxides (NO_x), sulfur dioxide (SO₂), and ammonia (NH₃), form secondary particulate matter through atmospheric chemical reactions. The EF method includes these precursor emissions in its calculations.
- **Exposure and Intake:** Human exposure is estimated based on population distribution, prevailing winds, particle dispersion, and rates of inhalation.

The results are commonly expressed in metrics such as "disease incidence per unit emission" as midpoint indicator which are used throughout the document. Using the method "Years of life lost" it is an endpoint indicator and should not be used. They reflect the final health impact attributable to particulate matter from a product or activity's life cycle.

If the region where the emission occurs is known, use the regionalized factors. For regionalized figures see guidance on page 17.

Table 29: EF3.1 Particulate Matter characterization factors for Europe and for emissions to air, unspecified, expressed in disease incidence per kg, (EF3.1)

Flow	CF [Disease Incidence per kg) for Human Health
Ammonia	2.1E-05
Nitrogen Dioxide	1.6E-06
Nitrogen Monoxide	1.6E-06
Nitrogen Oxides	1.6E-06
Particles (PM2.5)	2.4E-04
Particles (PM10)	5.5E-05
Sulfur Dioxide	8.0E-06
Sulfur Trioxide	8.0E-06
Sulfur Oxides	8.0E-06

To access the full list of characterization factors of characterization factors for Particulate Matter, please use the following link: [EF 3.1](#).

Selection guidance

Generally, EF 3.1 provides global CFs for the PM relevant elementary flows. However, depending on the database used (e.g., ecoinvent, Sphera MLC), the PM is assessed using averages of emissions from different sources like air emissions from high stacks, urban, non-urban areas. If no regionalization applies use Averages. In addition, choose the most appropriate sub-compartment as urban / high-stacks and non-urban areas. The goal for the future should remain to switch from average to more regionalized CFs.

12.2.2. LCI Flows

In Table 30 several LCI flows are shown with the relevant description of the flow elements to give further background on the information needed for accurate assessments of them.

Table 30: Description of relevant LCI flows concerning Particulate matter

LCI Flow	Description of Flow
Ammonia	Ammonia (NH ₃) is primarily produced through agricultural activities, particularly from livestock waste and the application of nitrogenous fertilizers. It can also be emitted during the combustion of fossil fuels and biomass.
Nitrogen Oxides	Nitrogen oxides (NO _x) are a group of gases that includes both nitrogen monoxide (NO) and nitrogen dioxide (NO ₂). They are emitted from vehicle exhaust, industrial processes,

	and power generation, primarily during combustion.
Nitrogen oxides [lower stratosphere + upper troposphere]	These nitrogen oxides form naturally through lightning, which produces high-energy reactions between nitrogen (N_2) and oxygen (O_2). They also arise from the photochemical oxidation of nitrous oxide (N_2O) emitted by soils, oceans, and microbial activity. At high altitudes, these reactions contribute to natural NO and NO_2 concentrations.
Sulphur Dioxide	Sulphur dioxide (SO_2) is mainly produced from the burning of fossil fuels, particularly coal and oil, in power plants and industrial facilities. It can also be emitted from volcanic eruptions.
Sulphur Trioxide	Sulphur trioxide (SO_3) is produced during the oxidation of sulphur dioxide (SO_2) in the atmosphere or during industrial processes, particularly in the manufacture of sulfuric acid.
Aluminium oxide (dust)	Aluminium Oxide (dust) is naturally formed through weathering of aluminium-rich rocks, soil erosion, and mineral breakdown. Volcanic eruptions and strong winds can lift fine alumina dust into the air. Man-made sources include aluminium smelting, metal refining, abrasive blasting, and high-temperature industrial processes that release alumina particles.
Dust (PM_{10})	PM_{10} particles originate naturally from windblown soil and sand, desert dust and storms. It is majorly produced by fertilizers, cement and lime manufacturing industries.
Dust ($PM_{2.5}$)	$PM_{2.5}$ forms naturally from wildfires, volcanic emissions, sea spray, and secondary atmospheric reactions involving natural precursors (e.g., biogenic VOCs, natural sulfur compounds). Their small size allows them to stay airborne for long

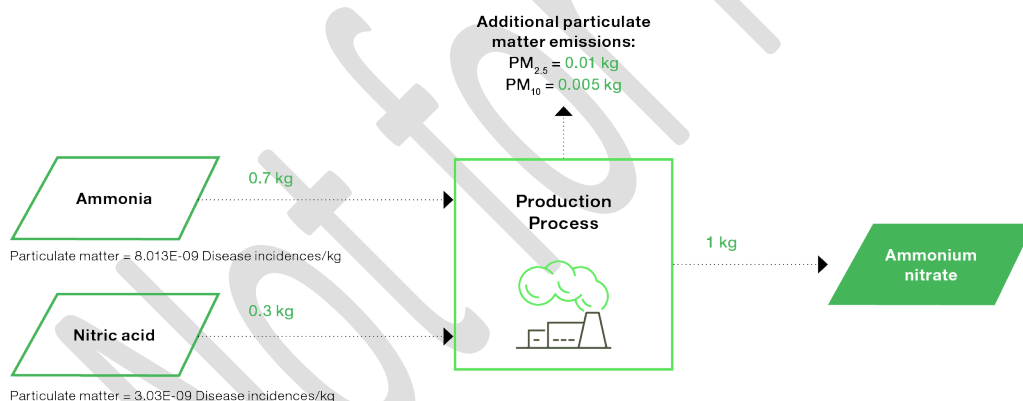
	durations It is majorly produced by fertilizers, cement and Lime manufacturing industries.
Metals (unspecified)	Metals occur naturally from volcanic eruptions, mineral dust uplift, sea spray, and weathering of rocks and soils. Man-made emissions come from metal smelting, refining, fossil-fuel combustion, cement production, waste incineration, and brake and tire wear.

To access the full list of characterization factors for Particulate matter, please use the following link: [EF 3.1](#).

12.3. Assessment Examples

For the illustration of impacts of a chemical process, the relevant flows need to be identified and connected with the characterization factor. In this example, two inputs are relevant, and emission flows are identified. The calculation is shown in the formula at the bottom of the Figure 17.

The production of ammonium nitrate requires ammonia and nitric acid. Calculate the amount of particulate matter released during this process



Particulate matter = $8.013\text{E-}09 \text{ Disease incidences/kg} \times 0.7 \text{ kg} + 3.03\text{E-}09 \text{ Disease incidences/kg} \times 0.3 \text{ kg} + 2.4\text{E-}04 \text{ Disease incidences/kg} \times 0.01 \text{ kg} + 5.5\text{E-}05 \text{ Disease incidences/kg} \times 0.005 \text{ kg} = 2.61\text{E-}09 \text{ Disease incidences/kg}$

Figure 17: Calculation of impacts of a chemical process of the impacts of particulate matter (PM)

13. Ionising radiation (human health)

13.1. General Description

13.1.1. Issue of concern

Ionising radiation refers to energy that can remove electrons from atoms, creating ions. In this context, the issue of concern is in regard to the effect on human health related to the routine releases of radioactive material to the environment (World Health Organization (WHO), 2023; Occupational Safety and Health Administration (OSHA), 2026a; Occupational Safety and Health Administration (OSHA), 2026b; Occupational Safety and Health Administration (OSHA), 2026c; Occupational Safety and Health Administration (OSHA), 2026d).

Exposure to ionising radiation can lead to both acute and long-term health effects, depending on dose, duration, and exposure pathway. High doses received over a short period may result in acute radiation effects, including radiation burns and acute radiation syndrome (ARS), with symptoms such as nausea, vomiting, diarrhoea, and, at very high doses, death. Cutaneous radiation injury has been reported at doses as low as approximately 2 Gy (Centers for Disease Control and Prevention, 2024; Centers for Disease Control and Prevention, 2024).

Long-term and low-dose exposures are associated with stochastic health effects, for which no threshold dose is assumed. These include increased lifetime risks of cancers such as thyroid, lung, breast cancer, and leukemia (World Health Organization (WHO), 2023; Occupational Safety and Health Administration (OSHA), 2026a; Occupational Safety and Health Administration (OSHA), 2026b; Occupational Safety and Health Administration (OSHA), 2026c; Occupational Safety and Health Administration (OSHA), 2026d). Additional long-term health outcomes linked to chronic exposure include cardiovascular disease, cerebrovascular disorders, and hereditary effects resulting from radiation-induced DNA damage (Little, et al., 2023; International Commission on Radiological Protection (ICRP), 2022).

Certain population groups are more vulnerable to the effects of ionising radiation. Children and pregnant individuals are considered particularly sensitive due to developing tissues and longer post-exposure life expectancy, with potential risks including adverse fetal development outcomes. Occupational exposure may also occur among workers operating near radiation sources or handling radioactive materials, where appropriate shielding, distance, and exposure time management are critical risk-mitigation measures (Centers for Disease Control and Prevention, 2025; World Health Organization (WHO), 2023; Occupational Safety and Health Administration (OSHA), 2026a; Occupational Safety and Health Administration (OSHA), 2026b; Occupational Safety and Health Administration (OSHA), 2026c; Occupational Safety and Health Administration (OSHA), 2026d).

13.1.2. Key components of potential impact

The radionuclides normally considered relevant contributors to ionising radiation in life cycle assessment are those associated with nuclear fuel cycles, industrial activities, and naturally occurring radioactive materials mobilised by human activities. These may include, for example, uranium-238 (U-238), uranium-235 (U-235), radium-226 (Ra-226), radon-222 (Rn-222), and cobalt-60 (Co-60). Common sources include emissions from uranium mining, fuel fabrication,

reactor operation, spent fuel and waste management, the use of radioactive materials in medical and industrial applications, and the mobilisation of naturally occurring radionuclides through mineral extraction, processing, and fossil fuel combustion.

13.1.3. Regulatory compliance

Global regulatory compliance for ionising radiation is founded based on internationally recognized safety standards and coordinated by key organizations to ensure consistent protection of workers, public, and environment (World Health Organization (WHO), 2023). The International Atomic Energy Agency (IAEA) develops safety standards based on global consensus, incorporating scientific findings from United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (Shannoun, 2015; Chen J. , 2024) and recommendations from the International Commission on Radiological Protection (ICRP, 2014) (IAEA, 2014). These standards emphasize justification of practices, optimization through the As Low As Reasonably Achievable (ALARA) principle, and strict dose limits for all exposure scenarios—planned, existing, and emergency (ICRP, 2007) (IAEA, 2014). The ICRP sets widely adopted dose limits of 20 mSv per year for occupational exposure (averaged over five years) and 1 mSv per year for public exposure, forming the basis of most national regulations (ICRP, 2007). Complementing these efforts, the WHO focuses on health implications and promotes harmonization of standards globally, ensuring evidence-based guidance for public and occupational health. Together, these organizations create a unified framework for global radiation safety.

Regional compliance also builds on these principles. In Europe, regulation is primarily governed by the Euratom Treaty and its directives (European Commission (EC), 2013), which establish uniform safety standards and require continuous monitoring of radioactivity in air, water, and soil, as well as information exchange on waste disposal and emergencies. Directive 2013/59/Euratom sets dose limits of 20 mSv per year for workers and 1 mSv per year for the public, with special provisions for pregnant workers. It applies to all exposure situations and sources, including natural radiation, mandates justification of practices, optimization under ALARA, emergency preparedness, monitoring, and reporting, and aligns closely with ICRP recommendations.

Similarly, in the United States, compliance is enforced through multiple federal agencies and supplemented by state and institutional requirements. The Nuclear Regulatory Commission (NRC) regulates occupational and public exposure under 10 CFR Part 20, including Annual Limits on Intake (ALI), Derived Air Concentrations (DAC), licensing of radioactive materials, reactor design objectives, and emergency preparedness (U.S. Nuclear Regulatory Commission (NRC), 2016). The Department of Energy (DOE) applies 10 CFR Part 835 for occupational radiation protection in DOE facilities, including dose limits and monitoring requirements (U.S. Department of Energy (DOE), 2026). The United States Environmental Protection Agency (U. S. EPA) sets environmental radiation standards under 40 CFR Parts 190–192 (U.S. Environmental Protection Agency (EPA), 2025; U.S. Environmental Protection Agency (EPA), 2026) while OSHA enforces workplace safety through 29 CFR 1910.1096 (Occupational Safety and Health Administration (OSHA), 2026a) and 29 CFR 1926.53 (Occupational Safety and Health Administration (OSHA), 2026b), requiring exposure monitoring and worker training. State-level NRC Agreement regulate radioactive materials locally, and institutions such as “National Institutes of Health” (NIH, [National Institutes of Health \(NIH\)](#)) implement internal programs including Radiation Safety Committees, dose monitoring, and contamination control. Together, these layers of regulation ensure comprehensive radiation safety across industrial, research, and medical applications.

13.1.4. Importance for the chemical industry

Ionising radiation assessment is important for the chemical industry as it is critical for ensuring safety, regulatory compliance, and process integrity, while also supporting the ALARA principle by keeping exposures as low as reasonably achievable (Occupational Safety and Health Administration (OSHA), 2026c; U.S. Nuclear Regulatory Commission (NRC), 2016). Radiation is widely used for polymerization, sterilization, and analytical applications including both laboratory analytical equipment and operational devices such as level, density, and thickness gauge, but uncontrolled exposure can pose significant health risks to workers and lead to environmental contamination (International Atomic Energy Agency (IAEA), 2021; Naikwadi, Sharma, Bhatt, & Mahanwar, 2022). Continuous monitoring enables early detection of elevated radiation levels, verifies the effectiveness of protective measures, and helps maintain exposures within permissible limits set by agencies such as NRC, OSHA, and EPA (Occupational Safety and Health Administration (OSHA), 2026c; U.S. Nuclear Regulatory Commission (NRC), 2024). It also provides documentation for audits, supports process optimization, and identifies trends for continuous improvement (Centers for Disease Control and Prevention, 2024; U.S. Department of Energy (DOE), 1999). Beyond compliance, effective monitoring safeguards product quality, minimizes liability, and reinforces the industry's commitment to sustainable and responsible operations (Centers for Disease Control and Prevention, 2024) (ICRP, 2007).

13.2. Methodology of characterization

13.2.1. Chosen method: EF 3.1

Ionising radiation (IR) is an impact category in several commonly used LCIA methods including Environmental Footprint 3.1 (EF 3.1; (Zampori & Pant, 2019)), ReCiPe 2016 Midpoint (Huijbregts, Steinmann, & Elshout, ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level, 2017) as well as IMPACT World+ (Bulle C. , et al., 2019). These LCIA methods include a wide variety of radionuclides, including prominent radionuclides such as uranium and plutonium, as well as less commonly cited radionuclides such as americium and specific radioactive isotopes such as ruthenium-106. For all ionising radiative elements, both waterborne and airborne emissions are considered. Although several LCIA methods contain an ionising radiation midpoint category, their indicators are not fully harmonized.

EF 3.1 measures ionising radiation as “human exposure efficiency relative to U-235” in kBq U-235 equivalents, following the characterization model of (Frischknecht, Braunschweig, Hofstetter, & Suter, 2000). By contrast, ReCiPe's midpoint ionising radiation uses a different reference basis to measure ionising radiation - kBq Co-60 to air eq, resulting in difference in results that go beyond unit formatting but stems from a fundamentally different reference radionuclide for the measurement. As a result, comparability requires explicit conversion and careful mapping of elementary-flows and compartments.

IMPACT World+ is a combined midpoint/damage methodology, where ionising radiation is modelled using the general source-to-impact pathway (emission → fate/exposure → human health relevance), drawing on the ExternE/Frischknecht foundations (Bulle C. , et al., 2019) widely in LCA for routine radionuclide releases. Nonetheless, the method expresses the result of ionising radiation in units of Bq C-14-eq/Bq, differing from both EF3.1 and ReCiPe.

In line with the overall methodological approach of this guideline, the Environmental Footprint (EF) method v3.1 is recommended as the default LCIA method for ionising radiation (human health) for chemical intended to support EU-oriented DMP/DPP implementation. This is

consistent with the approach taken in other impact categories in this document where EF is preferred when alternative methods are available, to avoid hybrid LCIA application and to facilitate interoperability of DMP/DPP data across organizations and tools.

At midpoint level, ionising radiation indicator represents ionising radiation potential / exposure efficiency rather than direct health damage. The method proposed by Frischknecht *et al.* (Frischknecht, Braunschweig, Hofstetter, & Suter, 2000) is widely used and is explicitly referenced as a basis for the ILCD-recommended midpoint modelling of ionising radiation in the European context (Hauschild, et al., 2011).

Formula

The calculation is as follows and shown in Formula 18:

$$IR = \sum_{j=1}^N (q_j \times CF_j)$$

Formula 18: Equation for “Ionising radiation” calculation

Where:

- **IR:** Ionising radiation impact result, reported in kBq U235-eq (U-235 equivalents).
- **N:** Number of radionuclide flows in the inventory that have a matching EF 3.1 ionising-radiation characterization factor and are therefore included.
- **j:** Index that labels each included radionuclide elementary flow from 1 to N
- **q:** Inventory quantity of radionuclide flow j, expressed in kBq
- **Characterization factor (CF):** EF 3.1 characterization factor for radionuclide flow j, with units (kBq U235-eq / kBq emitted) and specific to the emission compartment.

Characterization Factors in EF Method

The indicator of ionising radiation in the EF method is the quantification of the impact of ionising radiation on the population, in comparison to Uranium 235. According to the current ILCD nomenclature, the elementary flows of radionuclides are expressed in kBq; the CFs were thus expressed per kBq. It is applicable at a global scale (no spatial differentiation).

To access the full list of characterization factors for ionising radiation, please use the following link [EF 3.1](#).

Selection guidance

As this is a global impact category, no selection is needed.

13.2.2. LCI flow

Many industrial processes during routine operations release radionuclides into the environment in the form of air- or water-borne materials or solid wastes. The nuclear, coal, oil and gas, fertiliser and building industries are among the major contributors (Paulillo, et al., 2018).

Table 31 shows a few examples of LCI flows for Ionising Radiation. For the full table see [EF 3.1](#)

If the region where the emission occurs is known, use the regionalized factors. For regionalized figures see guidance on page 17.

Table 31: Description of relevant LCI flows concerning ionising radiation

LCI flow	Description
Uranium-238 (emission to air)	Emission of uranium-238 to air. This may occur, for example, through dust or particulate releases during handling or processing of uranium-bearing raw materials or Naturally Occurring Radioactive Material (NORM) and Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) (TENORM, 2025) containing materials.
Uranium-238 (emission to sea)	Emission of uranium-238 to sea water. This flow is relevant to the nuclear energy value chain because uranium is used in nuclear fuel production and power generation.
Radium-226	Release of radium-226 to fresh water. Radium-226 can be relevant in NORM/TENORM-related materials, including certain mineral processing and phosphate-related value chains.
Radon-222	Emission of radon-222 to air. Radon is a gaseous radionuclide and may be released from materials or residues containing radionuclides from the uranium decay series.
Lead-210	Emission of lead-210 to air. This radionuclide may occur in airborne releases associated with radionuclide-containing dusts or decay-series related emissions.

13.3. Assessment examples

This example illustrates how ionising radiation, human health (IR) is calculated for a representative product system (phosphoric acid production) using the EF 3.1 characterisation factors. The ionising radiation indicator is expressed as kBq U235 eq, representing human exposure efficiency relative to U235 as a reference.

A company produces phosphoric acid from phosphate rock and sulfuric acid. During upstream supply of purchased inputs and the on-site production step, radionuclides may be released to air and to water. For emissions to water, the receiving compartment (e.g., groundwater vs ocean) shall be specified because characterization factors can differ by compartment and therefore influence the IR result.

With the CFs from EF 3.1, the ionising radiation, human health impact can be calculated as follows (unit: kBq U235-eq, i.e., human exposure efficiency relative to U235): Ionising radiation, human health = ionising radiation, human health (*inputs / upstream*) + ionising radiation, human health (*emissions to air*) + ionising radiation, human health (*emissions to water: groundwater + ocean*). The complete calculation is shown in Formula 19.

$$\begin{aligned}
 \text{Total IR} &= \sum_{j \in \text{input material}} (q_j \times CF_j) \\
 &+ \sum_{j \in \text{emission to air}} (q_j \times CF_j) \\
 &+ \sum_{j \in \text{emission to water}} (q_j \times CF_j) = 0.140 + 0.00326 + 0.00152 \\
 &= 0.145 \text{ kBq U325}_{eq}
 \end{aligned}$$

Formula 19: Equation for “Ionising radiation” calculation of all impact flows

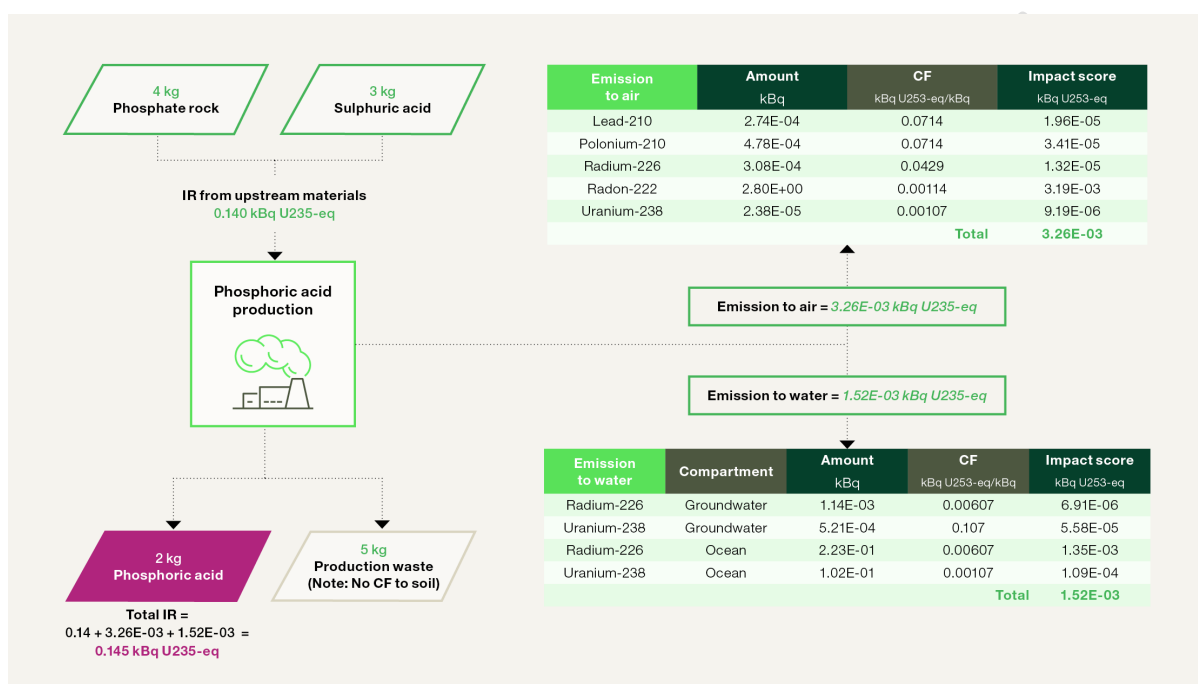


Figure 18: Example of impact assessment for different inputs of a chemical process linked with their characterization factors

Note: The example is simplified and provided for illustrative purposes only; it demonstrates how inventory flows (kBq) are multiplied by EF 3.1 CFs and then summed across compartments. When calculating IR from emissions to water, always specify the receiving compartment (e.g., groundwater vs ocean), because compartment-specific CFs may apply. There is no CF to soil in ionising radiation.



14. Land use

14.1. General Description

14.1.1. Issues of Concern

Land use constitutes a significant environmental impact because it reflects how human activities occupy, modify, and transform terrestrial ecosystems, often leading to long-term changes in ecological structure and function. Unlike emission-based impacts, which primarily act through releases to air, water, or soil, land use directly alters the physical and biological characteristics of landscapes. These alterations influence ecosystem processes over extended spatial and temporal scales, which justifies the explicit treatment of land use as a distinct impact category in life cycle assessment (LCA) frameworks (ISO 14044, 2006) (ISO 14040, 2006).

Land use is a major threat to terrestrial biodiversity, connected with aquatic systems as well. Life cycle assessment is a tool that can assess such threats (Scherer, et al., 2023). Within the Global Guidance for Life Cycle Impact Assessment (GLAM) project, multiple impact categories, including land use impacts on ecosystem quality LCA methods were developed.

The environmental relevance of land use is formally recognized within the UNEP-SETAC¹⁴ Life Cycle Initiative, which established a conceptual framework distinguishing land occupation and land transformation as separate mechanisms of environmental pressure. This framework emphasizes that land-related impacts arise not only from the area of land used, but also from the duration of use and the extent to which land is converted from a reference state, typically natural or semi-natural ecosystems (European Commission, 2016) (Milà i Canals, et al., 2007).

A central reason land use is environmentally important is its strong association with biodiversity change. Land use and land-use change are widely identified as major drivers of biodiversity loss, as they influence habitat availability, landscape connectivity, and ecosystem heterogeneity. Conversion of natural ecosystems to intensive land uses such as agriculture, urban development, or extractive activities typically reduces species richness and alters ecological interactions. Within LCA, these effects are understood as cumulative and spatially differentiated, particularly when assessed across global supply chains (European Commission, 2016).

Land use is also closely linked to soil quality and soil-mediated ecosystem functions. Soils play a fundamental role in regulating biogeochemical cycles, water movement, and biological productivity. Changes in land use and management can modify soil structure, increase erosion, reduce filtration capacity, alter groundwater recharge, and diminish soil organic carbon stocks.

Beyond biodiversity and soils, land use affects the provision of ecosystem services essential to human well-being. Terrestrial ecosystems supply food and biomass, regulate hydrological processes, contribute to climate regulation through carbon storage, and support ecosystem resilience. Alterations in land use can reduce the capacity of ecosystems to deliver these services, leading to broader environmental and socio-economic consequences. Importantly, these effects are interconnected, such that impacts on one ecosystem service may propagate to others (UNEP-SETAC Life Cycle Initiative, 2016).

¹⁴ UNEP-SETAC refers to the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC).

The environmental importance of land use is further reinforced by the finite nature of land as a resource. Only a limited fraction of the Earth's surface is suitable for human use, and increasing demand for agricultural production, infrastructure, and material extraction intensifies competition for land. Allocating land to one function inherently constrains its availability for alternative ecological or societal uses. Unlike certain emissions, which may be reduced or mitigated over time, land transformation often involves irreversible trade-offs, particularly when natural ecosystems are permanently converted (European Commission, 2016).

From the LCA perspective, inclusion of land use is essential to avoid burden shifting between environmental impact categories, especially if biobased products are produced. Interventions aimed at improving performance in one dimension—such as reducing greenhouse gas emissions—may increase pressure on land through changes in sourcing, production routes, or material demand. Accounting for land use therefore supports a more comprehensive interpretation of environmental trade-offs, consistent with the principles articulated in ISO 14040 and ISO 14044 and UNEP-SETAC guidance (ISO 14040, 2006) (Milà i Canals, et al., 2007). Reflecting these considerations, land use is incorporated as a mandatory impact category in the EU Environmental Footprint (EF) methodology.

14.1.2. Key Components of Potential Impact

This section focuses on the key components of land use impact assessment in LCA, which are commonly structured around land occupation and land use change. These components are differentiated by land use type, intensity, and temporal aspects and describe how land use interventions affect ecosystem properties such as biodiversity, soil quality, and ecological functioning. Together, they form the basis for linking land use flows to quantified ecosystem damage within life cycle impact assessment frameworks (Vidal-Legaz, Sala, Antón, & Milà i Canal, 2016).

LANCA® characterization factors from Fraunhofer IBP explains the LANCA framework, which is stated to provide the basis for calculating the Land use impact category in PEF / EF 3.1. It explicitly notes that LANCA covers both land occupation and land transformation, and that the resulting characterization factors are aggregated into the Land Use – Soil Quality Index (Fraunhofer IBP, 2026).

Key Components of Land Use Impact in LCA

Land Occupation

Land occupation refers to the physical area of land required for an activity over a specified period, commonly expressed in m² year. It captures the ongoing pressure on ecosystems caused by agricultural, forestry, industrial, or urban land use and is explicitly addressed in UNEP SETAC land use impact assessment guidelines and the EF 3.1 methodology.

Land Transformation (Land Use Change)

Land transformation involves the conversion of land from one use or cover type to another (e.g., forest to cropland or urban land). Such transformations can cause long lasting or irreversible ecological impacts and are treated separately from land occupation in LCA to reflect their distinct impact pathways and regeneration dynamics (Koellner, 2013).

The following implications can be direct consequences resulting from the above-mentioned two land use activities.

Biodiversity Impact

Land use is a major driver of biodiversity loss, affecting species richness, abundance, and ecosystem integrity. LCA evaluates biodiversity impacts by linking land occupation and transformation to changes in habitat quality, fragmentation, and species extinction risk, following global guidance developed under the UNEP-SETAC Life Cycle Initiative and the Global Guidance for Life Cycle Impact Assessment (GLAM) project.

Soil Quality and Function

Changes in land use influence soil fertility, erosion, compaction, and soil organic carbon (SOC) stocks. Recent LCA methods increasingly use SOC as a proxy indicator for soil quality impacts of land occupation and transformation, in line with recommendations from the Life Cycle Initiative.

Carbon Emissions and Sequestration

Land use and land use change play a significant role in the carbon cycle. Deforestation and soil disturbance can release stored carbon, while afforestation, reforestation, and soil restoration can enhance carbon sequestration. LCA accounts for both emissions and removals to assess the net climate impact of land use interventions.

Ecosystem Services

Land use influences the provision of ecosystem services such as food and biomass production, climate regulation, water purification, and cultural services. UNEP SETAC guidelines explicitly frame land use impact assessment around multiple ecosystem service pathways to ensure a comprehensive evaluation of environmental consequences.

14.1.3. Regulatory Compliance

Regulatory compliance for land use in LCA primarily involves standardized methods to quantify impacts like soil quality degradation, biodiversity loss, and ecosystem services disruption caused by land occupation or transformation. Key requirements stem from international and European standards embedded in building codes, product declarations, and sustainability directives (Fraunhofer IBP, 2026).

Directives like Corporate Sustainability Reporting Directive (CSRD), Energy Performance of Buildings Directive (EPBD) (phased from 2026 for new buildings), and Ecodesign for Sustainable Products Regulation (ESPR) (via Digital Product Passports) require LCA-derived data on land use for Scope 3 emissions, biodiversity, and resource efficiency reporting. National rules (e.g., France's RE2020, Denmark's BR18) enforce these in public procurement and building permits, often demanding verified EPDs with land use metrics (Hedeghog, 2025).

Spatial Differentiation and Regionalization: Regulatory standards often require, or are moving towards requiring, that land use impacts be specific to the region where they occur (e.g., distinguishing between land use in a biodiverse tropical forest versus a temperate managed forest). Failure to properly apply regionalized characterization factors can lead to inaccurate compliance reporting (Beck, et al., 2010) (Bos, 2020).

Biodiversity and Ecological Quality Loss: Compliance with environmental targets (such as those in the EU CSRD) requires quantifying the impact of land occupation on biodiversity (existence

value) and ecological soil quality (life support functions). This is challenging because it requires complex, high-quality data to model impacts such as habitat fragmentation (Chaudhary, 2015).

SOC and Soil Quality: Regulations often demand, as part of land-use impact assessments, the evaluation of land use on soil, particularly for agriculture and forestry. This includes measuring soil organic carbon stocks as a proxy for soil quality and ensuring sustainable land management (De Laurentiis V. M., 2024).

Data Availability, Quality, and Transparency: A significant barrier to compliance is the lack of, or difficulty in obtaining, accurate data on land-use changes across the entire supply chain. Regulations, such as ISO 14067, require high-quality, transparent, and documented data.

Alignment with International Standards (ISO 14040, ISO 14044, ISO 14067): Regulatory compliance often mandates adherence to ISO 14040 and ISO 14044 and ISO 14067, which includes specific requirements for reporting on land-use change, carbon uptake, and biogenic carbon emissions (EPA – United States Environmental Protection Agency, 2026) (ISO 14040, 2006) (ISO 14044, 2006).

14.1.4. Importance for the Chemical Industry

Land use is highly relevant for the chemical industry because it captures the direct occupation and transformation of land ecosystems resulting from the production of bio-based raw materials, agricultural inputs, and natural feedstocks used in the chemical sector (Frenzel, 2014).

Chemical manufacturers that source plant-derived materials — such as palm oil, soy, or sugarcane contribute to land occupation that can degrade soil quality, reduce biodiversity, and disrupt ecosystem services (Oláh, 2023). Compliance with sustainability reporting frameworks is pushing chemical companies to assess and disclose land use impacts across their entire value chain. Industries such as agrochemicals, bio-based polymers, and specialty chemicals are particularly exposed due to their deep dependency on land-intensive agricultural supply chains.

Land use change referring to the conversion of natural landscapes into agricultural or industrial areas is also a relevant consideration for the chemical industry, as it may be associated with broader environmental pressures such as changes in carbon stocks and shifts in biodiversity (Frenzel, 2014). For chemical companies increasingly turning to bio-based feedstocks, incorporating land use change into their LCA's can contribute to a more complete and transparent picture of their overall environmental footprint.

As demand for agricultural commodities increases to meet sustainability targets, the pressure on land resources intensifies — meaning the chemical industry will carry a greater land use burden through its suppliers, making responsible sourcing and land stewardship strategies essential for credible sustainability performance.

14.2. Methodology of characterization

In the current life cycle assessment framework, soil properties and functions are still not systematically incorporated and evaluated (De Laurentiis, et al., Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA, 2019), at the endpoint level, the damage caused to biodiversity has generally been the main target. In line with the objective of the guideline and to ensure consistency with the other impact categories, endpoint (damage) results are out of scope and will not be further elaborated.

Impact pathway and methodological approaches

Potential Impact Assessment Methods in LCA

- **Quantitative Metrics:** Land occupation ($\text{m}^2 \text{ year}$) and land transformation (m^2) form the core inventory indicators for land use in LCA, as defined in ISO compliant methodologies and UNEP SETAC guidance (ISO 14044, 2006) (Koellner, 2013).
- **Qualitative Evaluations:** Biodiversity indicators, ecosystem quality metrics, and ecosystem service assessments are used to interpret land use impacts beyond simple area-based measures, reflecting the need to capture impacts on species, ecosystem functions, and services within LCA frameworks (Koellner, 2013) (Vidal-Legaz, Sala, Antón, & Milà i Canal, 2016).
- **Modelling Tools:** Geographic Information Systems (GIS), remote sensing, and spatially explicit land use models are widely applied to regionalize land use impacts and improve ecological relevance in LCA studies, enabling the integration of spatial variability, land-use change dynamics, and ecosystem service impacts (Chaplin-Kramer, 2017) (Shi S. a., 2024).

At the midpoint level, land-use impacts are quantified by converting **land occupation** and **land transformation** inventory flows into a midpoint indicator as defined by the chosen LCIA method. These midpoint indicators may represent soil quality/soil functions (e.g., LANCA-based approaches recommended in Environmental Footprint framework) or a biodiversity proxy such as relative species loss (e.g., ReCiPe midpoint land use result) (Table 32).

Table 12: Addressed environmental issues and damage pathway by LCIA methods (Modahl & Lyng, 2025)

LCIA method	Current model / impact category name	Inventory data involved	Basis for CF
ReCiPe 2016 (Midpoint)	Land use	Land occupation Land transformation	Relative species loss
Ecological Scarcity 2021	Land use	Land occupation	Species lost, distance to target principle and Swiss policy targets
Land use biodiversity (Chaudhary et al., 2015), global and regional models	Land use biodiversity / Potential Species Loss (PSL)	Land occupation Land transformation	Potential Species Loss
LC-IMPACT	Land stress, terrestrial ecosystems	Land occupation Land transformation	Species lost
IMPACT World+ (Midpoint)	Land occupation, biodiversity	Land occupation	Biotic production, freshwater recharge, erosion resistance, phys.-chemical filtration, mechanical filtration
IMPACT World+ (Midpoint)	Land transformation, biodiversity	Land transformation	
LANCA in Environmental Footprint 3.1 (adapted)	Land use	Land occupation Land transformation	Dimensionless, aggregated index of kg biotic production/ m^2/year : kg soil/ m^2/year

			m ³ water/m ² /year m ³ groundwater/m ² /year
CML-IA non-baseline	Land competition	Land occupation	Not characterized

14.2.1. Chosen method: EF

In this guideline, EF 3.1 is recommended as the land-use impact assessment method to ensure methodological consistency with the other midpoint impact categories applied.

Within EF 3.1, LANCA® (LANd Use Indicator Value CAlculation) is used to quantify the environmental impacts of land occupation and land use change through their effects on soil functions. Based on the UNEP-SETAC land use framework, LANCA applies spatially explicit, map based characterization factors to estimate changes in soil quality relative to a natural reference state across different land use types and geographic locations (Beck, et al., 2010) (Vidal-Legaz, Sala, Antón, & Milà i Canal, 2016). Impacts from both land occupation (area over time) and land transformation (changes between land-use types) are assessed and aggregated into a single, dimensionless Soil Quality Index (SQI), which combines four soil function indicators: biotic production, erosion resistance, mechanical filtration, groundwater replenishment/regeneration. Country level default characterization factors support consistent application across studies, while site specific data may be used where available, making LANCA the standardized and mandatory approach for land-use impact assessment in EF (European Commission, 2023).

Nevertheless, the application of LANCA in EF 3.1 entails several well-documented limitations that affect result interpretation. The method assumes that land occupation inherently degrades soil quality relative to a natural reference state and primarily scales impacts with land area and duration, which can lead to disproportionately high impacts for extensive or low-intensity systems while favouring intensive systems with smaller land footprints (IWTO (International Wool Textile Organisation), 2026). In addition, the aggregation of multiple soil function indicators into a single SQI, which enhances comparability but reduces transparency and obscures trade-offs between individual soil functions (De Laurentiis, et al., Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA, 2019). The reliance on country-average characterization factors further limits sensitivity to local conditions, with empirical studies demonstrating substantial deviations from site-specific results (Terranova et al., 2021). Finally, biodiversity impacts are not explicitly captured in LANCA as implemented in EF 3.1, representing a recognized methodological gap that is currently being addressed in the development of future EF versions (European Commission, 2023).

The EF “soil quality index” builds upon the aggregation of selected indicators from the LANCA®:

- Erosion resistance
- Mechanical filtration
- Groundwater replenishment
- Biotic Production

Furthermore, a characterization factor reflecting biodiversity, is currently being developed, which will lead to a new indicator of “land use - biodiversity”, to be incorporated into the next PEF version.

Formula

For the assessment of Land use occupation, the occupied area is multiplied by the occupation duration and the conversion ratio and then divided by the amount of crop yield (see Formula 20).

$$q^{occ} (\text{m}^2 \text{ yr/kg crop}) = (\text{Total area used for crop cultivation in m}^2) \times (\text{Occupation duration in years}) \times (\text{Crop conversion ratio in kg crop / kg product}) / (\text{Total crop yield in kg})$$

Formula 20: EF 3.1 land occupation in the land use impact category

The land transformation addresses the change from one land-use type to another and is expressed in the land use occupation divided by the annualization period (Formula 21).

$$q^{tr} (\text{m}^2/\text{kg product}) = \text{Land use occupation (m}^2 \cdot \text{yr/kg crop)} / (\text{Annualization period in years})$$

Formula 21: EF 3.1 land transformation in the land use impact category

The land use impact is calculated as the sum of characterized land occupation flows and characterized land transformation flows, based on LANCA® soil quality indicators.

The calculation of Land use impact is as follows:

$$LU = \sum_{j=1}^{N_{occ}} (q_j^{occ} \times CF_j^{occ}) + \sum_{k=1}^{N_{tr}} (q_k^{tr} \times CF_k^{tr})$$

Formula 22: EF 3.1 land use impact calculation based on land occupation and land transformation flows

Where:

- **LU**: Land use impact result (EF 3.1), reported as soil quality index (dimensionless, expressed in points "pt")
- **N_{occ}**: Number of land occupation flows in the inventory that have a matching EF 3.1 land-use characterization factor and are therefore included.
- **N_{tr}**: Number of land transformation flows in the inventory that have a matching EF 3.1 land-use characterization factor and are therefore included.
- **j**: Index that labels each included occupation elementary flow from 1 to N_{occ}.
- **k**: Index that labels each included transformation elementary flow from 1 to N_{tr}.
- **q^{occ}**: Inventory quantity of land occupation flow j, expressed in m²·a (area occupied × time).
- **q^{tr}**: Inventory quantity of land transformation flow k, expressed in m² (area converted).
- **CF^{occ}**: EF 3.1 characterization factor for land occupation flow j, with units Pt/(m²·a), specific to the land-use type and (where applicable) the geographic context implemented in the method.

- **CF^{tr}**: EF 3.1 characterization factor for land transformation flow k, with units Pt/m², specific to the land-use type and (where applicable) the geographic context implemented in the method.

Characterization factors in EF method

The LANCA® model provides a set of CFs for different soil quality indicators both at global and at country level. When the country is not known the practitioner can use the global-default CFs, those are calculated as world averaged CFs based on the area of each country. The land-use characterization factors provided in EF 3.1 are based on the LANCA® model, as EF 3.1 applies this model for the assessment of land-use impacts. To access the full list of characterization factors for land use impact, please use the following link [EF 3.1](#).

14.2.2. LCI Flows

Land-use LCI flows specify whether the land is occupied or transformed, what type of forest, agriculture or industrial use is involved, and how intensively the activities are managed. This makes the impact assessment more meaningful, especially for biodiversity, soil quality, carbon storage, and ecosystem-service impacts. Table 33 provides an overview of different types of LCI flows in land use.

Table 33: LCI flows and their description used in LCA

LCI Flow	Description of Flow
Permanent crops, irrigated, extensive	Land used for long-lived crops (orchards, vineyards) with irrigation and low-intensity management.
Permanent crops, irrigated, intensive	Irrigated permanent crop land with high-intensity management (fertilizer, pruning, high yield).
Permanent crops, non-irrigated	Land for permanent crops without irrigation; lower environmental modification.
Forest, natural	Semi-natural forest ecosystems with limited management; high biodiversity value.
Forest, intensive	Intensively managed forest used for timber or biomass production (high input, lower naturalness).
Grassland, for livestock grazing	Grassland is actively used as grazing area for livestock.
Urban, continuously built	Dense urban fabric with continuous building structures and sealed surfaces.
Wetlands, inland	Inland wetland ecosystems such as marshes, peatlands, or bogs.
Shrub land	Land dominated by shrubs; semi-natural ecosystems with moderate biodiversity.
Industrial area	Land occupied by industrial zones (manufacturing plants, logistics, processing sites).
Snow and ice	Land covered by snow or ice; tundra, polar, glacier-influenced areas (very low productivity).

To access the full list of characterization factors for Land Use, please use the following link: [EF 3.1](#).

14.3. Assessment Examples

This example presents a LUC assessment for ethanol production. Most commercial ethanol today is produced from crops such as maize, sugar cane, and sugar beet. In this example, the assessment covers two feedstocks: maize (United States) and sugar cane (Brazil). The functional unit is 1 kg of ethanol, and the assessment distinguishes between two distinct land-use impacts:

1. **Land occupation** from crop cultivation — expressed as 1 m² per year per kg of crop, scaled by the amount of crop required per kg of ethanol produced.
2. **Land transformation** is associated with the underlying LUC — for example, conversion from grassland to arable land (as in the maize case) or from primary forest to arable land (as in the sugar cane case).

The following information is used to calculate the land use impact for ethanol production (Our world in data 2024):

- 1 kg of ethanol out of maize requires ≈ 3 kg of maize¹⁵
- 1 kg of maize production requires 0.95 m² of agricultural land occupation¹⁶
- 1 kg of ethanol out of sugar cane requires ≈ 15 kg of sugar cane¹⁷
- 1 kg of sugar cane production requires 0.12 m² of agricultural land occupation¹⁸
- Duration of occupation is 1 year for both crops
- Annualization of 20 years is considered, as land change after 20 years is not included in the land use impact calculation and the annualization is (BSI, 2012)
- Characterization factors (CF) are retrieved from EF 3.1

The examples provided in this assessment are theoretical cases intended to illustrate the logic behind land use change calculations. Land transformation data does not need to be manually researched or calculated, as this information is already embedded in LCA databases. Appropriate market process flows that include regional scenarios for different land transformations can be selected from these databases, allowing the complexity of land use change calculations to be automatically handled by the LCA software.

¹⁵ U.S. dry-mill ethanol yield is ≈ 2.8 gallons of ethanol per bushel of maize. (Lee, Kwon, Wu, & Wang, 2021) One bushel of maize = 25.4 kg; 2.8 gal * 3.785 L/gal * 0.789 kg/L $\approx$ 8.36 kg ethanol per bushel $\rightarrow$ 25.4 kg maize / 8.36 kg ethanol = 3.03 kg corn per kg ethanol.

¹⁶ Maize yield = 10.5 t/ha (Lee, Kwon, Wu, & Wang, 2021); 10,000 m²/10,500 kg = 0.95 m²/kg.

¹⁷ Brazilian sugar cane yields are roughly 85 liters of ethanol per ton of sugar cane. (Pazuch, et al., 2017) Converted to mass (ethanol density $\approx$ 0.789 kg/L): 85 L * 0.789 kg/L $\approx$ 67 kg ethanol per 1,000 kg sugar cane = 14.91 kg sugar cane per kg ethanol.

¹⁸ Sugar cane yield = 85 t/ha (Hayashi T. , 2023); 10,000 m²/85,000 kg = 0.12 m²/kg.

Table 34: Land Use Impact in the Ethanol example

LCA Land Use Impact – Ethanol Production			
Parameter	from Maize (US)	from Sugar Cane (BR)	Unit
SECTION 1 – Inventory Inputs			
Total area used for crop cultivation per kg crop (based on yield)	0.95	0.12	m ² / kg feedstock
Occupation duration	1.00	1.00	year
Crop conversion ratio	3.03	14.91	kg crop / kg ethanol
Annualization period (transformation) (BSI, 2012)	20.00	20.00	years
Formulas for: <i>Land occupation inventory = Feedstock conversion ratio × Land required per kg feedstock × Occupation duration</i> <i>Annualized transformation area = land occupation inventory / annualized period</i>			
Land occupation inventory (per kg ethanol)	0.95 * 1 * 3.03 = 2.88	* 0.12 * 1 * 14.91 = 1.79	m ² ·year / kg ethanol
Annualized transformation area	2.88 / 20 = 0.14	1.79 / 20 = 0.09	m ² / kg ethanol
SECTION 2 – Characterization Factors (EF 3.1)			
CF – Land occupation (arable)	61.39	104.13	pt / m ² ·year
CF – Transformation FROM (grassland/pasture)	-335.82	-	pt / m ²
CF – Transformation FROM (forest, primary)	-	-499.51	pt / m ²
CF – Transformation TO (arable)	613.91	1,041.30	pt / m ²
Formula for: <i>Net CF – Transformation for crop X = CF_FROM + CF_TO</i>			
Net CF – Transformation for Maize (US) (FROM “grassland/pasture” + TO “arable”)	-335.82 + 613.91 = 278.09	-	pt / m ²
Net CF – Transformation for Sugar Cane (BR) (FROM “forest, primary” + TO “arable”)	-	-499.51 + 1,041.30 = 541.79	pt / m ²
SECTION 3 – Land Use Impact Calculation			
Formulas for: <i>Land Occupation Impact = land occupation inventory * CF land occupation</i> <i>Land Transformation Impact = annualized transformation area * Net CF_transformation</i>			
Land Occupation Impact	2.88 * 61.39 = 176.71	1.79 * 104.13 = 186.31	pt / kg ethanol
Land Transformation Impact	0.14 * 278.09 = 40.02	0.09 * 541.79 = 48.47	pt / kg ethanol
TOTAL Land Use Impact (Occupation + Transformation)	216.74	234.78	pt / kg ethanol

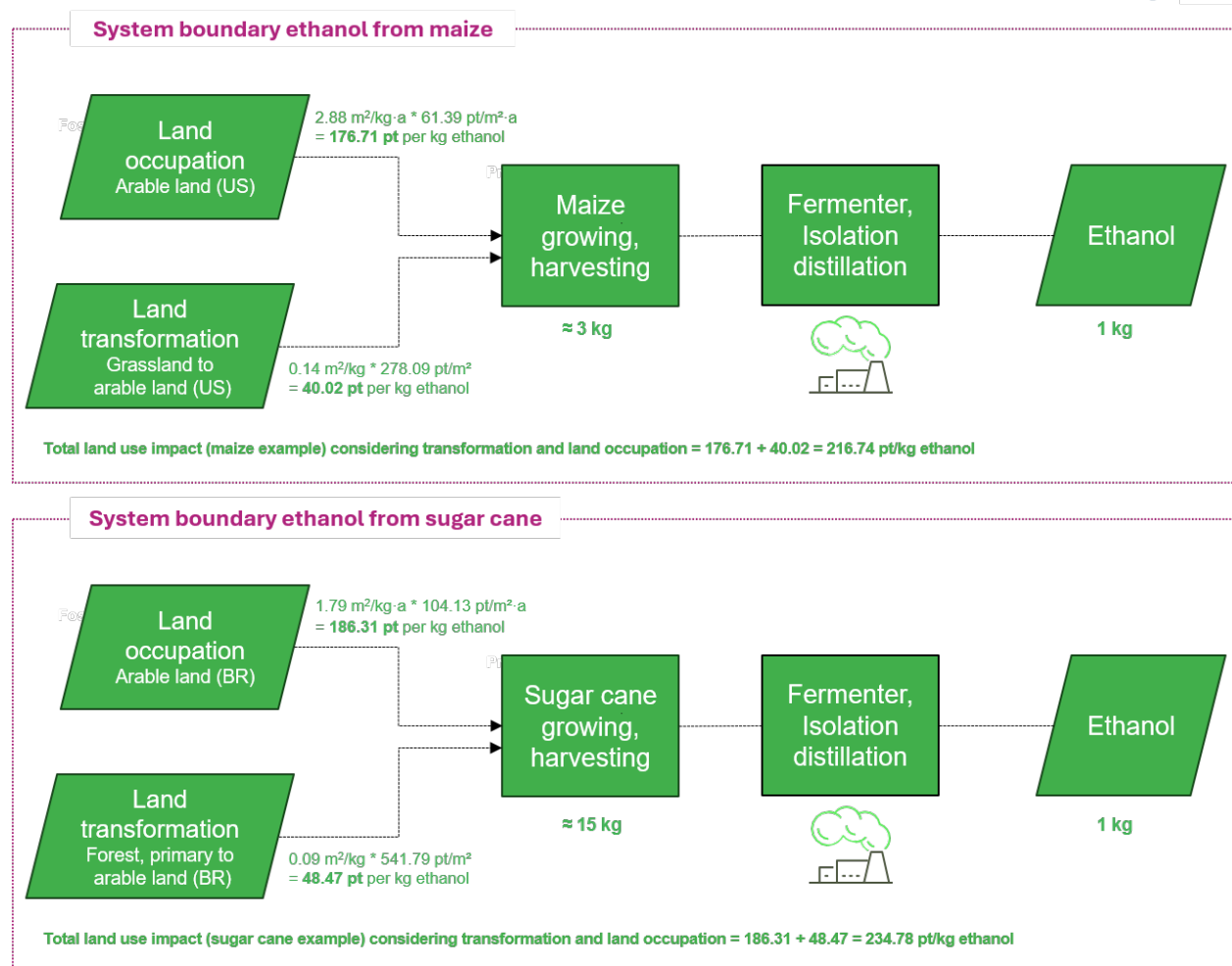


Figure 19: Land use impact calculation of Ethanol from maize (US) and from sugar cane (BR) as crops including land transformation and land occupation.

15. Ecotoxicity, freshwater

15.1. General Description

15.1.1. Issues of Concern

The impact category “Ecotoxicity, freshwater” addresses the potential harm of chemical emissions to freshwater ecosystems, focusing on effects on aquatic organisms such as algae, invertebrates, and fish.

In current LCIA practice, this category is typically assessed using the USEtox model, which calculates characterization factors (CFs) based on three components:

- Fate (distribution and persistence of a substance in the environment)
- Exposure (bioavailability to organisms)
- Effect (toxicity based on species sensitivity data)

The results are expressed as comparative toxic units (CTUe), representing the potentially affected fraction of species over time and volume. USEtox is recommended by the UNEP/SETAC Life Cycle Initiative and adopted in the EU Environmental Footprint (EF) method. (Rosenbaum R. K., et al., 2008) (Life Cycle Initiative, 2026) (UNEP/SETAC, 2017) (European Commission, 2026)

Several topics need to be concerned when calculating and interpreting this impact category. First, many chemicals lack characterization factors due to missing data, leading to potential underestimation of impacts (Rosenbaum R. K., et al., 2008) (Fantke, et al., 2018). Besides that, the USEtox method uses generic, steady-state conditions with limited spatial differentiation which does not reflect site-specific realities (UNEP/SETAC, 2017). Ecotoxicity factors are based on limited laboratory data and species sensitivity distributions, with weak representation of ecosystem complexity and chronic effects (Rosenbaum, Bachmann, & Gold, 2008) (Fantke, et al., 2018). Combination or synergy effects of multiple substances are not addressed, and local conditions and temporal emission patterns are not considered.

Therefore, “Ecotoxicity, freshwater” provides an important but highly uncertain indicator in LCA. Results should therefore be used primarily for hotspot identification and relative comparison, interpreted with caution and should not be interpreted as actual ecological damage predictions.

15.1.2. Key Components of Potential Impact

The goal of Ecotoxicity, freshwater characterization in Life Cycle Assessment (LCA) is to estimate the potential toxic impact of chemical emissions on freshwater ecosystems. The assessment addresses substances emitted to air, water, or soil and evaluates how much these substances contribute to toxic effects on freshwater organisms such as algae, crustaceans, fish, and other aquatic species (Saouter E. B., 2020).

This potential is determined by a three-step toxicological chain—Fate, Exposure, and Effect—most implemented through the USEtox model (Rosenbaum R. K., et al., 2008) (Fantke, et al., 2017) and underpinning major LCA methods, including the European Commission's Environmental Footprint (EF 3.1).

The Fate Factor (FF) evaluates how long a chemical remains in freshwater before degrading or shifting to another medium. Governed by multimedia modelling, it tracks transport across air, soil, and water, factoring in natural degradation and water current advection (Fantke, et al.,

2017). A higher fate factor indicates that a pollutant persists longer, directly increasing its potential ecological impact over time (Rosenbaum R. K., et al., 2008).

The Exposure Factor (XF) dictates how much of the chemicals in the water column can actively interact with living organisms. Rather than treating the total mass as hazardous, exposure modelling accounts for environmental partitioning, such as binding to suspended solids or settling into bottom sediment (Fantke, et al., 2017). This isolates the bioavailable, dissolved fraction that free-swimming aquatic species will realistically absorb (Rosenbaum R. K., et al., 2008).

The Effect Factor (EF) establishes the inherent toxicity of a substance to aquatic life once exposure occurs. While standard USEtox derives this factor from the Hazard Concentration affecting 50% of species (HC_{50}), the EF 3.1 framework instead uses the more protective Hazard Concentration affecting 20% of species (HC_{20}) (Sala, Biganzoli, Sanye Mengual, & Saouter, 2022).

Together these components define the characterization factor, expressed in Comparative Toxic Units for ecosystems (CTUe). A severe impact arises when persistence, bioavailability, and toxicity combine. Finally, EF 3.1 applies a Robustness Factor (RF) scaling results by compound type—organic (1.0), inorganic (0.1), essential metals (0.01)—to limit uncertainty from inorganic estimates (Sala, Biganzoli, Sanye Mengual, & Saouter, 2022).

15.1.3. Regulatory Compliance

Environmental regulatory compliance provides the legal baseline for environmental assessment in Life Cycle Assessment (LCA). It demonstrates that a product, process, chemical, or activity meets applicable legal requirements designed to protect the environment, ecosystems, and natural resources.

In a chemical and sustainability context, this usually covers (European Union, 2026a) (European Union, 2026b):

Hazard classification and communication:

Compliance with environmental hazard classification and communication requirements, e.g. under CLP/GHS, including environmental hazard classes (e.g. aquatic toxicity), hazard statements (H400–H413), pictograms, and labelling requirements that indicate potential effects on ecosystems.

Chemical registration and environmental risk assessment:

For the EU, this includes REACH obligations such as substance registration, environmental exposure assessment, Predicted No Effect Concentrations (PNECs), environmental fate and behaviour, risk characterization ratios (RCRs), restrictions, authorization requirements, and defined safe-use conditions for environmental protection.

Environmental protection in industrial operations:

Compliance with relevant environmental legislation governing emissions and releases, including air emissions, wastewater discharges, soil protection, and waste management. This may include permits, Best Available Techniques (BAT), emission limit values (ELVs), monitoring obligations, and environmental management systems.

Protection of ecosystems and biodiversity:

Ensuring that the manufacture, use, and disposal of substances, mixtures, or articles do not cause unacceptable impacts on aquatic and terrestrial ecosystems, including effects on biodiversity, persistence, bioaccumulation, and long-range transport.

Product-specific environmental regulations:

Depending on the product, additional environmental requirements may apply, for example under biocidal product regulation (BPR), detergents regulation, plant protection products regulation, packaging and waste legislation, or eco-design and extended producer responsibility (EPR) frameworks.

Environmental releases and life cycle considerations:

Environmental releases to air, water, and soil across the life cycle (manufacturing, use, disposal) are regulated through permitting systems, environmental quality standards (EQS), waste legislation, and specific restrictions on emissions and substance uses.

Documentation and traceability:

Compliance typically requires documented evidence such as environmental exposure assessments, ecotoxicological data, environmental fate studies, monitoring data, emission inventories, safety data sheets, and regulatory dossiers submitted to authorities.

For environmental impact assessment in LCA and SSbD, regulatory compliance usually represents a minimum legal baseline: substances or processes must not violate REACH environmental requirements, emission limits, restrictions, authorization conditions, or environmental protection legislation. (Caldeira, et al., 2022)

However, compliance alone does not necessarily indicate low environmental impact. Additional assessment methods such as USEtox, multimedia fate modelling, lifecycle inventory analysis, or environmental footprinting are typically required to compare alternatives or identify improvement potential. (Rosenbaum, Bachmann, & Gold, 2008)

15.1.4. Importance for the Chemical Industry

Freshwater ecosystems cover less than 1% of the Earth's surface yet host a disproportionate share of global biodiversity (Dudgeon, et al., 2007). At the same time, they are among the most sensitive environmental compartments to chemical contamination (Sayer, et al., 2025).

Multiple pressures drive the degradation of freshwater ecosystems. Among the most significant are emerging contaminants, engineered nanomaterials, microplastics pollution, and freshwater salinization (Reid, et al., 2018; Owsianiak, et al., 2023). These stressors are intimately linked to industrial activity, and the chemical industry contributes significantly to freshwater emissions through process effluents, wastewaters, and leaching from solid waste streams (Kosnik, Hauschild, & Fantke, 2022). Substances of concern that may affect freshwater ecosystem health include, among others, pharmaceuticals, per- and polyfluoroalkyl substances (PFAS), and organic solvents. Even after on-site wastewater treatment, residual loads of such substances may persist and enter the receiving environment at concentrations relevant to aquatic organisms (Yang, Ok, Kim, Kwon, & Tsang, 2017). The persistence and bioaccumulation potential of several of these substance classes amplify their long-term ecotoxicological impact, even at low emission rates.

Assessing Ecotoxicity, freshwater within a life cycle framework enables companies to identify high-impact processes and substances along their value chains. It lays the foundation for justified and effective reduction of environmental harm — whether through substance substitution, process optimization, or investment in advanced treatment technologies. In doing so, Ecotoxicity, freshwater assessment becomes a strategic tool for informed decision-making and credible communication of environmental performance.

15.2. Methodology of characterization

15.2.1. Chosen method: EF

In this guideline the Environmental Footprint EF 3.1 is recommended. Based on the European Commission, the recommended method for assessing Ecotoxicity, freshwater is the EF 3.1 Ecotoxicity, freshwater midpoint indicator, which is based on the USEtox 2.1 consensus model for life cycle impact assessment (LCIA) (Andreasi Bassi, et al., 2023).

The EF 3.1 Ecotoxicity, freshwater method evaluates the potential impacts of toxic chemical emissions on freshwater aquatic ecosystems by estimating the Potentially Affected Fraction (PAF) of species, integrated over environmental volume and time. Results are expressed in Comparative Toxic Units for ecosystems (CTUe), representing the potentially affected fraction of freshwater species per cubic metre of freshwater over time (Rosenbaum R. K., et al., 2008) (Andreasi Bassi, et al., 2023).

Within EF 3.1, characterization factors (CFs) are derived using the USEtox model and updated European data sources, including REACH-IUCLID, EFSA OpenFoodTox, and the Pesticide Properties Database (PPDB). The method combines information on a substance's environmental fate, exposure potential, and ecotoxicological effects to estimate the potential freshwater ecosystem damage associated with emissions to air, water, and soil (Saouter E. D., 2018) (Andreasi Bassi, et al., 2023).

The impact category covers a broad range of organic and inorganic substances emitted throughout the life cycle, including metals, pesticides, industrial chemicals, and transformation products for which characterization factors are available. The method is integrated into the official EF 3.1 package and shall be applied using the corresponding EF characterization factor database to ensure consistency and comparability across studies (Andreasi Bassi, et al., 2023).

Nevertheless, several limitations should be considered when interpreting Ecotoxicity, freshwater results. First, characterization factors are influenced not only by the intrinsic toxicity of substances but also by their modelled environmental fate and exposure pathways; therefore, highly toxic substances may receive lower overall characterization factors if their environmental persistence or exposure potential is limited (Andreasi Bassi, et al., 2023).

Second, the USEtox framework relies on large-scale environmental modelling assumptions and generic environmental conditions, which may not accurately represent site specific exposure situations or regional ecological sensitivities. Therefore, results are generally more suitable for comparative assessments than for predicting actual ecological damage at a specific location (Fantke, et al., 2017); (Owsianiak, Fantke, Frischknecht, Jolliet, & Verones, 2019).

Furthermore, uncertainties remain regarding ecotoxicological data availability, particularly for emerging ingredients, substances and certain inorganic compounds, requiring the use of proxies and extrapolation approaches in some cases. This can lead to the risk of potential overestimation

of environmental impacts for substance groups that are currently insufficiently represented in the framework.

Finally, the indicator quantifies potential impacts on freshwater ecosystems only and does not explicitly address impacts on marine ecosystems, terrestrial ecosystems, or biodiversity loss beyond freshwater ecotoxic effects (Andreasi Bassi, et al., 2023).

Alternative

USEtox and ProScaleE are both life-cycle-oriented approaches for assessing toxicity-related impacts of chemicals, but they answer different questions and are designed for different decision contexts. USEtox is primarily a LCIA model that characterizes potential human toxicity and Ecotoxicity, freshwater impacts from chemical emissions, using fate, exposure and effect modelling to calculate characterization factors. ProScaleE, in contrast, is a risk-oriented chemical footprinting method that combines substance hazard, exposure potential, person-hours and mass flows to assess direct chemical exposure potentials along product life cycles.

USEtox primarily addresses far-field emissions and their impacts via the environment: it estimates potential damage or impact from emissions via the environment, typically expressed as comparative toxic units for human toxicity and ecotoxicity. It is therefore highly valuable for comparative LCA studies where emissions to air, water or soil are inventoried and translated into potential impacts.

ProScaleE is exposure- and risk-oriented and primarily addresses near-field exposure situations: it focuses on the potential for direct exposure to the environment by hazardous substances during production, use, service life and end-of-life stages. It uses regulatory and workplace-relevant information such as GHS/CLP H-phrases, occupational exposure limits, PNECs, process categories, exposure modifiers, risk management measures, person-hours and mass flows. This makes ProScaleE closer to the way chemical risks are already managed in industrial practice. The approach is described in detail in the Annex of this document.

Impact pathway and methodological approaches

Formula

For the assessment of Ecotoxicity, freshwater according to the Environmental Footprint (EF 3.1) method, the following approach is used (European Commission, JRC, 2024):

Ecotoxicity, freshwater quantifies the potential impact of chemical emissions on freshwater aquatic ecosystems. The impact result is expressed in Comparative Toxic Units for ecosystems (CTUe), representing the potentially affected fraction of species integrated over time and volume. The calculation of Ecotoxicity, freshwater is as follows:

$$EcT = \sum_{i=1}^N (m_i \times CF_i)$$

Formula 23: Ecotoxicity, freshwater calculation

Where:

- EcT: Ecotoxicity, freshwater impact result (EF 3.1), reported as CTUe (Comparative Toxic Units for ecosystems).
- N: Number of elementary flows (emissions to air, water, or soil) in the inventory that have a matching EF 3.1 Ecotoxicity, freshwater CF and are therefore included.
- i: Index that labels each included elementary flow from 1 to N.
- m_i: Inventory quantity of emitted substance *i*, expressed in kilograms (kg).
- CF_i: EF 3.1 Ecotoxicity, freshwater CF for substance *i*, expressed in CTUe/kg emitted. The CF is specific to the substance and emission compartments (air, freshwater, seawater, agricultural soil, industrial soil, etc.).

For the sake of understanding, the following formula shows how the characterization factor used in EF 3.1, derived from the USEtox 2.1 model, combines the environmental fate, exposure, and effects of a substance:

$$CF_i = FF_i \times XF_i \times EF_i \times RF_i$$

Formula 24: Characterization factor calculation for Ecotoxicity, freshwater

Where:

- FF_i: Fate Factor, representing the persistence and distribution of the substance in the environment.
- XF_i: Exposure Factor, representing the bioavailable fraction reaching freshwater ecosystems.
- EF_i: Effect Factor, representing the toxicity of the substance to aquatic species.
- RF_i: Robustness Factor applied within the EF 3.1 characterization framework.

Thus, the total Ecotoxicity, freshwater impact is calculated as the sum of all emitted substances multiplied by their respective EF 3.1 Ecotoxicity, freshwater characterization factors, resulting in a final score expressed in CTUe (Fantke, et al., 2017).

Characterization factors in EF method

EF 3.1 provides characterization factors derived from the USEtox model. These factors represent the potential impact of a chemical substance on human health and freshwater ecosystems and are calculated based on three components: environmental fate, exposure, and toxic effects. The resulting CFs allow to evaluate and compare the toxicity impacts of thousands of chemical emissions. The EF method continuously updates these factors using high-quality physicochemical and toxicological data sources to improve scientific robustness, transparency, and coverage of substances.

EF 3.1 provides regionalized as well as average CFs for “Ecotoxicity, freshwater”. Furthermore, they distinguish between inorganics and organics as well as emission to air, soil or water. The impact is expressed in CTUe (Comparative Toxic Units for ecosystems).

Table 35 present some exemplary and non-exhaustive examples CFs for Ecotoxicity, freshwater. Link to download the full list of CFs for Ecotoxicity, freshwater can be found under: [EF 3.1](#)

Table 35: EF3.1 Ecotoxicity, freshwater CFs, expressed in CTUe per kg emissions to air, soil and water (EF3.1)

Flow	Emission to ¹	CF [CTUe per kg]
Acetaldehyde	Air	1.12
	Soil	34.46
	Water	192.93
Arsenic	Air	1196.48
	Soil	1725.89
	Water	3263.33
Hexane	Air	0.001
	Soil	0.061
	Water	298.96
Lead	Air	27.77
	Soil	40.34
	Water	68.26
Nickel	Air	9671.49
	Soil	13934.09
	Water	27049.48
Toluene	Air	0.272
	Soil	10.094
	Water	973.20
Methylene chloride	Air	0.781
	Soil	4.49
	Water	141.60
¹ unspecified		

15.2.2. LCI Flows

As the list of LCI flows to be considered is very long, Table 36 presents a selection of grouped flows that are particularly relevant to the chemical industry.

Table 36: Description of relevant and exemplary LCI flows concerning Ecotoxicity, freshwater

LCI Flow	Description of Flow
Metals and metal compounds (e.g. Copper, Zinc, Nickel, Chromium (VI), Mercury, Cadmium)	Metal emissions are among the most important contributors to Ecotoxicity, freshwater due to their inherent toxicity, persistence, and potential bioavailability in aquatic environments.
Organic solvents (e.g. Benzene, Toluene, Ethylbenzene, Xylenes, Chlorobenzenes)	Industrial solvents released to the environment can exert acute and chronic toxic effects on aquatic organisms and may contribute through emissions to air, water, or soil.
Auxiliary and process chemicals (e.g. Phenol, Styrene, Formaldehyde, Acetic acid, Process-specific organic intermediates)	Various chemicals used in manufacturing processes may enter the environment through process losses, fugitive emissions, or wastewater discharges and contribute to aquatic toxicity.
Combustion-related PAHs (e.g. Naphthalene, Anthracene, Phenanthrene, Fluoranthene, Benzo[a]pyrene)	Polycyclic aromatic hydrocarbons (PAHs) are generated during incomplete combustion processes and are often persistent, bioaccumulative, and toxic to aquatic organisms.
Wastewater emissions of specific organic substances (e.g. Nonylphenol, Chlorophenols, Phthalates, Surfactants, Specific process-related organic compounds)	Organic substances discharged to freshwater via wastewater streams can directly affect aquatic ecosystems, particularly when they exhibit toxicity, persistence, or limited biodegradability.

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#)

15.2.3. Data granularity

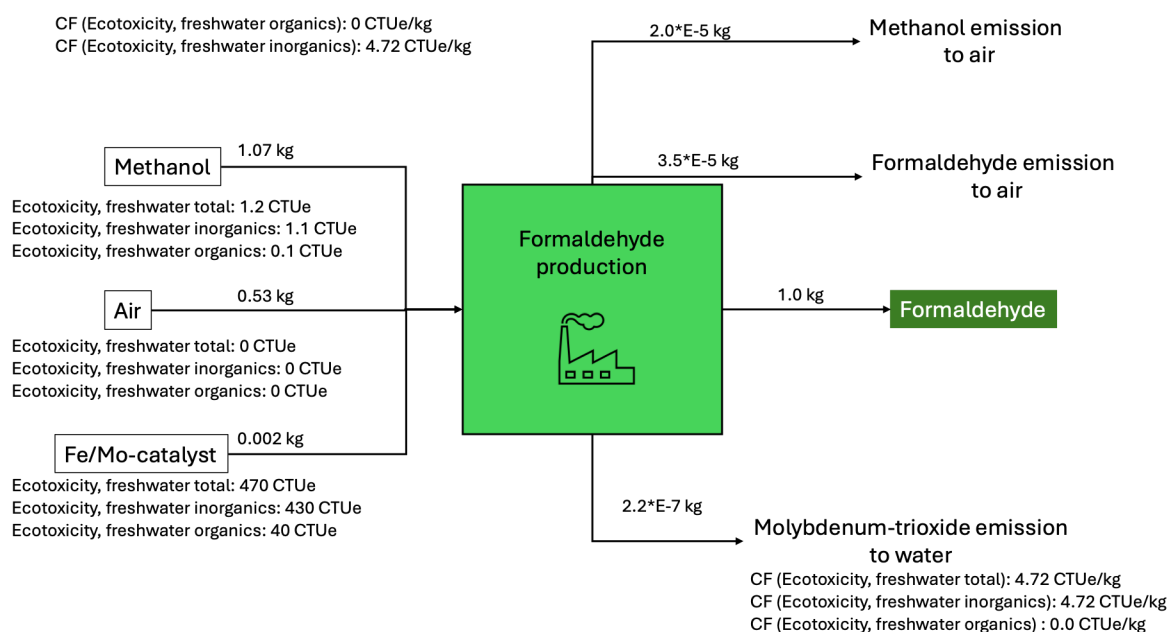
In EF 3.1, Ecotoxicity, freshwater characterization is strongly driven by the identity and speciation of emitted substances, because characterization factors are predominantly substance specific and can differ by orders of magnitude between chemicals (Saouter E. D., 2018) (European Commission, 2023). Therefore, the Ecotoxicity, freshwater results are highly sensitive to inventory resolution: emissions have to be modelled at the most disaggregated elementary flow level available (substance specific flows, and where relevant, ionic form/metal species), and the use of generic or aggregated categories (e.g., “unspecified organics,” “heavy metals, unspecified,” or grouped pesticides/solvents) have to be avoided whenever possible.

In addition to substance identity, the receiving compartment is critical: CFs are defined per elementary flow and typically differ for emissions to air, water, and soil due to different fate, transport, and exposure pathways (Fantke, et al., 2017). Therefore, emissions should be

assigned to the correct compartment specific elementary flows (e.g., “substance X, to freshwater” vs “substance X, to air”), and “unspecified” emission compartments should be avoided as they may lead to inappropriate CF selection and biased results.

EF 3.1 may provide CFs with different levels of geographical resolution depending on the impact category and the implementation in the LCA software/database. For Ecotoxicity, freshwater regionalized as well as global CFs are available, however regionalized values only for elementary flows belonging to the flow class "emissions to air".

15.3. Assessment Examples



Consider the production of formaldehyde by methanol oxidation via the Formox process. Per kilogram of formaldehyde, 1,07 kg of methanol is required, which is oxidized by oxygen from air using a mixed iron/molybdenum-oxide based catalyst. Note that the amount of catalyst in this example is the amount that needs to be replenished.

Figure 20: Exemplified flows in formaldehyde production relevant for Ecotoxicity, freshwater. This example is for illustration purposes and contains fictious numbers.

The contributions of each input and output flow to the Ecotoxicity, freshwater potential are listed below.

Table 37: Contribution of flows to Ecotoxicity, freshwater organics and Ecotoxicity, freshwater inorganics.

Flow	Contribution to Ecotoxicity, freshwater organics	Contribution to Ecotoxicity, freshwater inorganics
Methanol input	$1.07 \text{ kg methanol} * 0.1 \frac{CTUe}{\text{kg methanol}} = 0.11 \text{ CTUe}$	$1.07 \text{ kg methanol} * 1.1 \frac{CTUe}{\text{kg methanol}} = 1.18 \text{ CTUe}$
Air input	0	0
Fe/Mo-catalyst input	$0.002 \text{ kg catalyst} * 40.0 \frac{CTUe}{\text{kg catalyst}} = 0.08 \text{ CTUe}$	$0.002 \text{ kg catalyst} * 430.0 \frac{CTUe}{\text{kg catalyst}} = 0.86 \text{ CTUe}$
Methanol emissions to air	$2.0E - 5 \text{ kg methanol to air} * 0.35 \frac{CTUe}{\text{kg methanol to air}} = 7.00 * E - 6 \text{ CTUe}$	0
Formaldehyde emissions to air	$3.5E - 5 \text{ kg formaldehyde to air} * 179.86 \frac{CTUe}{\text{kg formaldehyde to air}} = 6.30 * E - 3 \text{ CTUe}$	0
Molybdenum-trioxide emissions to water	0	$2.2E - 7 \text{ kg MoO}_3 \text{ to water} * 4.72 \frac{CTUe}{\text{kg MoO}_3 \text{ to water}} = 1.04 * E - 6$
Total	0.20 CTUe	2.04
Ecotoxicity, freshwater total	$0.20 \text{ CTUe} + 2.04 \text{ CTUe} = 2.24 \text{ CTUe}$	

16. Human toxicity (cancer & non-cancer)

16.1. General Description

16.1.1. Issues of Concern

Human toxicity assessment aims to evaluate the likelihood of adverse health outcomes resulting from exposure to hazardous substances. Human exposure to toxic chemicals can occur through inhalation, ingestion, and dermal contact, originating from industrial activities, agricultural practices, consumer products, and environmental contamination (World Health Organization (WHO), 2023). Human toxicity is generally categorized into carcinogenic (cancer) and non-carcinogenic (non-cancer) effects, both of which are widely assessed in environmental risk assessment and Life Cycle Assessment (LCA) frameworks (Rosenbaum R. K., 2008). The rapid growth in chemical production and consumption has increased the release of hazardous substances into the environment. According to the European Environment Agency (European Environment Agency, 2022), thousands of chemicals are currently used in industrial and commercial applications, many of which have not been fully evaluated for long-term human health effects. Consequently, understanding and assessing human toxicity has become a priority for sustainable environmental management. Modern assessment frameworks such as USEtox provide scientifically robust methods for evaluating these impacts within environmental and life cycle assessment studies (Rosenbaum R. K., et al., 2008) (Fantke P. C., 2021).

Despite significant progress in toxicity assessment, several challenges remain. Therefore, when interpreting the results of this potential impact calculation, these deficits need to be appropriately considered as they lead to higher uncertainties. Many chemicals currently in commerce lack comprehensive toxicological data, making risk estimation uncertain (European Chemicals Agency, 2023). Furthermore, humans are exposed to complex mixtures of chemicals rather than individual substances, yet most toxicity assessments evaluate chemicals separately (Fantke P. C., 2021). Emerging contaminants such as per- and polyfluoroalkyl substances (PFAS), microplastics, pharmaceuticals, and engineered nanomaterials present additional concerns due to their persistence, bioaccumulation potential, and uncertain long-term health effects (European Environment Agency, 2022). Future research should focus on improving exposure assessment, integrating biomonitoring data, and developing cumulative risk assessment methods capable of addressing combined chemical exposures (Fantke P. C., 2021).

16.1.2. Key Components of Potential Impact

Human toxicity potential is determined by the interplay of three core components: fate, exposure, and effect, which together describe the pathway from the emission of a substance to the occurrence of adverse health outcomes in humans (Rosenbaum R. K., et al., 2008) (USEtox, 2026). These components represent sequential stages linking environmental behavior, human intake, and toxicological response across multiple environmental compartments and exposure pathways.

The fate component describes how a substance distributes, persists, and transforms in the environment after release. It includes processes such as transport between air, water, and soil, as well as degradation and partitioning. These mechanisms determine how long a substance remains in the environment and how widely it can spread, thereby influencing the likelihood of human contact (Rosenbaum R. K., et al., 2008). In advanced LCIA approaches, fate modelling

also considers interactions between different environmental compartments to capture broader spatial and temporal dynamics of substance dispersion (Fantke, et al., 2018).

The exposure component reflects the extent to which humans come into contact with a substance. It accounts for multiple pathways, including inhalation, ingestion of contaminated food and water, and dermal contact. Importantly, exposure modelling increasingly distinguishes between far-field exposure (e.g., environmental dispersion) and near-field exposure (e.g., indoor or consumer-related exposure), which together determine overall human intake (Fantke, et al., 2018).

The effect component represents the inherent toxicity of a substance and describes how the absorbed dose leads to adverse health outcomes. It distinguishes between cancer and non-cancer effects, which differ in their toxicological behaviour. Cancer effects are typically associated with probabilistic responses, where even low doses may contribute to an increased risk over time, whereas non-cancer effects are commonly characterized by threshold-based responses, where effects occur only above a certain exposure level. This distinction reflects differences in dose-response relationships and health endpoints considered in toxicity assessment (Rosenbaum R. K., et al., 2008).

Together, these three components define the overall potential for a substance to impact human health. A significant impact arises when a substance combines environmental persistence, effective exposure pathways, and sufficient toxic potency, highlighting the importance of considering fate, exposure, and effect jointly rather than in isolation (Rosenbaum R. K., et al., 2008) (Fantke, et al., 2018).

16.1.3. Regulatory Compliance

Regulatory compliance for human health impacts generally means demonstrating that a product, process, chemical, or activity meets applicable legal requirements designed to protect human health (European Commission, 2006) (European Chemicals Agency, 2023).

In a chemical and sustainability context, this usually covers (European Commission, 2006) (European Chemicals Agency, 2023):

- **Hazard classification and communication**
Compliance with classification, labelling and safety data sheet requirements, e.g. CLP/GHS, including H-statements, pictograms, signal words, and exposure warnings.
- **Chemical registration and risk assessment**
For the EU, this includes REACH obligations such as substance registration, exposure scenarios, Derived No-Effect Level (DNELs), risk characterization, restrictions, authorization requirements, and safe-use conditions.
- **Occupational health protection**
Compliance with workplace exposure rules, such as occupational exposure limits (OELs), workplace risk assessments, personal protective equipment, ventilation, monitoring, and worker training.
- **Consumer and downstream-user safety**
Ensuring that uses of substances, mixtures, or articles do not create unacceptable risks

for consumers or professional users under intended and reasonably foreseeable conditions.

- **Product-specific regulations**

Depending on the product, additional rules may apply, for example cosmetics, food-contact materials, biocides, pharmaceuticals, toys, medical devices, or detergents.

- **Environmental releases with human health relevance**

Human exposure via air, water, soil, food chains, or waste streams may be regulated through permitting, emission limits, wastewater rules, waste legislation, or environmental quality standards.

- **Documentation and traceability**

Compliance typically requires documented evidence: safety data sheets, exposure assessments, toxicological data, risk management measures, supplier declarations, monitoring results, and regulatory dossiers.

For human health impact assessment within LCA, used in Safe and Sustainable by Design (SSbD), regulatory compliance usually represents a minimum legal baseline: substances or processes must not violate REACH, CLP (Classification, Labelling and Packaging), OELs, restrictions, authorization conditions, or sector-specific safety requirements. However, compliance alone does not necessarily mean low impact; additional assessment methods such as ProScale, USEtox, exposure modelling, or mixture assessment may still be needed to compare alternatives or identify improvement potential (Rosenbaum R. K., et al., 2008).

Under REACH — the EU Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals — companies have obligations to ensure that chemicals are manufactured, imported, used, and placed on the EU market without unacceptable risks to human health or the environment (European Commission, 2006).

The central principle of REACH is: “no data, no market.” A substance generally cannot be manufactured or imported at ≥ 1 tonne/year per legal entity unless it is registered, unless an exemption applies. The Registration obligations are different depending on the sales of the product.

Registration is required mainly for: EU manufacturers of substances, EU importers of substances or mixtures, EU importers of articles if a substance is intentionally released from the article, and only representatives appointed by non-EU manufacturers.

Registration normally applies when a substance is manufactured or imported at one tone or more per year per registrant.

The registration dossier must be submitted to ECHA and includes information on:

- substance identity,
- manufacture and use,
- classification and labelling,
- physicochemical properties,
- toxicological and ecotoxicological information,
- guidance on safe use,

- and exposure information depending on tonnage and hazard profile.

This information is openly available and can be utilized for human toxicity impact assessment in LCA studies (European Chemicals Agency, 2021).

16.1.4. Importance for the Chemical Industry

Human toxicity is an important impact category in Life Cycle Assessment (LCA), particularly for the chemical industry. It quantifies the potential harm that chemical emissions — released during production, use, or disposal — may have on human health (Hauschild M. Z., 2015). Given that chemical manufacturers handle hazardous substances throughout their value chain, this category plays a meaningful role in building a comprehensive environmental and health risk profile. Within established LCA methodologies such as ReCiPe or USEtox, human toxicity is divided into carcinogenic and non-carcinogenic effects, enabling a more differentiated assessment of substance-specific risks (Rosenbaum R. K., et al., 2008). For the chemical industry, this granularity can be valuable, as many intermediates and by-products exhibit complex toxicological profiles. Integrating human toxicity into LCA can therefore support both compliance efforts and the drive toward safer chemical design and process optimization.

16.2. Methodology of characterization

16.2.1. Chosen method: EF

In line with the EF 3.1 framework, this guideline recommends applying the USEtox method, as it is the toxicological assessment method for calculating human toxicity impacts, including both cancer and non-cancer effects. USEtox is endorsed as a scientific consensus model under the UNEP/SETAC Life Cycle Initiative and is used in the EU Environmental Footprint context for toxicity-related impact categories.

The USEtox method considers human exposure in consumer and indoor environments as well as emission-related outdoor environments. It accounts for intake via inhalation, dermal and oral exposure pathways. Recent USEtox developments explicitly integrate near-field exposure from chemicals in products with far-field exposure from environmental emissions. Sources of human contact with harmful chemicals may include emissions to the environment, chemicals present in products and, where relevant, chemical fractions released back into the environment after human intake, for example via exhalation (Fantke P. A., 2018) (Fantke P. C., 2021).

The results are calculated using characterization factors that combine fate, exposure and effect information. For human toxicity, results are expressed in CTUh, Comparative Toxic Units for humans, which represent potential disease cases per kilogram of emitted or product-contained chemical, depending on the modelled exposure pathway (Fantke, et al., 2017).

Human toxicity indicators should be interpreted alongside data quality and uncertainty information and not be used in isolation for procurement decisions.

However, despite several years of method development (Fantke P. A., 2018) (Fantke P. C., 2021), some methodological limitations and uncertainties remain, for example:

- **Metals and inorganic substances remain challenging to model**, as their potential impact on human health depends strongly on chemical form, speciation, complexation, bioavailability and other physicochemical characteristics. In the EF method update, robustness factors were introduced partly to reduce the dominance of metals and to

address the inappropriate modelling of non-organic compounds in USEtox (Sala, Biganzoli, Sanye Mengual, & Saouter, 2022)

- **Results are highly influenced by fate and exposure assumptions**, including the relevant exposure routes and environmental compartments. Consequently, comparative assessments may yield substantially different results when exposure pathways differ, even for the same substance. This is particularly relevant for chemicals in products, where near-field exposure during product use may dominate total human exposure (Fantke P. C., 2021).
- **Data gaps remain despite the use of official and regularly updated databases**, such as REACH, European Food Safety Authority (EFSA), and Pesticides Properties DataBase (PPDB) data sources. The EF update improved the reliability of input data by using databases from EU agencies, but limited measured toxicity data still require extrapolation, in-silico estimates or additional robustness considerations for many substances. In addition, REACH registration obligations generally apply from one tonne per year per manufacturer or importer, meaning that substances below this threshold may not be covered by the standard registration requirements (Saouter E. B., 2020).
- The lack of Human Toxicity and Ecotoxicity, freshwater characterization factors for certain Substance of Very High Concern (SVHC) substances requires the use of generic proxies, which may lead to inaccurate impact estimates and invalid comparative assertions. Adequate coverage of substance-specific characterization factors, particularly for SVHCs, is essential to ensure consistent assessments and to avoid the potential underestimation of impacts associated with chemicals of high concern.

For the future, it may be beneficial to establish criteria for evaluating the completeness and robustness of Characterization Factors (CFs) derived within the USEtox framework, with particular attention to high-production-volume chemicals. Where ecotoxicity data are insufficient to derive reliable HC20 values from Species Sensitivity Distributions (SSDs), scientifically defensible approaches for deriving new or supplementary CFs should be explored. This would support broader chemical coverage while maintaining transparency regarding data limitations and associated uncertainties.

As an alternative assessment method, ProScale has been developed to overcome these challenges.

USEtox and ProScale are both life-cycle-oriented approaches for assessing toxicity-related impacts of chemicals, but they answer different questions and are designed for different decision contexts. USEtox is primarily a life cycle impact assessment model that characterizes potential human toxicity and Ecotoxicity, freshwater impacts from chemical emissions, using fate, exposure and effect modelling to calculate characterization factors. ProScale, in contrast, is a risk-oriented chemical footprinting method that combines substance hazard, exposure potential, person-hours and mass flows to assess direct chemical exposure potentials along product life cycles.

USEtox characterization factors are built on fate + exposure + effect modelling, so exposure is also an integral part of USEtox. It can be summarized as:

- USEtox primarily addresses far-field impacts via environmental emissions (ambient air, drinking water, food chain, etc.) and is therefore well suited for classic LCA emission-to-impact modelling; while
- ProScale primarily addresses near-field/direct exposure situations and is therefore closer to workplace-/use-condition decision contexts.

In that sense, the key difference is less “impact vs exposure” and more the exposure setting and target population covered by the currently applied modules.

ProScale is exposure- and risk-oriented: it focuses on the potential for direct human exposure to hazardous substances during production, use, service life and end-of-life stages. It uses regulatory and workplace-relevant information such as GHS/CLP H-phrases, occupational exposure limits, DNELs, process categories, exposure modifiers, risk management measures, person-hours and mass flows. This makes ProScale closer to the way chemical risks are already managed in industrial practice.

Table 38 shows for different aspects the differences between the two models:

Table 38: Comparison of USEtox and ProScale methods

Aspect	USEtox	ProScale
Primary purpose	Characterization of human toxicity and Ecotoxicity, freshwater impacts in LCA.	Assessment of direct exposure-related toxicological potentials in a life-cycle perspective.
Core logic	Fate, exposure and effect modelling of emissions into environmental compartments.	Combination of hazards, exposure potential, person-hours and mass flow.
Main output	Characterization factors and impact scores, e.g. comparative toxic units.	ProScale scores for substances, unit processes and product systems.
Data basis	Substance properties, environmental fate, exposure and effect data.	Regulatory and operational data such as H-phrases, OELs, DNELs, process categories, exposure conditions, and risk management measures.
Exposure perspective	Mostly indirect exposure from emissions into the environment, including human and ecosystem exposure pathways.	Direct exposure potential for workers, consumers, professional users and potentially end-of-life actors.
Industry usability	Scientifically robust but can be data-intensive and less directly connected to workplace risk management. USEtox CFs are readily available in LCA tools for selected chemicals and connected to standard LCI databases. For new compounds that are not available in databases, USEtox needs to calculate CF separately.	Practical, transparent and aligned with information already used in chemical safety and regulatory workflows. For ProScale, however, substance-specific factors/scores typically must be calculated separately, as a full tool implementation is not yet broadly available
Strength	Strong scientific consensus model for environmental toxicity impact assessment in LCA.	Strong practical decision-support tool for comparing chemical risks in products and processes.
Typical limitation	Can be difficult to apply where direct exposure, risk management measures or process-specific occupational conditions dominate the decision.	Less focused on detailed multimedia fate modelling of far-field environmental emissions.

Despite the clear advantages of one assessment method over the other, USEtox is recommended in this document to ensure consistency with the EF 3.1 methodology. Further details on ProScale are provided in Chapter 6.2.

Formula

$$Human\ Tox_cancer = \sum_{j=1}^{N_{htc}} (q_j^{htc} \times CF_j^{htc})$$

Formula 25: Equation for “human toxicity cancer” calculation (adapted from Fantke et al., 2017)

Where:

- **N_{htc}**: Number of human tox cancer flows in the inventory that have a matching EF 3.1 human tox cancer characterization factor and are therefore included.
- **j**: Index that labels each included Human tox cancer flows from 1 to N_{htc}.
- **q^{htc}**: Inventory quantity of Human tox cancer j, expressed in kg.
- **CF^{htc}**: EF 3.1 characterization factors (CTUh/kg) for FF Fate Factor (kg*day/kg emitted) * XF Exposure Factor (kg intake/day per kg in environment) * EF Effect Factor (cases per kg intake).

$$Human\ Tox_Non - cancer = \sum_{j=1}^{N_{htn}} (q_j^{htn} \times CF_j^{htn})$$

Formula 26: Equation for “human toxicity Non- cancer” calculation (adapted from Fantke et al., 2017)

Where:

- **N_{htn}**: Number of human tox non-cancer flows in the inventory that have a matching EF 3.1 human tox non-cancer characterization factor and are therefore included.
- **j**: Index that labels each included Human tox non-cancer flows from 1 to N_{htn}.
- **q^{htn}**: Inventory quantity of Human tox non-cancer j, expressed in kg.
- **CF^{htn}**: EF 3.1 characterization factors (CTUh/kg) for FF Fate Factor (kg*day/kg emitted) * XF Exposure Factor (kg intake/day per kg in environment) * EF Effect Factor (cases per kg intake).

Characterization factors in EF method

For Human Toxicity, cancer, and Human Toxicity, non-cancer in the Environmental Footprint (EF) (Zampori & Pant, 2019) method, the characterization factors are derived from USEtox (Rosenbaum R. K., et al., 2008) (Fantke, et al., 2017) and represent the potential increase in cancer cases resulting from the emission of a chemical. The characterization factor (CF) is expressed in CTUh/kg emitted, where CTUh (Comparative Toxic Unit for humans) represents the estimated increase in cancer disease cases or non-cancer disease cases in the human population per kilogram of substance emitted (Sala, Biganzoli, Sanye Mengual, & Saouter, 2022). USEtox calculates CTUh for a product, combining the life-cycle emissions of substances with their human-toxicity characterization factors. The product itself does not have an intrinsic CTUh value.

For each emission, select the appropriate human toxicity characterization factor:

$$CF_i$$

with units: CTUh per kg emitted

The CF must match substance, emission compartment, impact category, and method version. For human toxicity, there are separate factors defined for: cancer effects, non-cancer effects. For cancer only global CF and for non-cancer global and regionalized CF are applied. CTUh is derived by linking emissions to human health effects through the USEtox impact pathway (Fantke et al., 2017):

emission mass → environmental fate → human exposure/intake → health effect

The characterization factor is built from fate, exposure, and effect modelling:

$$CF_{x,c} = \sum_{i,r} F_{x,c \rightarrow i} \times XF_{x,i,r} \times EF_{x,r}$$

Formula 27: Equation for human toxicity characterization factor calculation (adapted from Fantke et al., 2017)

where:

- *FF*= fate factor, describing how the chemical is distributed and persists in environmental compartments
- *XF*= exposure factor, translating environmental presence into human intake
- *EF*= effect factor, translating intake into expected disease cases
- *i*= receiving or intermediate environmental compartment
- *r*= exposure route, such as inhalation, drinking water, or food ingestion

The fate and exposure parts can also be combined into an intake fraction:

$$iF_{x,c} = \sum_{i,r} F_{x,c \rightarrow i} \times XF_{x,i,r}$$

Formula 28: Intake fraction for human toxicity as part of the characterization factor calculation (adapted from Fantke et al., 2017)

CTU is derived from CF as follows:

$$CTUh_{x,c} = \sum_{x,c} m_{x,c \rightarrow i} \times CF_{xc}$$

Formula 29: Calculation of CTUh with mass flows

Where:

- **CTUh**: Comparative Toxic Unit human
- **m_{x,c}** = emitted mass of substance x to compartment c, kg per functional unit.

- $CF_{x,c}$ = characterization factor for substance x emitted to compartment c, in CTUh per kg emitted

In simple terms:

- $m \times FF$ gives time-integrated environmental presence
- $m \times FF \times XF$ gives human intake
- $m \times FF \times XF \times EF$ gives potential disease cases, expressed as CTUh
- Summing across all substances, compartments, receiving media, and exposure routes gives the total CTUh per functional unit

Where endpoint assessment is performed, midpoint disease cases can be converted to damage using severity factors:

$$\text{Damage} = CF_{\text{midpoint}} \times SF$$

Here,

- SF is a severity factor, for example expressed in DALY per disease case.

Endpoint results are more assumption-dependent than midpoint results and should be interpreted with additional caution. Therefore, this guideline refers only to the midpoint factors to be consistent with the methodological approaches used in EF 3.1.

An overview is shown in Table 39.

Table 39: Input factors for USEtox assessments

Calculation Level	Formula	Meaning	Typical Unit
Inventory emission	$m_{x,c}$	Mass of chemical x emitted to compartment c per functional unit.	kg/FU
Fate Factor	FF	Persistence, transport and distribution of chemicals in the environment.	day or kg·day/kg emitted, depending on formulation
Human Exposure Factor	XF	Human intake per environmental mass or concentration.	kg intake/kg in compartment, or related route-specific unit
Intake fraction	$iF = FF \times XF$	Fraction of emitted mass taken in by humans.	kg intake/kg emitted
Cancer/non-cancer Effect Factor	EF	Expected human health effect per unit intake.	cases/kg intake

Characterization factor	$CF = iF \times EF$	Potential human toxicity impact per kg emitted.	CTUh/kg emitted
Impact score	$CTUh = \sum m \times CF$	Total potential human toxicity impact per functional unit.	CTUh/FU

Practical calculation workflow (Fantke et al 2017):

1. identify the emitted substance and compartment;
2. retrieve or calculate the corresponding USEtox characterization factor;
3. multiply the emission mass by the characterization factor;
4. repeat for all substances and compartments; and
5. sum all results to obtain CTUh per functional unit.

This workflow is described in more detail in chapter 6.2.

Table 40 summarizes all inputs that are needed to calculate a new USEtox data set for a substance that cannot be found in secondary databases or where the company did not calculate a primary dataset.

Table 40: Data needs in CTUh calculation in USEtox assessments

Data Category	Examples of Required Inputs	Purpose in USEtox
Substance identity	CAS number, name, molecular formula, ion or metal species, molecular weight.	Correct mapping of inventory flows to model substances.
Emission inventory	Mass emitted, life cycle stage, emission compartment, functional unit.	Calculation of life cycle impact scores.
Physicochemical properties	Vapor pressure, solubility, partition coefficients, Henry's law constant, dissociation behavior.	Environmental partitioning, multimedia fate and transport.
Degradation and removal	Half-lives or degradation rates in air, water, soil and sediment; transformation processes.	Persistence and time-integrated environmental mass.
Bioaccumulation and food-chain parameters	Bioconcentration or bioaccumulation indicators, partitioning to biota, food intake assumptions.	Human intake through food pathways.
Exposure parameters	Inhalation rates, drinking water intake, food consumption, population exposure assumptions.	Estimation of intake fraction and exposure factor.

Toxicity data	Cancer slope factors, non-cancer dose-response values, effect concentrations or benchmark doses.	Derivation of human effect factors.
Severity data	Disease severity, duration and disability weighting where endpoint modelling is used.	Conversion from cases to DALY or other damage indicators.

Table 41 shows examples of characterization factors for human toxicity.

Table 41: Selected EF 3.1 characterization factors for human toxicity, cancer.

Compound	CF Human toxicity, cancer [CTUh/kg] ¹
acetaldehyde	7,80E-08
arsenic	3,75E-05
benzene	8,62E-08
hexane	1,71E-10
lead	7,66E-06
nickel	1,74E-05
toluene	9,88E-10
methylene chloride	3,08E-08

¹: characterization factors for elementary flow category "emissions to soil, unspecified". Different CFs exist for emissions into soil, water and air.

16.2.2. LCI Flows

Table 42 shows the LCI flows that are used in USEtox calculations.

Table 42 LCI Flows for human toxicity assessment in USEtox.

LCI Flow	Description of Flow (Adapted from Rosenbaum et al., 2008; WHO, 2023)
Heavy Metals	Emissions of toxic metals such as mercury (Hg), cadmium (Cd), and lead (Pb). These substances are persistent in the environment, can accumulate in the food chain, and may cause neurological, developmental, kidney, and other chronic health effects in humans.
Chromium VI Compounds	Emissions of hexavalent chromium compounds. Chromium VI is highly toxic and classified as carcinogenic, with potential impacts including respiratory diseases, organ damage, and increased cancer risk.
Arsenic Compounds	Releases of arsenic-containing substances to air, water, or soil. Human exposure can occur through drinking water, food, and inhalation, potentially leading to cancer and other long-term health effects.
Carcinogenic Organic Compounds	Emissions of substances such as benzene, vinyl chloride, and 1,3-butadiene. These pollutants may contribute to increased cancer risk through inhalation or other exposure pathways.

Non-carcinogenic Organic Compounds	Emission of non-carcinogenic organic substances such as toluene, xylene and phenol to air, water, or soil over the life cycle, contributing to potential human health impacts through environmental fate, human exposure, and toxic effects that do not result in cancer. (LC-IMPACT, n.d.)
Persistent Organic Pollutants (POPs)	Emissions of substances such as dioxins and furans. These pollutants are highly persistent, bioaccumulate in the food chain, and may cause cancer, reproductive disorders, and other chronic health impacts.
PFAS and Other Persistent Fluorinated Compounds	Emissions of highly persistent, fluorinated chemicals that resist environmental degradation. Long-term exposure may lead to accumulation in humans and is associated with potential impacts on immune, endocrine, and other biological systems.
Toxic Organic Solvents and VOCs	Emissions of volatile organic compounds from manufacturing, processing, coatings, and solvent use. Depending on the substance, exposure through inhalation may contribute to irritation, respiratory effects, and chronic toxic impacts on human health.

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#)

Given the high influence of Ecotoxicity, freshwater on weighted EF results for chemical-based products, the uncertainty associated with the normalization factor should be explicitly considered. As inventory completeness and characterization factor coverage continue to evolve, a mechanism for periodic reassessment and revision of the Ecotoxicity, freshwater normalization factor should be considered to ensure that it remains representative, scientifically robust, and aligned with the latest available emissions and toxicity data.

16.3. Assessment Examples

The following examples illustrate the calculation based on existing CF. If new CF must be calculated, the process described above should be followed. Table 43 gives an overview of the results.

Table 43: Generic product calculation of USEtox results

1 kg of product A, cradle-to-gate

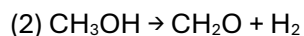
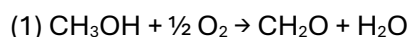
Emission	Amount emitted per kg product	CF [CTUh/kg]	CTUh contribution [Amount x CF]
Benzene to air	1.0×10^{-6} kg	2.0×10^{-4}	2.0×10^{-10} CTUh
Formaldehyde to air	2.0×10^{-7} kg	5.0×10^{-5}	1.0×10^{-11} CTUh
Chromium VI to water	1.0×10^{-9} kg	1.0×10^{-1}	1.0×10^{-10} CTUh

Total:

$$2.0 \times 10^{-10} + 1.0 \times 10^{-11} + 1.0 \times 10^{-10} = 3.1 \times 10^{-10} \text{ CTUh per kg product A}$$

Formaldehyde process

In the fasil process, formaldehyde is synthesized through the catalytic oxidation of methanol. The primary reactions are partial oxidation of methanol (1), and methanol dehydrogenation (2) (Franz et al 2016).



This exothermic chemical reaction is facilitated by a silver catalyst at high temperatures, typically around 600-650 °C (Millar et al 2017). The excess energy from the exothermic reaction is used to generate steam by burning the hydrogen-rich tail gas in a boiler or thermal oxidizer.

This simplified assessment demonstrates how the formaldehyde process can be translated into a USEtox human toxicity calculation. The values below are illustrative only and should be replaced by official USEtox characterization factors and process-specific emission data for a real LCA study. The results are shown in Table 44.

Table 44: Formaldehyde process calculation of USEtox with illustrative figures

Emission source	Emission compartment	Emission mass	USEtox CF, cancer in CTUh/kg	Cancer contribution in CTU/kg	USEtox CF, non-cancer in CTUh/kg	Non-cancer contribution in CTUh/kg	Total contribution to CTUh/kg
Formaldehyde	Urban air	0.050 kg	2.52E-05	3.0E-7	4.0E-6	2.0E-7	5.0E-7
Formaldehyde	Fresh water	0.005 kg	1.17E-07	6.0E-9	8.0E-7	4.0E-9	1.0E-8
Methanol	Urban air	0.100 kg	0	0	5.0E-7	5.0E-8	5.0E-8
Methanol	Fresh water	0.020 kg	0	0	1.0E-7	2.0E-9	2.0E-9
Spent Fe/Mo catalyst loss	Industrial soil	0.001 kg	1.0E-6	1.0E-9	4.0E-6	4.0E-9	5.0E-9
Total	All listed emissions	—	—	3.07E-7	—	2.60E-7	5.67E-7

Calculation: Human toxicity impact score = Σ emission mass $\times$ USEtox characterization factor = $5.0\text{E-}7 + 1.0\text{E-}8 + 5.0\text{E-}8 + 2.0\text{E-}9 + 5.0\text{E-}9 = 5.67\text{E-}7$ CTUh per functional unit which is defined as the production of 1 kg Formaldehyde in Europe.

The summary and main contributions to the overall results can be found in Figure 21.

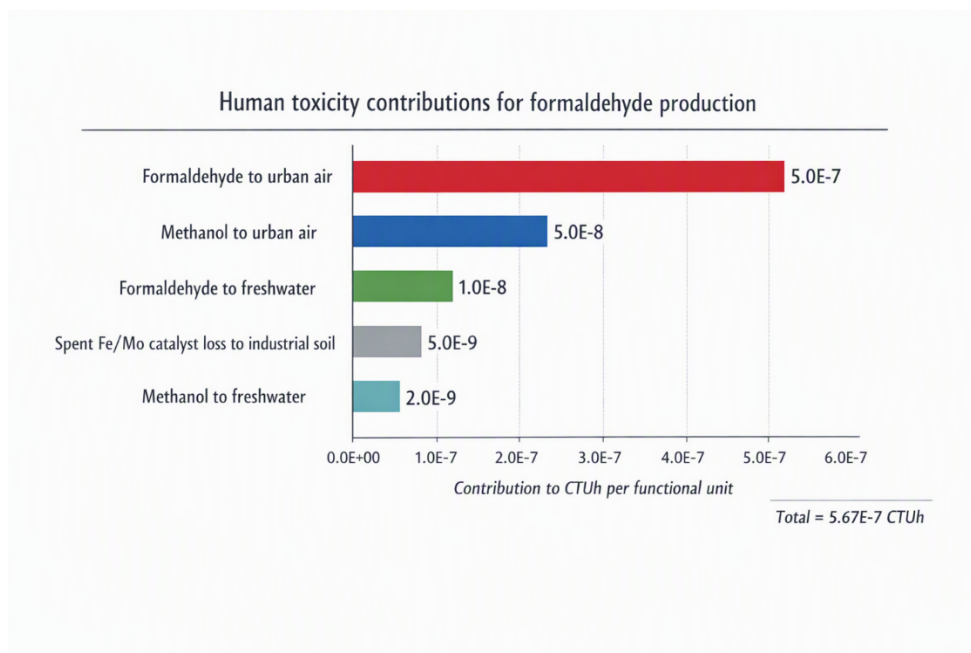


Figure 21: Human toxicity contributions for formaldehyde production.



17. Normalization and weighting, single scoring in LCA

Normalization

Normalization converts the characterized results of each impact category into dimensionless values so that categories with different units (kg CO₂ eq, CTUh, CTUe, m³ world eq, etc.) can be compared. This is done by dividing each characterized result by a corresponding normalization factor.

In EF 3.1 (Environmental Footprint method), normalization, weighting, and single score are optional interpretation steps used to make the results of different impact categories more comparable and easier to communicate. However, individual impact category results may give detailed information on environmental impacts and should be considered first hand.

Normalization Inventory: EF3.1 adopts a global normalization inventory, which is described in Sala et al. 2017. This inventory uses as much as possible available statistics on environmental emissions and resource use, complemented by modelled data. The current normalisation set uses an inventory set in 2010 and largely based on EU statistics. When data is collected at the EU level, data is extrapolated globally based on GDP, following the methodology outlined in Cucurachi et al. 2014. The EF 3.1 uses the following normalization and weighting factor scheme as described in Table 45 and Table 46 (Andreasi Bassi S. B., 2023).

17.1. Characterized results: the starting point

First, the life cycle inventory is converted into characterized impact results for each EF impact category.

Examples:

Impact category	Unit
Climate change	kg CO ₂ eq
Acidification	mol H ⁺ eq
Ecotoxicity, freshwater	CTUe
Land use	dimensionless soil quality index
Resource use, fossils	MJ

At this stage, the results are still in different units, so they cannot be directly added.

17.2. Normalization: “How large is this impact compared with a reference?”

Normalization expresses each characterized result relative to a reference value, usually the **annual impact of an average person** in a reference region.

In EF 3.1, global normalization factors are provided for each impact category.

The basic formula is:

$$\text{Normalized result}_i = \frac{\text{Characterized result}_i}{\text{Normalization factor}_i}$$

Formula 30: Equation the calculation of a normalized value

Where:

- i = impact category
- Characterized result = your product's result in category-specific units
- Normalization factor = reference impact for that category

The result is typically expressed in **person equivalents**.

Example

If a product has:

- Climate change result = 100 kg CO₂ eq
- Normalization factor = 8,000 kg CO₂ eq/person/year

Then:

$$\frac{100}{8,000} = 0.0125$$

This means the product contributes about 0.0125 person-equivalents per year for climate change.

Purpose of normalization

Normalization helps answer:

Is this impact category large or small compared with the overall environmental burden of an average person?

It makes different categories more comparable, but it does **not yet say which category is more important**.

17.3. Weighting: “How important is this impact category?”

Weighting applies a value-based importance factor to each normalized impact category.

The formula is:

$$\text{Weighted result}_i = \text{Normalized result}_i \times \text{Weighting factor}_i$$

Formula 31: Formula to calculate a weighted result with normalized results

Weighting factors reflect the relative importance assigned to different environmental impact categories in the EF method. For example, climate change, particulate matter, toxicity, land use, and resource use all receive different weights.

Purpose of weighting

Weighting defines which impact categories matter most in the overall EF result. Unlike normalization, weighting involves a **value choice**, because it assigns relative importance to impact categories often derived by polls or other accepted methods.

17.4. Single score: adding the weighted results

The impact categories analyzed may differ in relative importance across the alternatives. To ensure that the most relevant impact categories are addressed for each alternative, those impact categories with the largest relative importance are included in the analysis, ensuring that they collectively cover at least 80% of total impact.

Before generating a single score a meaningful number of impact categories shall be defined, it is recommended to cover at least 80% of the environmental impacts. A relevance check shall be done to evaluate if a significant number of impacts is covered. In some studies, the 80% can be reached with 3 or 4 impact categories, some studies need to cover 8 or 9 impact categories depending on the single contribution to the final results of the impact categories. The **single score** is calculated by summing all weighted normalized results across impact categories:

$$\text{Single score} = \sum_i \left(\frac{\text{Characterized result}_i}{\text{Normalization factor}_i} \times \text{Weighting factor}_i \right)$$

Formula 32: Formula to calculate a single score as summary of impact category results

The workflow is:

Characterized result → Normalized result → Weighted result → Single score

The single score is often expressed in points or dimensionless aggregated EF points.

17.5. Simple numerical example

Table 45 shows the calculation of a single score as an illustrative example

Table 45: Example of normalization and weighting of LCIA results to a single score

Impact category	Characterized result	Normalization factor eq/person year	Normalized result person year	Weighting factor	Weighted result
Climate change	100 kg CO ₂ -eq	8,000	0.0125	21.06%	0.00263
Acidification	0.5 mol H ⁺ -eq	55	0.0091	6.20%	0.00056
Land use	300 units	90,000	0.0033	7.94%	0.00026

Single score calculation:

$$0.00263 + 0.00056 + 0.00026 = 0.00345$$

The product's aggregated EF result would be 0.00345 points in this simplified example.

The largest contribution comes from climate change, followed by acidification and land use.

Table 46: Contributions of normalized and weighted results to the single score

Impact category	Weighted result	Contribution to single score
Climate change	0.00263	76%
Acidification	0.00058	16%
Land use	0.00026	8%

17.6. Interpretation

A higher single score means a higher overall environmental burden according to the EF normalization and weighting set.

However, it is important to interpret the single score carefully:

- It can hide reducing impacts in one category while increasing it in another
- It depends on value-based weighting factors.
- It should not replace the category-level results.
- Toxicity and ecotoxicity categories from USEtox often have higher uncertainty. Therefore, according to EF 3.1 they should be excluded from the generation of single scores.
- The EF method recommends reporting both characterized results and normalized/weighted results. ChemX follows this recommendation.

17.7. Practical meaning

In practice:

- **Characterized results** are best for technical analysis.
- **Normalized results** show relative relevance compared with a reference (person year).
- **Weighted results** show contribution to the overall EF profile.
- **Single score** is useful for communication, screening, and overall ranking alternatives.

A good EF 3.1 interpretation should usually show:

1. Characterized results by impact category
2. Normalized and weighted contribution analysis
3. Single score aggregates all single indicators
4. Sensitivity or uncertainty discussion where relevant

Normalization factors were developed and published in EF 3.1 for all impact categories. For transparency, all impact category results should be included and compared to the results without the impact categories rated with a low reliability factor. Table 47 shows the normalization factors for the EF 3.1 impact categories. Normalization and weighting factors are published by JRC under: https://eplca.jrc.ec.europa.eu/permalink/EF3_1/Normalisation_Weighting_Factors_EF_3.1.xlsx

Table 47: Weighting factors as defined in EF 3.1

EF impact category	Weighting factor
Climate change	21.06%
Ozone depletion	6.31%
Human toxicity, cancer	2.13%
Human toxicity, non-cancer	1.84%
Particulate matter	8.96%
Ionising radiation, human health	5.01%
Photochemical ozone formation, human health	4.78%
Acidification	6.20%
Eutrophication, terrestrial	3.71%
Eutrophication, freshwater	2.80%
Eutrophication, marine	2.96%
Land use	7.94%
Ecotoxicity, freshwater	1.92%
Water use	8.51%
Resource use, fossils	8.32%
Resource use, minerals and metals	7.55%
Total	100.00%

17.8. Other alternative approaches using normalization and weighting

Alternative approaches exist but are not in line with EF 3.1. The following text is given as additional information taking into consideration other LCIA methods: Swiss Ecoscarcity 2021 and Eco-Efficiency Analysis (EEA).

Swiss Ecoscarcity 2021

The method of ecological scarcity – sometimes called Swiss Ecoscarcity or Swiss Ecopoints method – allows a comparative weighting and aggregation of various environmental interventions

by use of so-called eco-factors. The method supplies these weighting factors for different emissions into air, water and top-soil/groundwater as well as for the use of energy resources. The eco-factors are based on the annual actual flows (current flows) and on the annual flow considered as critical (critical flows) in a defined area (country or region). The eco-factors were originally developed for the area of Switzerland (see references below). There, current flows are taken from the newest available statistical data, while critical flows are deduced from the partly scientifically supported goals of the Swiss environmental policy, each as of publication date. Later, sets of eco-factors were also made available for other countries, such as Belgium and Japan etc.

In the ecological scarcity method, an impact assessment of life cycle inventories is performed according to the 'distance-to-target' principle. The key metrics of this method are eco-factors, which indicate the environmental burden of an emission, resource use or other substance flows in the form of Ecopoints (UBP) per unit of quantity. An eco-factor is derived by relating the current situation to the tolerated maximum emission or use. The ecological scarcity method, for convenience also referred to as the eco points method, was first published in 1990.

This method is taken from (Frischknecht, Steiner, Braunschweig, Egli, & Hildesheimer, 2006), with adaptations by PRé as described below. The CFs have first been implemented by ESU-services Ltd. All files are provided without liability¹⁹. Ecological Scarcity 2006 is a follow-up of the Ecological scarcity 1997 method, which is called Ecopoints 97 (CH) in the SimaPro method library (superseded) and was lastly updated in 2021 (Federal Office for the Environment (FOEN), 2021).

The ecoinvent implementation contains seven specific impact categories, with for each substance a final UBP (environmental loading points) score as CF. This method only contains the impact category natural resources containing only water resources.

There are three important differences and reasons for not using it in the Chem-X guideline:

- The Ecopoint system does not use a specific classification. It assesses impacts individually. Although this allows for a detailed and very substance-specific method, it has the disadvantage that only a few impacts are assessed.
- The Ecopoint system uses a different normalization principle. It uses target values rather than current values.
- The Ecopoint system is based on Swiss policy levels instead of sustainability levels. Policy levels are usually a compromise between political and environmental considerations.

The following data are necessary in calculating a score in Ecopoints for a given product:

- quantified impacts of a product;
- total environmental load for each impact type in a particular geographical area;
- maximum acceptable environmental load for each impact in that particular geographical area.

Alternative Approach (Example): Eco-Efficiency Analysis

Eco-Efficiency Analysis is an alternative approach that uses LCA results, normalize them and apply a weighting scheme. In eco-efficiency analysis, normalization converts environmental impacts and costs into comparable relative values. Weighting then combines the environmental

¹⁹ Contact info: <http://www.esu-services.ch/address/>

impact categories according to their importance. The resulting environmental score is compared with the cost score to identify the alternative that provides the best balance between low environmental impact and low cost. Because *Eco-Efficiency Analysis combines costs and environmental impact it is out of scope of this cradle-to-gate guideline that focusses on environmental impacts. However, it can be an alternative approach addressing sustainability impacts and is therefore listed in this chapter.*

An eco-efficiency modular framework was therefore developed to accommodate a range of expectations in sustainability assessments (Grosse-Sommer, Grünenwald, Paczkowski, van Gelder, & Saling, 2020) called Eco-Efficiency Analysis (EEA). In contrast to earlier practice, a multi assessment tool was identified to be adequate for the expanding variety of business applications and analytical questions. EEA6 and EEA10 prescribe specific environmental indicators and impact assessment models, results from different studies that can be compared on a common methodological basis. EEA10 covers Climate change, Ozone depletion, Human toxicity, Photochemical ozone formation, Acidification, Eutrophication freshwater, Eutrophication marine, Land use, Resource depletion water, Resource depletion mineral, fossil. EEA6 covers Climate change, Human toxicity, Photochemical ozone formation, Acidification, Eutrophication freshwater and marine, Resource depletion mineral, fossil.

Environmental materiality is safeguarded through a relevance check designed to prevent selective reporting and unintended greenwashing. The check supports alignment with the goal-and-scope requirements of ISO 14040 and ISO 14044 by requiring the choice of impact categories, indicators, and characterization models to be both justified and consistent with the intended application of the assessment. Accordingly, the selected categories should cover the environmental issues that are material to the product system, while the suitability of each characterization model should be explained in relation to the study's goal and scope.

The procedure begins by normalizing the ten EEA impact categories against annual European reference data. The normalization factors are taken from the EU Product Environmental Footprint framework (Benini, et al., 2014) (Benini, Sala, & Pant, Normalization and Weighting Factors for Testing, 2015).

In the second stage, the normalized scores of all impact categories are added to obtain the overall unweighted environmental impact. Each dimensionless category score is then reported as a share of this total. For every alternative, the analysis retains the categories that contribute most strongly until they collectively represent at least 80% of its total impact. The impact categories analyzed may differ in importance across the alternatives; however, all categories are considered until they collectively account for 80% of the total impact. By concentrating on the dominant contributors, the toolbox directs the assessment toward the environmental aspects that are most relevant to the comparison.

Once the relevance check has identified the pertinent impact categories, the normalized scores for these categories—together with any additional categories considered useful—are combined with their respective weighting factors. The resulting weighted scores are then added to obtain an overall measure of environmental impact. This procedure follows the established aggregation sequence of external normalization and subsequent weighting (Huppel & van Oers, 2011) (Guinée et al., 2002).

Because each process or product is evaluated against external reference values, the calculated results do not depend on the other alternatives included in the comparison.

The aggregate normalized and weighted environmental impact is reported in units of “person time.” This unit is derived during normalization, when each impact-category result is divided by the relevant annual impact associated with a specified region and population. Per-capita normalization is a well-established approach (Laurent, Olsen, & Hauschild, 2011) and is also described as a “person equivalent” (Stranddorf, Hoffmann, & Schmidt, 2005). Depending on the scale of the functional unit, person time may be stated in person-years, person-days, or person-hours. The normalized person-time values are then multiplied by their respective weighting factors and aggregated to determine the overall environmental impact as single score.

18. Glossary

18.1. Overview of abbreviations, terms and definitions

Abbreviation	Term	Definition	Source
	Activity data	“Activity data are quantified measures of a level of activity that results in environmental impacts”¹. Activity data can be measured, modeled, or calculated. There are two categories of activity data: process activity data and financial activity data. Process activity data are physical measures of a process that results in environmental impacts. These data capture the physical inputs, outputs, and other metrics of the product’s life cycle (e.g. energy, mass, volume etc). Financial activity data are monetary measures of a process that results in environmental impacts. Alternatively, from ISO: quantitative measure of an activity that results in an environmental impact	TfS PCF Guideline v3.0 ISO 14033
	Allocation	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.	TfS PCF Guideline v3.0
	Annualization Period	Period over which the impacts associated with land-use change are allocated to subsequent production; a 20-year assessment period is commonly applied in product carbon-footprint and land-use accounting	(BSI, 2011; (GHG Protocol Product Standard, 2011)

	Background data	Data that is indirectly measured, calculated or obtained quantified value of a unit process or activity and related information within a product system or company, not based on specific original source measurements	(ISO14064:1 , 2018)
	Bill of materials (BOM)	A structured list of all the components, and their quantities that make up an assembly or product.	TfS PCF Guideline v3.0
	Biogenic carbon content	Fraction of carbon mass classified as biogenic (out of total material mass). Note 1: Can be attributed by means of a mass balance chain of custody model as defined in ISO 22095, where applicable by sector specific rules. Note 2: If analytically measurable via 14C-analysis, it can be classified as “bio-based carbon content” . Note 3: If not analytically measurable via 14C-analysis (e.g., by applying mass balance chain-of-custody model), it can be classified as “bio-attributed carbon content” . “Biogenic carbon content” will be used as leading term in this document.	Derived from ISO 59020:2024 Note 1: based on ISO 59020:2024 section A.2.1 “Introduction to resource inflow circularity indicators”, in analogy with “renewable content”
	Biogenic emissions	CO ₂ and CH ₄ emissions from the combustion or biodegradation of biomass.	TfS PCF Guideline v3.0, adopted
	Biogenic removals	The sequestration or absorption of GHG emissions from the atmosphere, which most typically occurs when CO ₂ is absorbed by biogenic materials during photosynthesis.	TfS PCF Guideline v3.0

	Biodiversity	The variability among living organisms, encompassing diversity within species, between species, and of ecosystems	(Convention on Biological Diversity, 1992; IPBES, 2019)
	Biomass	Material of biological origin, excluding material embedded in geological formations and material transformed to fossilized material. Note 1: Biomass includes organic material (both living and dead), e.g. trees, crops, grass, tree litter, algae, animals, manure and waste of biological origin. Note 2: Excludes peat.	ISO 14067:2018
	Burden Shifting	PEF assesses environmental impacts across a comprehensive set of 16 categories, each capturing a different dimension of environmental harm. These categories ensure that improvements in one area do not come at the expense of degradation in another, a phenomenon known as burden shifting.	(European Commission (EC))
CAS number	Chemical Abstracts Service Registry Number	A CAS Registry Number (CAS RN®) is a unique and unambiguous identifier for a specific substance that allows clear communication and, with the help of CAS scientists, links together all available data and research about that substance. Governmental agencies rely on CAS Registry Numbers for substance identification in regulatory applications because they are unique, easily validated, and internationally recognized.	TfS PCF Guideline v3.0 https://www.cas.org/cas-data/cas-registry
CCS	Carbon Capture and Storage	CCS involves the capture of carbon dioxide (CO ₂) emissions from industrial processes, such as steel	TfS PCF Guideline v3.0

		and cement production, or from the burning of fossil fuels in power generation. This carbon is then transported from where it was produced, via ship or in a pipeline, and stored deep underground in geological formations.	
CCU	Carbon Capture and Utilization	Carbon capture and utilization (CCU) involves the capture of the greenhouse gas CO ₂ from point sources or ambient air and its subsequent conversion into valuable products.	TfS PCF Guideline v3.0
CFP	Carbon footprint of a product	See Product Carbon Footprint (PCF).	TfS PCF Guideline v3.0
CFCs	Chlorofluorocarbon	See Greenhouse Gas definition.	TfS PCF Guideline v3.0
	Collective dose	This is the sum of the individual doses received in a given period by a specified population from exposure to a specified source of radiation	(NRC, 2026)
CSRD	Corporate Sustainability Reporting Directive	EU directive requiring companies within its scope to disclose material sustainability impacts, risks, and opportunities in accordance with European Sustainability Reporting Standards	(European Parliament and Council, 2022)
CH ₄	Methane	See Greenhouse Gas definition.	TfS PCF Guideline v3.0
CMP	Contract manufactured products	Contract manufacturing occurs when a company outsources part of the manufacturing process to a third-party company to reduce the expenses of production.	TfS PCF Guideline v3.0
	Characterization Factor	Factor derived from a characterization model which is applied to convert an assigned life	ISO 14044

		cycle inventory analysis result to the common unit of the category indicator NOTE The common unit allows calculation of the category indicator result.	
	Cradle-to-gate	An assessment that includes part of the product's life cycle, including material acquisition through the production of the studied product and excluding the use or end-of-life stages.	TfS PCF Guideline v3.0 ▲
	Cradle-to-grave	A cradle to grave assessment considers impacts at each stage of a product's life cycle, from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, recycling, and ultimately, disposal.	TfS PCF Guideline v3.0
	Conformity assessment	Demonstration that specified requirements relating to a product, process, system, person or organization are fulfilled. Note 1 to entry: Adapted from ISO/IEC 17000: 2004, definition 2.1. ISO/TS 14441:2013(en), 3.13	TfS PCF Guideline v3.0
	Consumption mix	This approach focuses on the domestic production and the imports taking place. These mixes can be dynamic for certain commodities (e.g., electricity) in the specific country/region.	TfS PCF Guideline v3.0
CO ₂ e	Carbon Dioxide Equivalent	Carbon dioxide equivalent, or CO ₂ e is a metric measure representing all greenhouse gases by converting them to the equivalent amount of CO ₂ .	TfS PCF Guideline v3.0

	Endpoint characterization models	Estimate the ultimate effects (or “endpoints”) of environmental impacts on areas of protection, such as human health, ecosystem quality, and resource availability. These models extend the analysis further along the cause-effect chain, translating inventory data through midpoint categories into final damage categories. In this sense Human health (DALYs), ecosystem damage (species loss), resource depletion are endpoint categories.	TfS PCF Guideline v3.0
C14-method	Radiocarbon dating	A form of radiometric dating used to determine the age of organic remains in ancient objects, such as archaeological specimens, on the basis of the half-life of carbon-14 and a comparison between the ratio of carbon-12 to carbon-14 in a sample of the remains to the known ratio in living organisms.	TfS PCF Guideline v3.0
DU	Declared Unit	Quantity of a product for use as a reference unit in the quantification of a partial LCA Note: Typically, the declared unit is referring to a physical quantity, for chemicals for example “1 kg of product (unpacked)”	ISO 14067:2019
DMP	Digital Material Passport	A structured digital record for a material that contains detailed information about sustainability and circularity, as well as required and potentially optional declarations, certificates, and additional material information. It focuses on intermediate materials in the value chain which may not be subject to regulation, but whose data are required to enable the issue of regulated Digital Product	Chem-X Definition

		Passports (DPPs). DPPs are designed to interoperate with one or more DPPs.	
DPP	Digital Product Passport	A structured digital record for a product that contains detailed information about sustainability and circularity, as well as required and potentially optional declarations, certificates and additional product information. It focuses on a regulated end product in the value chain. Both its information content and technical requirements follow regulatory requirements and/or standards delegated by the legislator to designated standardization bodies.	Chem-X Definition <i>Note 1: based on DPP definition in ESPR.</i>
dLUC	Direct Land-Use Change	change in the human use of land within the relevant boundary	ISO 14050
	Disease incidence	Disease incidence is the occurrence of cases of a disease or health condition in a defined population over a specified period of time. It is commonly expressed as a rate or proportion and reflects the risk of developing the disease.	New York State Department of Health, 2017
DUNS	Dun and Bradstreet Number	The Dun & Bradstreet D-U-N-S Number is a unique nine-digit identifier for businesses.	TfS PCF Guideline v3.0
	Ecological Scarcity Method	A distance-to-target LCIA method that weights environmental pressures according to the relationship between current conditions and legally or politically defined environmental targets; its land-use indicator is linked to biodiversity and policy objectives	(Frischknecht et al., 2021)
	Ecosystem	dynamic complex of communities of plants, animals and microorganisms and their non-living	ISO 14050

		environment, interacting as a functional entity	
	Ecosystem Services	benefit people obtain from <u>ecosystems (3.1.9)</u> Note 1 to entry: Benefits include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth.	ISO 14055-1:2017, 3.1.2
ECICS	European Customs Inventory of Chemical Substances	See table 4.2	TfS PCF Guideline v3.0
EEIO	Environmentally extended input and output	Environmentally extended input–output analysis (EEIOA) is used in environmental accounting as a tool which reflects production and consumption structures within one or several economies.	TfS PCF Guideline v3.0
EF	Environmental Footprint	It is a multi-criteria measure to calculate the environmental performance of a product, service or organization based on a life cycle approach. EF 3.1 is the currently official used approach for Environmental Footprint in the EU.	TfS PCF Guideline v3.0 adopted
	Effective dose	The effective dose is the total amount of equivalent doses to the total health of the whole body under consideration of the different sensitivities of the single organs and tissues for stochastic radiation effects.	(BfS, 2026), adapted
	Elementary flow	Material or energy entering the system being studied that has been drawn from the environment without	ISO 14044 Amd 2: 2020

		previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation	
	Energy flow	Input to or output from a unit process or product system, quantified in energy units	ISO 14044 Amd 2: 2020
EoL	End of Life	End-of-life describes the end of the life cycle of a product. Here one can distinguish between different treatment methods: Recycling, landfill and incineration	TfS PCF Guideline v3.0
ERP system	Enterprise resource planning system	Enterprise resource planning is a system that helps automate and manage business processes across finance, manufacturing, retail, supply chain, human resources, and operations.	TfS PCF Guideline v3.0
ESPR	Ecodesign for Sustainable Products Regulation	EU regulation establishing a framework for product-specific ecodesign circularity, resource efficiency, and overall environmental sustainability	(European Parliament and Council, 2024)
EU	European Union	The European Union is a supranational political and economic union of 27 member states that are located primarily in Europe.	TfS PCF Guideline v3.0
	Exposure factor	The exposure factor describes the pathways and mechanisms through which humans come into contact with radionuclides present in the environment. It includes parameters such as inhalation rates, ingestion rates (food and water), occupancy times, and behavioral patterns that influence the magnitude and	(ICRP, 2007)

		duration of exposure. Exposure factors are used in radiological protection to estimate radiation doses to individuals or populations from environmental contamination.	
FF	Fate factor	The fate factor indicates the distribution and transformation of chemicals or radionuclides released into the environment, and their transport among environmental compartments (e.g., air, water, soil). It thereby determines the concentrations available for exposure. Building on this, the exposure factor relates dissolved to total chemical mass in the environment, the ecotoxicity effect factor indicates potential ecotoxicity effects per unit of dissolved chemical mass in the environment, and the damage factor finally relates potential effects to damages on ecosystem quality.	(LC-Impact, a spatially differentiated life cycle impact assessment method, 2019; Paulillo, McKone, & Fantke, 2023)
	Functional unit	A functional unit describes the function of a product in question. For example, for a laundry detergent, the functional unit could be defined as “washing 4.5 kg of dry fabric with the recommended dosage with medium-hard water”. Understanding the functional unit is essential for comparability between products with the same function, as it provides the reference to which the input (materials and energy) and output (such as products, byproducts, waste) are quantified.	TfS PCF Guideline v3.0
GHG	Greenhouse Gases	Greenhouse gases constitute a group of gases contributing to global warming and climate change. The Kyoto Protocol, an environmental agreement adopted by many of the parties to the United Nations Framework Convention on climate	TfS PCF Guideline v3.0

		change (UNFCCC) in 1997 to curb global warming, nowadays covers seven greenhouse gases: The non-fluorinated gases: Carbon dioxide (CO₂) Methane (CH₄) Nitrous oxide (N₂O) The fluorinated gases: Hydrofluorocarbons (HFCs) Perfluorocarbons (PFCs) Sulphur hexafluoride (SF₆) Nitrogen trifluoride (NF₃) Converting them to carbon dioxide (or CO₂) equivalents makes it possible to compare them and to determine their individual and total contributions to global warming.	
GHG protocol	Greenhouse Gas Protocol Standard	International Standard on how to calculate Greenhouse Gases.	TfS PCF Guideline v3.0
GLO	Global		TfS PCF Guideline v3.0
GWP	Global Warming Potential	Global Warming potential is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere.	TfS PCF Guideline v3.0
HCFCs	Hydrochlorofluorocarbon	See Greenhouse Gas definition.	TfS PCF Guideline v3.0
HEFs	Fluorinated ethers	Liquid Chemical.	TfS PCF Guideline v3.0

HFCs	Hydrofluorocarbons	See Greenhouse Gas definition.	TfS PCF Guideline v3.0
HS	Harmonized Commodity Description and Coding Systems	See table 4.2	TfS PCF Guideline v3.0
IEC	International Electrotechnical Commission	Founded in 1906, the IEC (International Electrotechnical Commission) is the world's leading organization for the preparation and publication of international standards for all electrical, electronic and related technologies.	TfS PCF Guideline v3.0
ILCD	International Life Cycle Data System	The International Reference Life Cycle Data System is an initiative developed by JRC and DG ENV since 2005, with the aim to provide guidance and standards for greater consistency and quality assurance in applying LCA.	TfS PCF Guideline v3.0
ISO	International Organization for Standardization	The International Organization for Standardization is an international standard development organization composed of representatives from the national standards organizations of member countries.	TfS PCF Guideline v3.0
ISOPA	European Diisocyanate and Polyol Producers Association	ISOPA is the European trade association for producers of diisocyanates and polyols, the main building blocks of polyurethanes.	TfS PCF Guideline v3.0
ISO 14067: 2018	ISO standard on Greenhouse gases — Carbon footprint of products —	ISO 14067: 2018 specifies principles, requirements and guidelines for the quantification and reporting of the carbon footprint of a product (CFP), in a manner consistent with International Standards on life cycle assessment	TfS PCF Guideline v3.0

	Requirements and guidelines for quantification	(LCA) [ISO 14040 [ISO 14040: 2006] and ISO 14044].	
IT	Information technology		TfS PCF Guideline v3.0
kg	Kilogram		TfS PCF Guideline v3.0
kWh	Kilowatt-hour		TfS PCF Guideline v3.0
	Land Occupation	Land occupation refers to the physical area of land required for an activity over a specified period, commonly expressed in m ² ·year. It captures the ongoing pressure on ecosystems caused by agricultural, forestry, industrial, or urban land use and is explicitly addressed in UNEP SETAC land use impact assessment guidelines and the EF 3.1 methodology	(Koellner, 2013)
	Land Transformation (Land Use Change)	Land transformation involves the conversion of land from one use or cover type to another (e.g., forest to cropland or urban land). Such transformations can cause long lasting or irreversible ecological impacts and are treated separately from land occupation in LCA to reflect their distinct impact pathways and regeneration dynamics	(Koellner, 2013)
LCA	Life Cycle Assessment	The compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle [ISO 14040: 2006].	TfS PCF Guideline v3.0

LCI	Life Cycle Inventory	The phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle [ISO 14040:2006].	TfS PCF Guideline v3.0
LCIA	Life Cycle Impact Assessment	The phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product [ISO 14040:2006].	TfS PCF Guideline v3.0
	Midpoint characterization model	Approaches that assess the potential environmental impacts of a product or process at an intermediate stage in the cause-effect chain. Examples are climate change, acidification, eutrophication, ozone depletion.	TfS PCF Guideline v3.0
LHV	Lower heating value	The lower heating value (LHV; <i>net calorific value</i> ; <i>NCV</i> , or <i>lower calorific value</i> ; <i>LCV</i>) is another measure of available thermal energy produced by a combustion of fuel, measured as a unit of energy per unit mass or volume of substance. In contrast to the HHV, the LHV considers energy losses such as the energy used to vaporize water. Lower heating value (LHV) is defined as the amount of heat released when a fuel is combusted, starting from 25°C and with the combustion products returned to 150°C, excluding the latent heat of vaporization of water.	(Boyce, 2012)
NACE	Nomenclature of Economic Activities	NACE (Nomenclature of Economic Activities) is the European statistical classification of economic activities. It is established by law.	TfS PCF Guideline v3.0

NF ₃	Nitrogen trifluoride	See Greenhouse Gas definition.	TfS PCF Guideline v3.0
N ₂ O	Nitrous oxide	See Greenhouse Gas definition.	TfS PCF Guideline v3.0
	Nutrient Loading	Nutrient loading refers to the increased input of nutrients, particularly nitrogen (N) and phosphorus (P), into the environment, which alters ecological dynamics and can impact the quality of resources available to organisms, including hosts and parasites. So, nutrient loading fuels the ecosystem. Excessive loading results in a catastrophic collapse when the resulting increase in metabolism exceeds the available oxygen supply of the river.	(Aalto, Decaestecker, & Pulkkinen, 2015; K.E. Limburg, 2013)
OCF	Organizational Carbon Footprint	Carbon Footprint of an Organisation.	TfS PCF Guideline v3.0
ODS	Ozone-depleting substance	It refers to gases containing either chlorine or bromine that are released to the atmosphere because of human activity and are controlled under Annexes A, B, C, or E of the Montreal Protocol. These include, among other CFCs, CCl ₄ , CH ₃ CCl ₃ , halons, CH ₃ Br and HCFCs. These ODSs typically have sufficiently long atmospheric lifetimes to reach the stratosphere after being emitted at the surface. Methyl bromide is the shortest-lived of the controlled substances and has natural and anthropogenic sources. Other substances contribute chlorine and bromine to the atmosphere but are not	(WMO, 2022)

		controlled under the Montreal Protocol for various reasons.	
	Partial carbon footprint of a product	Sum of GHG emissions and GHG removals of one or more selected process(es) in a product system, expressed as CO₂ equivalents and based on the selected stages or processes within the life cycle. Note 1 to entry: A partial CFP is based on or compiled from data related to (a) specific process(es) or footprint information modules, which is (are) part of a product system and can form the basis for quantification of a CFP. More detailed information on information modules is given in ISO 14025:2006, 5.4. Note 2 to entry: “Footprint information modules” is defined in ISO 14026:2017, 3.1.4. Note 3 to entry: The results of the quantification of the partial CFP are documented in the CFP study report expressed in mass of CO₂e per declared unit.	ISO 14025:2006, 5.4.; ISO 14026:2017, 3.1.4.
	Primary data	Sometimes also called activity data. Data that concerns processes inside the operational control of the company or data from specific processes in the product life cycle. A partial LCIA is considered primary data if the measure of the activity data and the measure of the emission factor are based on data where the data generators have a direct access to via direct measurements or assessments where they have a direct control.	TfS PCF Guideline v3.0

		“Data pertaining to a specific product or activity within a company’s value chain. Such data may take the form of activity data, emissions or emission factors. Primary data is site-specific, company-specific (if there are multiple sites for the same product) or supply chain-specific. Primary data may be obtained through meter readings, purchase records, utility bills, engineering models, direct monitoring, material or product balances, stoichiometry or other methods for obtaining data from specific processes in the value chain of the company” [Path 2021:41]	
	Primary particulate matter	Primary particulate matter consists of solid particles or liquid droplets that are emitted directly into the atmosphere from identifiable sources, such as combustion processes, industrial activities, construction sites, road dust, and wildfires.	(U.S. Environmental Protection Agency (EPA), 2025)
PCF	Product Carbon Footprint	The Product Carbon Footprint is the most established method for determining the climate impact of a product, considering the total greenhouse gas (GHG) emissions caused to produce a product, expressed as carbon dioxide equivalent. The PCF can be assessed from cradle-to-gate (partial PCF) or from cradle-to-grave (total PCF).	TfS PCF Guideline v3.0
PCR	Product Category Rules	Set of specific rules, requirements, and guidelines for developing Type III environmental declarations and footprint communications for one or more product categories. [ISO 14025:2006] . [ISO 14027]	TfS PCF Guideline v3.0



PFCs	Perfluorocarbons	See Greenhouse Gas definition.	TfS PCF Guideline v3.0
PFPEs	Perfluoropolyethers	Perfluoropolyethers (PFPE) are a group of plastics, usually liquid to pasty at room temperature, that are fluoropolymers consisting of fluorine, carbon and oxygen.	TfS PCF Guideline v3.0
PM ₁₀	Particulate Matter ₁₀	PM₁₀ refers to inhalable particulate matter with an aerodynamic diameter of 10 micrometers or smaller. These particles can penetrate the upper respiratory tract and are associated with adverse respiratory and cardiovascular health effects. Often it is not well defined if PM10 refers to particles between 2.5 micrometers and 10 micrometers or if particles of 2.5 micrometers and smaller are included. However, Fantke et al. (2016) distinguish between “fine PM” as PM 2.5 and “coarse PM” as particle fraction between 2.5 and 10 micrometer.	(U.S. Environmental Protection Agency (EPA), 2025; Fantke, et al., 2016)
PM _{2.5}	Particulate Matter _{2.5}	PM _{2.5} refers to fine particulate matter with an aerodynamic diameter of 2.5 micrometers or smaller. Due to their small size, these particles can penetrate deep into the lungs and enter the bloodstream and are considered the most harmful fraction of particulate matter in terms of long-term health impacts.	(U.S. Environmental Protection Agency (EPA), 2025)
PRODCOM	Production Communautaire (Community Production)	See table 4.1	TfS PCF Guideline v3.0

	Production mix	This approach focuses on the domestic production routes and technologies applied in the specific country/region and individually scaled according to the actual production volume of the respective production route. This mix is generally less dynamic.	TfS PCF Guideline v3.0
	Programme operator	Body or bodies that conduct an environmental declaration programme or footprint communication programme. A programme operator can be a company or a group of companies, industrial sector or trade association, public authorities or agencies, or an independent scientific body or other organization. [ISO 14027]	TfS PCF Guideline v3.0
	Removal	The sequestration or absorption of GHG emissions from the atmosphere, which most typically occurs when CO ₂ is absorbed by biogenic materials during photosynthesis.	TfS PCF Guideline v3.0
	Secondary data	secondary data data obtained from sources other than primary data (3.2.2) Note 1 to entry: Such sources can include databases and published literature validated by competent authorities. “Data that is not from specific activities within a company’s value chain but from databases, based on averages, scientific reports or other sources.” [Path 2021:41]	TfS PCF Guideline v3.0, adopted ISO 14064-1
	Secondary particulate matter	Secondary particulate matter is not emitted directly, but forms in the atmosphere through chemical reactions of gaseous precursor	(U.S. Environmental Protection

		pollutants—such as sulfur dioxide (SO ₂), nitrogen oxides (NO _x), ammonia (NH ₃), and volatile organic compounds (VOCs)—resulting in fine particles, often in the PM _{2.5} size range.	Agency (EPA), 2025)
SF ₆	Sulphur hexafluoride	See Greenhouse Gas definition.	TfS PCF Guideline v3.0
SIC	Standard Industrial Classification	The Standard Industrial Classification (SIC) is a four-digit classification system that classifies industries according to business activities.	TfS PCF Guideline v3.0
SMILES	Simplified Molecular Input Line Entry System	See table 4.2	TfS PCF Guideline v3.0
SOC	Soil Organic Carbon	Carbon contained in soil organic matter and frequently used as an indicator of soil condition.	(Vidal-Legaz , Sala, Antón, & Milà i Canal, 2016)
	Spot transaction	A spot transaction is the sale of a commodity, asset or right, under the terms of which delivery is scheduled to be made within the longer of the following periods: (a) 2 trading days; (b) the period generally accepted in the market for that commodity, asset or right as the standard delivery period.	TfS PCF Guideline v3.0
SVHC	Substance of Very High Concern	SVHC (Substance of Very High Concern) refers to chemicals identified under the EU REACH Regulation as posing serious risks—such as carcinogenic, mutagenic, reproductive toxicity, PBT, vPvB, or endocrine-disrupting properties—and listed by ECHA on the official Candidate List.	

	System expansion	Expanding the product system to include the additional functions related to the co-products. System expansion is a method used to avoid co-product allocation.	TfS PCF Guideline v3.0
TÜV	Technischer Überwachungsverein (engl.: MOT)		TfS PCF Guideline v3.0
	Unit process	Smallest element considered in the life cycle inventory analysis for which input and output data are quantified.	ISO 14040:2006
UNSPSC	United Nations Standard Products and Services Code	See table 4.2	TfS PCF Guideline v3.0
	Utilities	The term “utilities” includes here: Electricity, process steam, excess steam, cooling water, demineralized water, process water, compressed air and nitrogen.	TfS PCF Guideline v3.0
	Validation	the process of evaluating a system or component to ensure compliance with the functional, performance and interface requirements. [ISO/IEC 14776: 2010]	TfS PCF Guideline v3.0
VAT	Value Added Tax		
	Verification	Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled. [ISO 9000: 2005; ISO 14025:2006]	TfS PCF Guideline v3.0

	Waste	Any substance or object which the holder discards or intends or is required to discard Note 1: A substance or object resulting from a production process the primary aim of which is not the production of that substance or object is considered not to be waste, but to be a by-product if the following conditions are met: (a) further use of the substance or object is certain; (b) the substance or object can be used directly without any further processing other than normal industrial practice; (c) the substance or object is produced as an integral part of a production process; and (d) further use is lawful (i.e., the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts).	(EU, 2008)
WBCSD	World Business Council for Sustainable Development	The World Business Council for Sustainable Development (WBCSD) is a business-led organization that focuses exclusively on business and sustainable development.	TfS PCF Guideline v3.0

19. Information Model

[The version 0.9 of Chem-X DMP information model, including sustainability metrics described in this Guideline, is currently subject to a parallel public consultation process.

A link to the final documents will be provided in the published final version of this Guideline .]

20. Literature

- JRC. (2018). Product Environmental Footprint Category Rules (PEFCR) Guidance. *Joint Research Centre*.
- Aalto, S., Decaestecker, E., & Pulkkinen, K. (2015). A three-way perspective of stoichiometric changes on host–parasite interactions. *Trends in Parasitology*, 31(7), pp. 333-340.
- Achakulwisut, P., Brauer, M., Hystad, P., & Anenberg, S. (2019, 3). Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO₂ pollution: estimates from global datasets. *Lancet Planet Health*, 3. *Lancet Planet Health*, pp. 166-178. Retrieved from [https://doi.org/10.1016/S2542-5196\(19\)30046-4](https://doi.org/10.1016/S2542-5196(19)30046-4)
- Adams, K. (2025). *What is ODP in Refrigeration: Understanding the Importance of Ozone Depletion Potential*. Retrieved from <https://applianceupdate.com/what-is-odp-in-refrigeration/>
- Amann, M., Cofala, J., Heyes, C., Klimont, Z., & Schöpp, W. (1999). The RAINS model: A tool for assessing regional emission control strategies in Europe. *Pollution Atmosphérique* 20, pp. 41-46.
- Andersen, S. O., Sherman, N. J., Carvalho, S., & Gonzalez, M. (2018). The global search and commercialization of alternatives and substitutes for ozone-depleting substances. *Comptes Rendus. Géoscience, 30th Anniversary of the Montreal Protocol: From the safeguard of the ozone layer to the protection of the Earth Climate*, 350(7), 410-424. doi:10.1016/j.crte.2018.07.010
- Andreasi Bassi, S. B. (2023). Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method. *JRC130796*.
- Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., & Ardente, F. (2023). *Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method*. Luxembourg: Publications Office of the European Union.
- ASTM International. (2024). *ASTM D6866-24: Standard Test Methods for Determining the Biobased Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis*. ASTM International.
- Baird, C., & Cann, M. (2012). Chapter 1 Stratospheric chemistry: the ozone layer. *Fiorillo, J., Murphy, B. (Eds.), Environmental Chemistry. W.H. Freeman and Company*, pp. 3–35.
- Baird, C., & Cann, M. (2012). Chapter 2 the ozone holes. *Fiorillo, J., Murphy, B. (Eds.), Environmental Chemistry. W.H. Freeman and Company, New York*, p. 37.
- Baker, J. P., & Christensen, S. W. (1991). Effects of acidification on biological communities in aquatic exocsystems. In D. F. Charles (Ed.), *Acidic deposition and aquatic ecosystems*. https://doi.org/10.1007/978-1-4613-9038-1_5, pp. 83-106.
- BASF SE. (2021). *Guideline for Product Carbon Footprint Calculations of companies*. Retrieved September 2, 2026, from <https://www.basf.com/dam/jcr:d2bc0895-e7a2-3f97-9a42->

b33579efb4d7/basf/www/global/documents/en/sustainability/we-drive-sustainable-solutions/quantifying-sustainability/product-carbon-footprint/MethodologyDocument.pdf

- Bassi et al. (2023). *Updated characterisation and normalisation factors for the environmental footprint 3.1 method*. Retrieved from <https://doi.org/10.2760/798894>
- Beck, T. B. (2010). *LANCA® – Land Use Indicator Value Calculation in Life Cycle Assessment*. Retrieved from Fraunhofer Institute for Building Physics (IBP).
- Beck, T., Bos, U., Wittstock, B., Baitz, M., Fischer, M., & Sedlbauer, K. (2010). *LANCA: Land Use Indicator Value Calculation in Life Cycle Assessment*. Stuttgart: Fraunhofer Verlag.
- Benini, L., Mancini, L., Sala, S., Manfredi, S., S. E., & Pank, R. (2014). Normalization Method and Data for Environmental Footprints. *JRC Technical Reports Report EUR 26842 EN*.
- Benini, L., Sala, S., & Pant, R. (2015). Normalization and Weighting Factors for Testing. Retrieved from [https://webgate.ec.europa.eu/fpfis/wikis/download/attachments/66618509/Normalization%20and%20weighting%20factors%20for%20testing%](https://webgate.ec.europa.eu/fpfis/wikis/download/attachments/66618509/Normalization%20and%20weighting%20factors%20for%20testing%20)
- Berger M., S. T. (2020). Mineral resources in Life Cycle Impact Assessment – part II: recommendations on application-dependent use of existing methods and on future method development needs. *Int. J. Life Cycle Assess.* doi:10.1007/s11367-020-01737-5
- BfS. (2026). *Effective dose*. Retrieved from BfS Glossary: <https://www.bfs.de/SharedDocs/Glossareintraege/EN/E/effective-dose.htm>
- Bhatti, S., Kumar, A., Reetu, R., & Singh, S. (2023). *Environment-Friendly Refrigerants for Sustainable Refrigeration and Air Conditioning: A Review*. Retrieved from <http://dx.doi.org/10.12944/CWE.18.3.03>
- Boulay, A.-M., Bare, J., & Benini, L. (2018). The WULCA consensus characterization model for water scarcity footprints: Assessing impacts of water consumption based on available water remaining (AWARE). *he International Journal of Life Cycle Assessment*, 23,, pp. 368–378.
- Bouwman, A., Beusen, A., & G., B. (2009). Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. *Glob Biogeochem Cycles*, 23:GB0A04. doi:<https://doi.org/10.1029/2009GB003576>
- Boyce, M. P. (2012). 10 - Combustors. In M. P. Boyce, *Gas Turbine Engineering Handbook (Fourth Edition)* (pp. 427–490). ISBN 9780123838421; <https://doi.org/10.1016/B978-0-12-383842-1.00010-X>; Butterworth-Heinemann.
- Brinkmann, T., Giner Santonja, G., Schorcht, F., Roudier, S., & Delgado Sancho, L. (2014). Best Available Techniques (BAT) Reference Document for the Production of Chlor-alkali (Industrial Emissions Directive 2010/75/EU), European Commission, Joint Research Centre, <https://publications.jrc.ec.europa.eu/repository/handle/JRC91156>.
- BSI. (2012). *Assessment of Life Cycle Greenhouse Gas Emissions from Horticultural Products. Supplementary requirements for the cradle to gate stages of GHG assessments of horticultural products undertaken in accordance with PAS 2050*. London: British Standards Institution (BSI). Retrieved 08 13, 2026, from chrome-extension://efaidnbmnnnibpcajpcgclclefindmkaj/<https://website-production-s3bucket->

1nevfd7531z8u.s3.eu-west-1.amazonaws.com/public/website/download/79ef13ea-6a07-4d0c-95d7-3ee3b8769595/2012-PAS_2050-1_2012.pdf

- Bulle, C., Margni, M., Patouillard, L., Boulay, A.-M., Bourgault, G., De Bruille, V., & Jolliet, O. (2019). IMPACT World+: a globally regionalized life cycle impact assessment method. *The International Journal of Life Cycle Assessment*, 1653–1674.
- Bulle, C., Margni, M., Patouillard, L., Boulay, A.-M., Bourgault, G., De Bruille, V., . . . Levasseur, A. (2019). IMPACT World+: a globally regionalized life cycle impact assessment method. *The International Journal of Life Cycle Assessment*, 1653–1674.
- Caldeira, C., Farcas, R., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., . . . Sala, S. (2022). *Safe and sustainable by design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials*. online: JRC Publications Office of the European Union.
- California Department of Public Health (CDPH) . (2024). Radiation safety and protection program requirement guidance.
- Centers for Disease Control and Prevention. (2024). *Acute radiation syndrome (ARS): Information for clinicians, U.S. Department of Health and Human Services*. Retrieved from <https://www.cdc.gov/radiation-emergencies/hcp/clinical-guidance/ars.html>
- Centers for Disease Control and Prevention. (2024). Guidelines for ALARA (as low as reasonably achievable): Time, distance, and shielding, U.S. Department of Health and Human Services.
- Centers for Disease Control and Prevention. (2025). Radiation and pregnancy: Information for clinicians, U.S. Department of Health and Human Services.
- Champmartin, C., & Clerc, F. (2014). Inhalable dust measurements as a first approach to assessing occupational exposure in the pharmaceutical industry. *J Occup Environ Hyg*(11(2)), pp. 85-92.
- Chaplin-Kramer, R. S. (2017). Life cycle assessment needs predictive spatial modelling for biodiversity and ecosystem services. *Nature Communications*, 15065.
- Chaudhary, A. V. (2015). Quantifying land use impacts on biodiversity: Combining species–area models and vulnerability indicators. *Environmental Science & Technology*, 9987–9995.
- Chen, D., Lan, Z., Bai, X., Grace, J., & Bai, Y. (2013). Evidence that acidification-induced declines in plant diversity and productivity are mediated by changes in below-ground communities and soil properties in a semi-arid steppe *J. Ecol.*, 101. 10.1111/1365-2745.12119., pp. 1322-1334.
- Chen, J. (2024). A summary of updated UNSCEAR evaluations on medical and occupational exposures to ionising radiation and call for participation in UNSCEAR Global Surveys on radiation exposure *Radiat Prot Dosimetry*, 2024 Nov 13;200(16-18):1495-1500. doi: 10.1093/rpd/ncae0.
- CML. (2016). *CML-IA Characterisation Factors*. Retrieved from <https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors>

- Commission, E. (2022). Environmental Footprint (EF) reference package 3.1. Retrieved from <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html>
- Corder, G. D. (2013). An integrated review of concepts and initiatives for mining the technosphere: towards a new taxonomy. *Journal of Cleaner Production*, 55, 35–44.
- data, O. w. (2024). Retrieved from <https://ourworldindata.org/grapher/sugar-cane-yields>
- De Haes, U. H., Finnveden, G., Goedkoop, M., Hauschild, M. Z., Hertwich, E., Hofstetter, P., . . . Stehen, B. (2002). Life-cycle Impact Assessment: Striving Towards Best Practice, Pensacola (FL): SETAC Press.
- De Laurentiis, V. M. (2024). Soil organic carbon as an indicator of land use impacts in life cycle assessment. *Cycle Assess* 29, 1190–1208. doi:<https://doi.org/10.1007/s11367-024-02307-9>
- De Laurentiis, V. S. (2019). Soil quality index: Exploring options for a comprehensive assessment of land-use impacts in LCA. *Journal of Cleaner Production*, 63–74.
- De Laurentiis, V., Secchi, M., Bos, U., Horn, R., Laurent, A., & Sala, S. (2019). Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA. *Journal of Cleaner Production*, 63-74.
- De Laurentiis, V., Secchi, M., Bos, U., Horn, R., Laurent, A., & Sala, S. (2019). Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA. *Journal of Cleaner Production*, 63-74.
- de Souza Zorzenão, P., dos Santos Silva, J., Moreira, C., Pinto, V., Tadano, Y., Yamamoto, C., & Godoi, R. (2024). Impacts of PM2.5 exposure near cement facilities on human health and years of life lost: A case study in Brazil. *Journal of Environmental Management*, Volume 370.
- de Vries, W. (2021). Impacts of nitrogen emissions on ecosystems and human health: A mini review, Current Opinion. *Environmental Science & Health*, Volume 21.
- Derwent, R. G., Jenkin, M. E., Saunders, S. M., & Pilling, M. J. (1998, 32(14-15)). Photochemical ozone creation potentials for organic compounds in northwest Europe calculated with a master chemical mechanism. *Atmospheric environment*, pp. 2429-2441.
- Derwent, R., Jenkin, M., Passant, N., & Pilling, M. (2007). Photochemical ozone creation potentials (POCPs) for different emission sources of organic compounds under European conditions estimated with a Master Chemical Mechanism. *Atmospheric Environment* 41:2570 2579.
- Dewulf, J., Bösch, M., De Meester, B., Van der Vorst, G., Van Langenhove, H., Hellweg, S., & Huijbregts, M. (2007). *Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting*. Retrieved from doi: 10.1021/es0711415.
- Donzelli, G., & Suarez-Varela, M. (2024). Tropospheric Ozone: A Critical Review of the Literature on Emissions, Exposure, and Health Effects. *Atmosphere* 2024, 15, p. 779.
- Dreicer, M., Tort, V., & Manen, P. (1995). *ExternE: Externalities of Energy. Vol. 5: Nuclear*. Luxembourg: Office for Official Publications of the European Communities.

- Drielsma, J., Russell-Vaccari, A., Drnek, T., Brady, T., Weihed, P., Mistry, M., & Perez Simbor, L. (2016). Mineral resources in life cycle impact assessment—Defining the path forward. *Int. J. Life Cycle*, 85–105.
- Dudgeon, D., Arthington, A., Gessner, M., Kawabata, Z.-I., Knowler, D., Lévêque, C., . . . Sullivan, C. (2007). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews*, 163-182.
- EC. (2016). *Economically and Ecologically Efficient Water Management in the European Chemical Industry*. Retrieved from <https://cordis.europa.eu/article/id/151163-cutting-water-use-in-the-european-chemical-industry>
- EC. (2021). *COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations*. Retrieved from European Commission: <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>
- EC. (2025). *The water cycle connects us all*. Retrieved from European Commission : <https://ec.europa.eu/environment/stories/water-cycle/>
- Ecoinvent. (2025). ecoinvent v 3.12. Zurich, Switzerland.
- Edelen, A., & Ingwersen, W. (2016, June). *Guidance on Data Quality Assessment for Life Cycle Inventory Data*. Retrieved from EPA/600/R-16/096, EPA/600/R-16/096: www.epa.gov/research
- EEA. (2024). *National Emission reduction Commitments Directive; European Environment Agency (EEA)*. Retrieved from European Environment Agency : <https://www.eea.europa.eu/en/topics/in-depth/air-pollution/necd>.
- EEA. (2024). *Resource use and materials*. Retrieved from European Environment Agency: <https://www.eea.europa.eu/en/topics/in-depth/resource-use-and-materials>
- Emberson, L. (2020). Effects of ozone on agriculture, forests and grass lands. *Phil. Trans. R. Soc. (A)* 378: 20190327).
- Emberson, L. (2020). Effects of ozone on agriculture, forests and grass lands. *Phil. Trans. R. Soc. A* 378.
- EN 15804. (2019). EN 15804:2012+A2:2019 + AC:2021, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction product.
- Envilience ASIA. (2019). Retrieved from <https://envilience.com/regions/east-asia/cn/cn-air/cn-air-act>
- EPA. (2026). (chapter 15.7): “AP-42: Compilation of Air Emissions Factors from Stationary Sources”, <https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors-stationary-sources>, last updated 09.02.2026, accessed 13.04.2026. *U.S. Environmental Protection Agency*.
- EPA – United States Environmental Protection Agency. (2026). *What are the trends in land use and their effects on human health and the environment?* Retrieved 03 26, 2026, from <https://www.epa.gov/report-environment/land-use#effects>

- EU. (2006). *The Groundwater Directive (GWD; full title: Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration)*. Retrieved from European Union: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0118&qid=1734378399907>
- EU. (2008). DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. *DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives*. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098>
- EU. (2015). *The Water Framework Directive*. Retrieved from WFD; 2000/60/EC: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02000L0060-20141120>
- EU. (2023). *2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC*. Retrieved 03 19, 2026, from European Union: <https://eur-lex.europa.eu/eli/reg/2023/1542/oj>
- EU. (2024). *Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1*. Retrieved 03 19, 2026, from European Union.
- EU Commission. (2021). *COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations*. Retrieved 10 25, 2025, from <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>
- European Chemicals Agency. (2021). *Information Requirements for REACH Registration. 4th edition*. Retrieved from DOI: 10.2823/969
- European Chemicals Agency. (2023). *Guidance on Chemical Safety Assessment*.
- European Commission (EC). (1991). Directive 91/271/EEC: European Commission (EC), Council Directive 91/271/EEC, Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources, Official Journal of European Community,. 1-8.
- European Commission (EC). (1991). Directive 91/676/EEC: European Commission (EC), Council Directive 91/676/EEC, Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment, Official Journal of European Community, Vol. L135. 40-52.
- European Commission (EC). (2013). Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, OJEU, L 13, 1–73.
- European Commission (EC). (2016). *Economically and Ecologically Efficient Water Management in the European Chemical Industry*. Retrieved from <https://cordis.europa.eu/article/id/151163-cutting-water-use-in-the-european-chemical-industry>

- European Commission (EC). (2019). *Communication from the Commission – The European Green Deal [COM(2019) 640 final]*. European Commission (EC). Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN>
- European Commission (EC). (2021). *COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations*. Retrieved from <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>
- European Commission (EC). (2021). *Pathway to a Healthy Planet for All: A European Union Action Plan for Zero Pollution [COM(2021) 400 final]*. European Commission (EC). Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0400>
- European Commission (EC). (2022). *Environmental Footprint reference packages, European Platform on LCA*. Retrieved from EPLCA: https://knowledge4policy.ec.europa.eu/european-platform-life-cycle-assessment-eplca/topic/environmental-footprint_en
- European Commission (EC). (2024). *Zero Pollution: Modernised rules on industrial and livestock rearing emissions come into effect*. European Commission (EC). News Article from 02.08.2024 from Directorate-General for Environment. Retrieved from https://environment.ec.europa.eu/news/revised-industrial-emissions-directive-comes-effect-2024-08-02_en
- European Commission (EC). (2026). *Industrial Emissions Portal Regulation (IEPR)*. European Commission (EC). Retrieved from https://environment.ec.europa.eu/topics/industrial-emissions-and-safety/industrial-emissions-portal-regulation-iepr_en
- European Commission (EC). (n.d.). *Environmental Footprint Methodology – Version 3.0 – PEF and OEF methods*. Publications Office of the European Union.
- European Commission (EC), Joint Research Centre, Institute for Environment and Sustainability. (2011). *International Reference Life Cycle Data System (ILCD) Handbook: Recommendations for Life Cycle Impact Assessment in the European context – based on existing environmental impact assessment models and factors*. Luxembourg: Publications Office of the European Union.
- European Commission. (2006). Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH. *Official Journal of the European Union*.
- European Commission. (2010). General guide for Life Cycle Assessment – Detailed guidance. *EUR 24708 EN*.
- European Commission. (2016). Land-use related environmental indicators for life cycle assessment. *EUR 27609 EN*. doi:10.2788/905478
- European Commission. (2023). Environmental Footprint Method: EF 3.1 – Characterisation Factors and Impact Assessment. *Publications Office of the European Union*.
- European Commission. (2026, 07 02). *European Platform on LCA / EPLCA*. Retrieved from <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html>

- European Commission, Joint Research Centre (JRC) . (2010). General guide for Life Cycle Assessment – Detailed guidance. EUR 24708 EN.
- European Commission, Joint Research Centre. (2024). *EF 3.1 Ecotox Explorer: Guide for correct interpretation of characterisation factors (CFs)*. Retrieved from <https://web.jrc.ec.europa.eu/rapps/pub/ecotox/>
- European Environment Agency (EEA). (2024). *Europe's air quality status 2024*. Retrieved from <https://www.eea.europa.eu/en/analysis/publications/europes-air-quality-status-2024>
- European Environment Agency (EEA). (2025). *Identifiers for EEA Briefing 08/2025. Air pollution in Europe - 2025 reporting status under the National Emission reduction Commitments Directive; European Environment Agency (EEA)*. Retrieved from <https://www.eea.europa.eu/en/analysis/publications/air-pollution-in-europe-2025-reporting-status-under-the-national-emission-reduction-commitments-directive>
- European Environment Agency. (2022). *Chemicals and Human Health*. Retrieved from https://www.eea.europa.eu/en/analysis/publications/zero-pollution/health/chemicals-and-health?utm_source
- European Parliament and Council . (2022). Directive (EU) 2022/2464 of 14 December 2022 as regards corporate sustainability reporting.
- European Parliament and Council. (2018). Directive (EU) 2018/2001 of 18 December 2018 on the promotion of the use of energy from renewable sources. Retrieved from <https://hansard.parliament.uk/Commons/2006-07-24/debates/06072411000013/EnvironmentalDirectives>
- European Parliament and Council. (2024). Regulation (EU) 2024/1781 of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products.
- European Parliament Research Service. (2021). *EU policy on air quality: Implementation of selected EU legislation*. Retrieved from [https://www.europarl.europa.eu/RegData/etudes/STUD/2021/654216/EPRS_STU\(2021\)654216_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/STUD/2021/654216/EPRS_STU(2021)654216_EN.pdf)
- European Union (EU). (1999). *Council Directive 1999/13/EC of 11 March 1999 on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain activities and installations*. Retrieved from <https://eur-lex.europa.eu/eli/dir/1999/13/oj/eng>
- European Union (EU). (2000). Directive 2000/60/EC: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community actions in the field of water policy. *Official Journal of the European Communities*, Vol. L327 1. 22.12.
- European Union (EU). (2002). *Directive 2002/3/EC of the European Parliament and of the Council of 12 February 2002 relating to ozone in ambient air*. Retrieved from <https://eur-lex.europa.eu/eli/dir/2002/3/oj/eng>
- European Union (EU). (2008). *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe*. Retrieved from <https://eur-lex.europa.eu/eli/dir/2008/50/oj/eng>

- European Union (EU). (2008). *Directive 2008/50/EC on ambient air quality and cleaner air for Europe*. Retrieved from <https://eur-lex.europa.eu/eli/dir/2008/50/oj/eng>
- European Union (EU). (2010). *Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions*. Retrieved from <https://eur-lex.europa.eu/eli/dir/2010/75/oj/eng>
- European Union (EU). (2015). *The Water Framework Directive (WFD; 2000/60/EC)*. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02000L0060-20141120>
- European Union (EU). (2024). *Consolidated text: Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81 /EC*. Retrieved from <http://data.europa.eu/eli/dir/2016/2284/2024-02-06>
- European Union. (2026a, 08 06). *Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/4*. Retrieved from European Union EUR-Lex: <https://eur-lex.europa.eu/eli/reg/2006/1907/oj/eng>
- European Union. (2026b, 08 06). *Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC)*. Retrieved from European Union EUR-Lex: <https://eur-lex.europa.eu/eli/reg/2008/1272/oj/eng>
- Fantke et al. (2018). *USEtox® 2.0 Documentation (Version 1.1), UNEP/SETAC scientific consensus model for characterizing human toxicological and ecotoxicological impacts of chemical emissions in life cycle assessment*. Retrieved from https://usetox.org/sites/default/files/assets/USEtox_Documentation.pdf
- Fantke, P. (., Bijster, M., Guignard, C., Hauschild, M., Huijbregts, M., Jolliet, O., . . . van Zelm, R. (2017). *USEtox® 2.0 Documentation (Version 1.1)*.
- Fantke, P. A. (2018). Advancements in life cycle human exposure and toxicity characterization. *Environmental Health Perspectives*.
- Fantke, P. C. (2021). Exposure and toxicity characterization of chemical emissions and chemicals in products. *International Journal of Life Cycle Assessment*, 899–915.
- Fantke, P., Aylward, L., Bare, J., Chiu, W. A., Dodson, R., Dwyer, R., . . . Judson, R. (2018). Advancements in Life Cycle Human Exposure and Toxicity Characterization. *Environmental Health Perspectives*.
- Fantke, P., Evans, J., Hodas, N., Apte, J., Jantunen, M., Jolliet, O., & McKone, T. (2016). Health impacts of fine particulate matter. In: Frischknecht, R., Jolliet, O. (Eds.), *Global Guidance for Life Cycle Impact Assessment Indicators*, vol. 1, UNEP/SETAC Life Cycle Initiative, Paris, 76-99 (available at: www.lifecycleinitiative.org/applying-lc).

- Fazio, S., Biganzioli, F., De Laurentiis, V., Zampori, L., Sala, S., & Diaconu, E. (2018). *Supporting Information to the Characterisation Factors o*. Retrieved from Recommended EF Life Cycle Impact Assessment Methods, Version 2, from ILCD to EF 3.0, EUR 29600 EN,.
- Federal Office for the Environment (FOEN). (2021). *Swiss Eco-Factors 2021 according to the Ecological Scarcity Method*. Retrieved from www.bafu.admin.ch/dam/bafu/en/dokumente/wirtschaft-konsum/
- Finnveden, G. (1996). "Resources" and related impact categories. In *Towards a Methodology for Life Cycle Impact Assessment*. Retrieved from SETAC-Europe
- Franz, A. K. (2016). Formaldehyde". Ullmann's Encyclopedia of Industrial Chemistry. 1–34.
- Fraunhofer IBP. (2026). *LANCA® characterization factors*. Retrieved from <https://www.ibp.fraunhofer.de/en/expertise/life-cycle-engineering/applied-methods/lanca.html>
- Frenzel, P. H. (2014). Increase in energy and land use by a bio-based chemical industry. *Chemical Engineering Research and Design*, 2006-2015.
- Frischknecht et al. (2021). *wiss Eco-Factors 2021 according to the Ecological Scarcity Method: Methodological Fundamentals and Their Application in Switzerland*. Federal Office for the Environment.
- Frischknecht, R., Braunschweig, A., Hofstetter, P., & Suter, P. (2000). Human health damages due to ionising radiation in life cycle impact assessment. *Environmental Impact Assessment Review*, 158-189.
- Frischknecht, R., Steiner, R., Braunschweig, A., Egli, N., & Hildesheimer, G. (2006). *Swiss ecological scarcity of water method: The new version 2006*. Retrieved from Swiss FederalOffice for the Environment (FOEN)
- Frischknecht, R., Wyss, F., Büsser Knöpfel, S., Lützkendorf, T., & Baloutski, M. (2015). Cumulative energy demand in LCA: the energy harvested approach. *Int. J. Life Cycle Assess* 2015, 20, 957-969.
- Gabrielli, P. R. (2023). Net-zero emissions chemical industry in a world of limited resources. *One Earth*, 682-704. doi:<https://doi.org/10.1016/j.oneear.2023.05.006>
- Gade, L., Hauschild, M., & Laurent, A. (2021, Volume 761). Globally differentiated effect factors for characterising terrestrial acidification in life cycle impact assessment. *Science of The Total Environment*, pp. 143280, ISSN 0048-9697, <https://doi.org/10.1016/j.scitotenv.2020.143280>.
- GHG Protocol Product Standard. (2011). *Product Life Cycle Accounting and Reporting Standard*. Retrieved from <https://ghgprotocol.org/product-standard>
- GLAM – Global Guidance for LCIA Indicators and Methods. (2026). *Life Cycle Assessment Data and Methods, GLAM – Global Guidance for LCIA Indicators and Methods - Life Cycle Initiative*. Retrieved from <https://www.lifecycleinitiative.org/activities/life-cycle-assessment-data-and-methods/global-guidance-for-life-cycle-impact-assessment-indicators-and-methods-glam/>

- Glibert, P. M., & Burford, M. A. (2017). Globally Changing Nutrient Loads and Harmful Algal Blooms: Recent Advances, New Paradigms, and Continuing Challenges. *Oceanography*, 30 (1), 58–69. doi:<https://doi.org/10.1007/978-3-319-70069-4>
- Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors, first edition.
- Grosse-Sommer, A., Grünenwald, T., Paczkowski, N., van Gelder, R., & Saling, P. (2020). Applied Sustainability in Industry: The BASF Eco-Efficiency Toolbox. *Journal of Cleaner Production*, 258. doi:<https://doi.org/10.1016/j.jclepro.2020.120792>
- Guinée et al. (2002). *J.B. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background.* Kluwer Academic Publishers. Retrieved from <http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html>
- Hauschild, M. Z. (2015). Life cycle impact assessment. *Springer*. doi:<https://doi.org/10.1007/978-94-017-9744-3>
- Hauschild, M., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Joliet, O., . . . Wolf, M. (2011). *Recommendations for Life Cycle Impact Assessment in the European context – based on existing environmental impact assessment models and factors (ILCD Handbook) (EUR 24571 EN).* Publications Office of the European Union. Retrieved from <https://publications.jrc.ec.europa.eu/repository/handle/JRC61049>
- Hayashi, K., Okazaki, M., Itsubo, N., & Inaba, A. (2004, 9(1)). Development of Damage Function of Acidification for Terrestrial Ecosystems Based on the Effect of Aluminum Toxicity on Net Primary Production. *International Journal of Life Cycle Assessment*, pp. 13-22.
- Hayashi, T. (2023). *Sugar Semi-annual. Brazil-Brasília; Sugar.* -: United States Department of Agriculture (USDA) Foreign Agricultural Service. Retrieved 09 01, 2026, from chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Sugar+Semi-annual_Brasilia_Brazil_BR2023-0025
- Hedeghog. (2025). *Use an LCA to meet these 5 standards and legislations.* Retrieved from <https://www.hhc.earth/knowledge-base/articles/use-an-lca-to-meet-these-5-standards-and-legislations>
- Heijungs, R., Guinée, J., & Huppes, G. (1997). *Impact Categories for Natural Resources and Land Use; CML-report 138; Leiden University: Leiden, The Netherlands, 1997.*
- Henderson, A. D. (2015). Eutrophication. In: Hauschild, M., Huijbregts, M. (eds) *Life Cycle Impact Assessment. LCA Compendium – The Complete World of Life Cycle Assessment.* Springer, Dordrecht,. doi:https://doi.org/10.1007/978-94-017-9744-3_9
- Hettelingh, J., Posch, M., Slootweg, J., Reinds, G. J., Spranger, T., & Tarrason, L. (2007). Critical loads and dynamic modelling to assess European areas at risk of acidification and eutrophication. *Water Air Soil Pollution Focus* 7, pp. 379–384.

- Holland, R., H., A., Khan, M., & Shallcross, D. (2025). Photochemical Ozone Creation Potential. *Encyclopedia of Green Chemistry, Volume 1*, p. 85 91. doi:<https://doi.org/10.1016/B978-0-443-15742-4.00067-3>
- Holmquist, H., Bernander, M., Fantke, P., Gottfridsson, M., G. J., A.K, H., . . . Snape, J. (2021). A life cycle-based assessment toolbox to assess and improve safety and sustainability of chemicals. *SETAC Europe 31st Annual Meeting*. (virtual). Retrieved from SETAC Europe 31st Annual Meeting (virtual).
- Horn, R. a. (2018). *LANCA® characterisation factors for land use impacts*. Retrieved from Fraunhofer Institute for Building Physics (IBP): <https://www.ibp.fraunhofer.de/en/expertise/life-cycle-engineering/applied-methods/lanca.html>
- Huijbregts, M., Steinmann, Z., & Elshout, P. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *Int J Life Cycle Assess* 22, pp. 138–147. doi:<https://doi.org/10.1007/s11367-016-1246-y>
- Huijbregts, M., Verkuijlen, S., Heijungs, R., & Reijnders, L. (2001). Spatially explicit characterization of acidifying and neutrophying air pollution in life-cycle assessment. *Journal of Industrial Ecology* 4(3), pp. 75-92.
- Humbert, S., Marshall, J. D., Shaked, S., Spadaro, J. V., Nishioka, Y., Preiss, P., . . . Jolliet, O. (2011). Intake fraction for particulate matter: recommendations for life cycle impact assessment, *Environ Sci Technol*, 45, 4808–4816, <https://doi.org/10.1021/es103563z>.
- Huppes, G., & van Oers, L. (2011). Evaluation of Weighting Methods for Measuring the EU-27 Overall Environmental Impact. *JRC Scientific and Technical Reports*(IES 2011. Report EUR 24985 EN).
- IAEA. (2014). *Annual Report 2014*. Retrieved 09 01, 2026, from https://www.iaea.org/sites/default/files/2023-04/gc59-7_en.pdf
- ICCA. (2019). *The Global Chemical Industry: Catalyzing Growth and Addressing Our World's Sustainability Challenges*. Retrieved from <https://icca-chem.org/wp-content/uploads/2020/10/Catalyzing-Growth-and-Addressing-Our-Worlds-Sustainability-Challenges-Report.pdf>
- ICRP. (2007). The 2007 recommendations of the International Commission on Radiological Protection. *ICRP Publication 103. Annals of the ICRP*, 37(2–4). Retrieved from [https://icrp.org/docs/ICRP_Publication_103-Annals_of_the_ICRP_37\(2-4\)-Free_extract.pdf](https://icrp.org/docs/ICRP_Publication_103-Annals_of_the_ICRP_37(2-4)-Free_extract.pdf)
- ICRP. (2007). The 2007 recommendations of the International Commission on Radiological Protection (ICRP Publication 103). *Annals of the ICRP*, 37(2–4).
- ICRP. (2014). Radiological Protection in Security Screening. *ICRP Publication 125. Ann. ICRP* 43(2). Retrieved from https://journals.sagepub.com/doi/pdf/10.1177/ANIB_43_2
- International Atomic Energy Agency (IAEA). (2004). Radiotracer Applications in Industry — A Guidebook (Technical Reports Series No. 423). Vienna: International Atomic Energy Agency.
- International Atomic Energy Agency (IAEA). (2010). *Technetium-99m Radiopharmaceuticals: Status and Trends (IAEA Radioisotopes and Radiopharmaceuticals Series No. 1)*. Vienna: International Atomic Energy Agency.

- International Atomic Energy Agency (IAEA). (2021). *Radiation effects on polymer materials commonly used in medical devices*. Vienna, Austria:
https://nucleus.iaea.org/sites/diif/PublishingImages/Pages/IAEAPublications/IAEA%201st%20RCM%20F23035%20Report_Final.pdf.
- International Commission on Radiological Protection (ICRP). (2022). *Effects of radiation exposure on offspring and next generations: Genetic and epigenetic effects (ICRP Task Group 121)*.
https://icrp.org/admin/TG121_Budapest-2022_S-Salomaa.pdf.
- International Commission on Radiological Protection (ICRP). (2024). Dose coefficients for intakes of radionuclides by members of the public: Part 1 (ICRP Publication 158). *Annals of the ICRP*, 53(4–5).
- International Commission on Radiological Protection (ICRP). (n.d.). Radiation detriment calculation methodology (ICRP Publication 152). *Annals of the ICRP*, 51(1).
- International Organization for Standardization (ISO). (2020). Environmental management — Life cycle assessment — Requirements and guidelines — Amendment 2. *ISO Standard No. 14044:2006/Amd 2:2020*.
- International Organization for Standardization (ISO). (2025). *ISO 11137-1: Sterilization of health care products — Radiation — Part 1: Requirements for the development, validation and routine control of a sterilization process for medical devices*. International Organization for Standardization.
- International Organization for Standardization. (2014). Environmental management — Water footprint — Principles, requirements and guidelines. *ISO Standard No. 14046:2014*. Retrieved from ISO Standard No. 14046:2014.
- IRP. (2026). *From CFCs to Modern Alternatives. The Evolution of Refrigerants*. Retrieved 07 02, 2025, from Industrial Refrigeration Pros: <https://irpros.com/the-evolution-of-refrigerants-from-cfcs-to-modern-alternatives/#:~:text=Hydrofluorocarbons%20%28HFCs%29%20emerged%20as%20the%20next%20generation%20of,the%20industry%20standard%20for%20refrigeration%20and%20air%20conditioning>
- ISO 14040. (2006). *ISO 14040: Environmental management — Life cycle assessment — Principles and framework*. Geneva: International Organization for Standardization.
- ISO 14040:2006. (2020). *ISO 14040:2006+Amd 1*. Retrieved from Environment Management-Lifecycle Assessment-Principles and Framework.
- ISO 14044. (2006). *ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines*.
- ISO 14044. (2006). *ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines*. Geneva: International Organization for Standardization.
- ISO 14044. (2020). *ISO 14044:2006+Amd 2: 2020*. Retrieved from Environment Management-Lifecycle Assessment-Principles and Framework.
- ISO 14046. (2014). *ISO 14046:2014. Environmental management — Water footprint — Principles, requirements and guidelines*.

- ISO 14067. (2018). *ISO 14067:2018*. Retrieved from Greenhouse Gases- Carbon Footprint for products- Requirements & Guidelines for Quantification.
- ISO 22095. (2020). *ISO 22095:2020*. Retrieved from Chain of custody — General terminology and models.
- IVL. (2026). Retrieved from <https://proscale.org/>
- IWTO (International Wool Textile Organisation). (2026). *Position paper on land use in the Environmental Footprint (EF) method review*.
- Joint Research Centre (JRC) Publication Repository. (2018). *The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE)*. Retrieved from <https://publications.jrc.ec.europa.eu/repository/handle/JRC100097>
- Joint Research Centre (JRC): EU Science Hub. (2021). *New EU environmental norms for the chemical industry - European Commission*.
- Joint Research Centre. (2012). Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods, Database and Supporting Information, First edition.
- Jolliet, O., Müller-Wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R., . . . Rebitzer, G. (2004). The LCIA midpoint–damage framework of the UNEP-SETAC Life Cycle Initiative', *Int J Life Cycle Assess*, 9(6), 394–404.
- Joseph, B., & Stichnothe, H. (2024). Considering Grouped or Individual Non-Methane Volatile Organic Compound Emissions in Life Cycle Assessment of Composting Using Three Life Cycle Impact Assessment Methods. *Recycling*, 9(3), p. 35.
- JRC. (2020, 06 22). <https://publications.jrc.ec.europa.eu/repository/handle/JRC120170>. Retrieved from Joint Research Center : <https://publications.jrc.ec.europa.eu/repository/handle/JRC120170>
- Jungbluth, N. (2025). *Description of life cycle impact assessment methods: Supplementary information for tenders*. ESU-services Ltd., Schaffhausen, Switzerland. Retrieved from <https://esu-services.ch/fileadmin/download/tender/ESU-Description-of-LCIAMethods.pdf>
- K.E. Limburg, D. S. (2013). *River Ecosystems*. ISBN 9780123847201, <https://doi.org/10.1016/B978-0-12-384719-5.00222-7>: Academic Press.
- Kölsch, D., & Giebeler, S. (2023). *Data Quality Analysis as Part of Interpretation*. In: Curran, M.A. (eds) *Interpretation, Critical Review and Reporting in Life Cycle Assessment. LCA Compendium – The Complete World of Life Cycle Assessment*. Springer, Cham. Retrieved from https://doi.org/10.1007/978-3-031-35727-5_3
- Kärnman, T. (2024). *ProScale applied in a Mistra SafeChem case study with BASF – A comparative assessment of the human toxicity potential via direct exposure of a polyamide produced with two different flame retardants*, ISBN number: 978-91-7883-620-8. Retrieved from <https://proscale.org/download/18.77ac93b71919736e4d01e336/1725872387723/ProScale%20applied%20in%20a%20Mistra%20SafeChem%20case%20study%20with%20BASF%20-%20D5.1.10%20-%20C858.pdf>

- Kansas Department of Health and Environment. (2026). “Frequently Asked Questions: Which Particulate Matter (PM) emission factor should I use?”, <https://www.kdhe.ks.gov/m/faq?cat=17#question-95>, accessed 13.04.2026.
- Kavitha, G., Govindhan, M., & Premkumar, S. (2025). Dye pollution and its implications for human health, aquatic ecosystems, and sustainable wastewater treatment: A comprehensive review, *Journal of Water Process Engineering*, 80, 109071, ISSN 2214-7144, <https://doi.org/10.1016/j.jwpe.2025.109071>.
- Kemna, R., Van Elburg, M., W., L., & Van Holsteijn, R. (2005). *MEEUP – Methodology Report. EC, Brussels. (Final version, 28-11-2005)*.
- Kim, M., Kim, J., Yoon, S., Cho, S., Yu, J., Kang, C., . . . Lee, H. (2023). Evaluating the feasibility of air environment management system for VOCs through ‘VOCs specification’ of petroleum refining industry. *Journal of the Air & Waste Management Association*, pp. 362-373.
- Koellner, T. d. (2013). UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. *Int J Life Cycle Assess* 18, 1188.
- Kosnik, M. B., Hauschild, M. Z., & Fantke, P. (2022). Toward Assessing Absolute Environmental Sustainability of Chemical Pollution. *Environmental Science & Technology*, 4776-4787.
- Kros, J. (2002). *Evaluation of Biogeochemical Models at Local and Regional Scale. Wageningen (The Netherlands), Wageningen University*.
- Lao, Q., Li, H., & Yan, J. (2024). Hemispherical scale mechanisms of nitrate formation in global marine aerosols. *npj Clim Atmos Sci* 7, 139 (2024). <https://doi.org/10.1038/s41612-024-00694-2>.
- Lattanzio, R. (2022). *Clean Air Act: A Summary of the Act and Its Major Requirements. CRS Product (Library of Congress). CRS Product Number: RL30853*. Retrieved from <https://www.congress.gov/crs-product/RL30853>
- Laurent, A., Olsen, S., & Hauschild, M. (2011). Normalization in EDIP97 and EDIP2003: updated European inventory for 2004 and guidance towards a consistent use in practice. *Int. J. Life Cycle Assess*. 16. doi:<https://doi.org/10.1007/s11367-011-0278-6>.
- LC-IMPACT . (2026). *Human Toxicity*. Retrieved from https://lc-impact.eu/HHhuman_toxicity.html
- LC-Impact, a spatially differentiated life cycle impact assessment method*. (2019). Retrieved May 2026, from https://lc-impact.eu/EQterrestrial_ecotoxicity.html
- Lewandowska, A., Joachimiak-Lechman, K., & Kurczewski, P. A. (2021). *Dataset Quality Assessment*. Retrieved from An Insight and Discussion on Selected Elements of Environmental Footprints Methodology. *Energies* : <https://doi.org/10.3390/en14165004>
- Lexen, J. B. (2021). *ProScale - A life cycle oriented method to assess toxicological potentials of product systems, Guidance Document version 1.5. .* Retrieved from <https://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-3844>
- Life Cycle Initiative. (2026, 07 02). *USEtox(R)*. Retrieved from <https://www.lifecycleinitiative.org/applying-lca/usetox/>

- Little, M. P., Azizova, T. V., Richardson, D. B., Tapio, S., Bernier, M.-O. K., & Einstein, A. J. (2023). Ionising radiation and cardiovascular disease: Systematic review and meta-analysis. *BMJ*, p. 380.
- MET. (2026). *How to Calculate AQI and NowCast Indices*. Retrieved from <https://metone.com/how-to-calculate-aqi-and-nowcast-indices/>
- Milà i Canals, L. B.-W. (2007). Key elements in a framework for land use impact assessment within LCA. *The International Journal of Life Cycle Assessment*, 5–15.
- Milà i Canals, L. B.-W. (2007). Key elements in a framework for land use impact assessment within LCA. *The International Journal of Life Cycle Assessment*, 5–15.
- Milà i Canals, L., Bauer, C., Depestele, J., Dubreuil, A., Freiermuth Knuchel, R., Gaillard, G., . . . Müller-Wenk, R. a. (2007). Key elements in a framework for land use impact assessment within LCA. *The International Journal of Life Cycle Assessment*, 5–15. doi:doi:10.1065/lca2006.05.250
- Millar, G. C. (2017). Industrial Production of Formaldehyde Using Polycrystalline Silver Catalyst. *Industrial & Engineering Chemistry Research*, 9247–9265.
- Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Well-being: General Synthesis*. Island Press, Washington, DC, ISBN 1-59726-040-1. Retrieved from <https://www.millenniumassessment.org/documents/document.356.aspx.pdf>
- Ministry of Ecology and Environment of the People's Republic of China. (2012). *Ambient Air Quality Standards (GB3095-2012)*. Retrieved from https://english.mee.gov.cn/Resources/standards/Air_Environment/quality_standard1/201605/t20160511_337502.shtml
- Modahl, I. a.-A. (2025). Life cycle impact assessment of environmental issues and damage pathways in LCA.
- Modahl, I., & Lyng, K.-A. (2025). From landfill to natural vegetation – An exploration of available land use LCIA models and application in a specific case. *Journal of Cleaner Production*.
- Morelli, B., Hawkins, T. R., Niblick, B., Henderson, A. D., Golden, H. E., Compton, J. E., . . . Bare, J. C. (2018). Critical Review of Eutrophication Models for Life Cycle Assessment. *Environ Sci Technol*, 52 (17), 9562-9578. Retrieved from <https://pubs.acs.org/doi/10.1021/acs.est.8b00967>
- Naikwadi, A. T., Sharma, B. B., Bhatt, K. D., & Mahanwar, P. A. (2022). Gamma radiation processed polymeric materials for high-performance applications: A review. *Front Chem*(837111), p. 10.
- Nazarenko, Y., Pal, D., & Ariya, P. A. (2021). 'Air quality standards for the concentration of particulate matter 2.5 — global descriptive analysis', Bulletin of the World Health Organization, 99(2), 125–137. <https://doi.org/10.2471/BLT.19.245704>.
- New York State Department of Health. (2017). *Basic Statistics: About Incidence, Prevalence, Morbidity, and Mortality - Statistics Teaching Tools*.

- Nikolaidis, N. P., Poikane, S., Bouraoui, F., Salas Herrero, F. M., Free, G., Ioanna, V., & Van de Bund, W. (2024). *Comparison and harmonization of eutrophication assessment criteria under the WFD and the Nitrate Directives*. Retrieved from <https://data.europa.eu/doi/10.2760/23475>
- Norris, G. (2003). Impact Characterization in the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts: Methods for Acidification, Eutrophication, and Ozone Formation. pp. 79-101. Retrieved from *Journal of Industrial Ecology* 6 (3&4).
- NRC. (2026). *Nuclear Regulatory Commission*. Retrieved 09 02, 2026, from <https://www.nrc.gov/reading-rm/basic-ref/glossary/collective-dose>
- Occupational Safety and Health Administration (OSHA). (2026a). *29 CFR 1910.1096 – Ionising radiation*. Retrieved March 2026, from <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1096>
- Occupational Safety and Health Administration (OSHA). (2026b). *29 CFR 1926.53 – Ionising radiation (construction)*. Retrieved March 2026, from <https://www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.53>
- Occupational Safety and Health Administration (OSHA). (2026c). *Ionising radiation – Control and prevention*. Retrieved from <https://www.osha.gov/ionizing-radiation/control-prevention>
- Occupational Safety and Health Administration (OSHA). (2026d). *Ionising radiation: Health effects, U.S. Department of Labor*. Retrieved March 2026, from <https://www.osha.gov/ionizing-radiation/health-effects>
- OECD. (2026). *Material Resources*. Retrieved from Organisation for Economic Co-operation and Development : <https://www.oecd.org/en/topics/material-resources.html>
- Oever, A. E., Puricelli, S., Costa, D., Thonemann, N., Philippot, M. L., & Messagie, M. (2024). Revisiting the challenges of ozone depletion in life cycle assessment. *Cleaner Environmental Systems*, 13. Elsevier Ltd, p. <https://doi.org/10.1016/j.cesys.2024.100196>.
- Oláh, J. C. (2023). The socio-environmental challenges in the transition to sustainable bioeconomy: a review. *Acta Montanistica Slovaca*, 98-112.
- Our world in data. (2020). *CO2 & Greenhouse Gas Emissions*. Retrieved from <https://ourworldindata.org/co2-emissions>
- Owsianiak, M., Fantke, P., Frischknecht, R., Jolliet, O., & Verones, F. (2019). *Global Guidance for Life Cycle Impact Assessment Indicators. Volume 2*. Nairobi, Kenya: United Nations Environment Programme (UNEP).
- Owsianiak, M., Hauschild, M. Z., Posthuma, L., Saouter, E., Vijver, M. G., Backhaus, T., . . . Fantke, P. (2023). Ecotoxicity characterization of chemicals: Global recommendations and implementation in USEtox. *Chemosphere*, 136807.
- PACT . (2025). *PACT Methodology V3*. Retrieved from Methodology for Calculating and Exchanging Cradle-to-Gate Product Carbon Footprints (PCFs: <https://www.carbon-transparency.org/resources/pact-methodology-v3-methodology-for-calculating-and-exchanging-cradle-to-gate-product-carbon-footprints-pcfs>

- Paerl, H. W., & Otten, T. G. (2014). Harmful cyanobacterial blooms: Causes, consequences, and controls. *Microbial Ecology*, 65(4), 995-1010.
- Patil, T., Voris, A., Kane, S., & Northrop, W. (2025). Ammonium nitrate nanoparticle emissions from ammonia-fueled internal combustion engines, *Journal of Aerosol Science*, Volume 188, 2025, 106614, ISSN 0021-8502, <https://doi.org/10.1016/j.jaerosci.2025.106614>.
- Paulillo, A., Clift, R., Dodds, J., Milliken, A., Palethorpe, S., & Lettieri, P. (2018). Radiological impact assessment approaches for life cycle assessment: a review and possible ways forward. *Environmental Reviews*, 239-254.
- Paulillo, A., McKone, T. E., & Fantke, P. (2023). Characterizing human health damage from ionising radiation in life cycle assessment, *Int J Life Cycle Assess*, 28, 1825–1843.
- Pawłowski, L. (1997, Volume 8, Issue 4 ISSN 0925-8574, [https://doi.org/10.1016/S0925-8574\(97\)00023-2](https://doi.org/10.1016/S0925-8574(97)00023-2)). Acidification: its impact on the environment and mitigation strategies. *Ecological Engineering*, pp. 271-288.
- PEF. (2012). *Product Environmental Footprint (PEF) Guide*. Retrieved from <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>
- Pope, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, *J Am Med Assoc*, 287, 1132-1141.
- Posch, M., Seppälä, J., Hettelingh, J., Johansson, M., M., M., & Jolliet, O. (2008). The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. *International Journal of Life Cycle Assessment* (13), pp. 477–486.
- Preiss, P. (2015). Photochemical Ozone Formation. In M. H. Hauschild, *Life Cycle Impact Assessment. LCA Compendium – The Complete World of Life Cycle Assessment*. Springer. doi:https://doi.org/10.1007/978-94-017-9744-3_7
- Reid, A., Carlson, A., Creed, I., Eliason, E., Gell, P., Johnson, P., . . . Cooke, S. (2018). Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biology Reviews*, 849-873.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., . . . Folke, C. A. (2009). A safe operating space for humanity. *Nature*, 472–475. doi:<https://doi.org/10.1038/461472a>
- Rosenbaum, R. K. (2008). USEtox—The UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle assessment. *International Journal of Life Cycle Assessment*.
- Rosenbaum, R. K., Bachmann, T. M., Gold, L. S., Huijbregts, M. A., Jolliet, O., Juraske, R., . . . Hauschild, M. Z. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *The International Journal of Life Cycle Assessment*, 532-546.
- Rosenbaum, R. K., Bachmann, T. M., Gold, L. S., Huijbregts, M. A., Jolliet, O., Juraske, R., . . . Van de Meent, D. a. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact

assessment, *Int J Life Cycle Assess*, 13, 532–546, <https://doi.org/10.1007/s11367-008-0038-4>. *Int J Life Cycle Assess* 13, 532–546.

- Rosenbaum, R., Bachmann, T., & Gold, L. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *The International Journal of Life Cycle Assessment*, 532–546.
- Roy, P., & Sardar, A. (2015). SO₂ emission control and finding a way out to produce sulphuric acid from industrial SO₂ emission, *Journal of Chemical Engineering & Process Technology*, 6(2), Article 230, <https://doi.org/10.4172/2157-7048.1000230>.
- Rybczewska-Błazejowska, M., & Jezierski, D. (2016). Comparison of ReCiPe 2016, ILCD 2011, CML-IA baseline and IMPACT 2002+ LCIA methods: a case study based on the electricity consumption mix in Europe. *The International Journal of Life Cycle Assessment*, 29(10), 1799–1817.
- Rydberg, T. (2023). *A concise technical presentation explaining the four components of the score—HF, ECF, PHF and MF—as well as hazard classes, PROCs and default modelling assumptions*. Retrieved from https://proscale.org/download/18.7b0d6088187fc7471be6466/1684216492339/230512%20ProScale%20-%20the%20method_v2b%20-%20for%20distribution.pdf
- Sala S., B. A.-M. (2019). Indicators and Assessment of the environmental impact of EU consumption. Consumption and Consumer Footprint for assessing and monitoring EU policies with Life Cycle Assessment. *Publications Office of the European Union*, ISBN 978-92-79-99672-6, doi:10.2760/403263, JRC114814.
- Sala, S. B.-M. (2022). Toxicity impacts in the Environmental Footprint method: calculation principles. *International Journal of Life Cycle Assessment*, 587–602.
- Sala, S. C. (2023). Development of the Environmental Footprint (EF) Method: EF 3.1 Background and Methodological Improvements. *Publications Office of the European Union*.
- Sala, S., & Cerutti, A. (2018). *Development of a weighting approach for the environmental footprint*. Retrieved from <https://doi.org/10.2760/446145>
- Sala, S., Benini, L., Castellani, V., Vidal-Legaz, B., De Laurentiis, V., & Pant, R. (2019). *Suggestions for the update of the Environmental Footprint Life Cycle Impact Assessment: Impacts due to resource use, water use, land use, and particulate matter*. Luxembourg : Publications Office of the European Union (European Commission, Joint Research Centre).
- Sala, S., Biganzoli, F., Sanye Mengual, E., & Saouter, E. (2022). Toxicity impacts in the environmental footprint method: Calculation principles. *International Journal of Life Cycle Assessment*, 587–602.
- Saling, Gelder, v., & Krüger. (2019). *Human toxicity assessment in LCA, LCM*. Retrieved from https://www.basf.com/dam/jcr:8d6b5c5b-f05a-31f2-89db-e10c8a8fc32e/basf/www/global/documents/en/sustainability/publications/lcm-2021/210902_BASF_SE_ProScale.pdf
- Sanjh, S. (2023). *The role of volatile organic compounds in photochemical smog formation*. *Journal of Earth Science & Climatic Change*. Retrieved from <https://www.omicsonline.org/open->

access-pdfs/the-role-of-volatile-organic-compounds-in-photochemical-smog-formation.pdf

- Saouter, E. B. (2020). Environmental Footprint: Update of Life Cycle Impact Assessment Methods – Ecotoxicity freshwater, human toxicity cancer, and non-cancer. *EUR 29495 EN*, ISBN 978-92-76-17143-0, doi:10.2760/300987, JRC114227.
- Saouter, E. D. (2018). Estimating chemical ecotoxicity in EU ecolabel and in EU product environmental footprint. *ENVIRONMENTAL TOXICOLOGY AND CHEMISTRY*, 44-47.
- Sayer, C., Fernando, E., Jimenez, R., Macfarlane, N., Rapacciuolo, G., & Böhm, M. (2025). One-quarter of freshwater fauna threatened with extinction. *Nature*, 138-145.
- Scherer, L., Rosa, F., Sun, Z., Michelsen, O., De Laurentiis, V., Marques, A., & Pfister, S. V. (2003). Biodiversity impact assessment considering land use intensities and fragmentation. *Environ. Sci. Technol.*, 19612-19623.
- Scherer, L., Rosa, F., Sun, Z., Michelsen, O., De Laurentiis, V., Marques, A., . . . Verones, F. a. (2023). Biodiversity impact assessment considering land use intensities and fragmentation. *Environ. Sci. Technol.*, 19612-19623.
- Segers, A., Kranenburg, R., Jonas, H., Hohenberger, T. L., Geers, L., & Manders-Groot, A. (2025). *LOTOS-EUROS Reference Guide, Version 3, TNO Public TNO2025R10849*. Retrieved from https://airqualitymodeling.tno.nl/downloads/?PagClsIdt=158538#PagCls_158538
- Seppälä, J., Posch, M., Johansson, M., & Hettelingh, J. (2006, 11(6)). Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. *International Journal of Life Cycle Assessment*, pp. 403-416.
- Shannoun, F. (2015, July). Medical exposure assessment: the global approach of the United Nations Scientific Committee on the Effects of Atomic Radiation Get access Arrow. *Radiation Protection Dosimetry*, 165(1-4), pp. 125-128.
- Sheikh, Q.-t.-a. A., Solangi, A. H., & Meraj, M. (2024). Discovering Water Scarcity Risks and The Strategic Significance of Water Management in Pakistan. *Journal of Social Sciences and Humanities*. Retrieved from <https://doi.org/10.12982/CMUJASR.2025.012>
- Shi, S. a. (2024). A critical review on spatially explicit life cycle assessment methodologies and applications. *Sustainable Production and Consumption*.
- Shi, Z., Zhang, J., Xiao, Z., Lu, T., Ren, X., & Wei, H. (2021, Volume 297 113213, ISSN 0301-4797, <https://doi.org/10.1016/j.jenvman.2021.113213>). Effects of acid rain on plant growth: A meta-analysis,. *Journal of Environmental Management*,.
- Shimada, K., & Kai, M. (2015). Calculating disability-adjusted life years (DALY) as a measure of excess cancer risk following radiation exposure, *J Radiol Prot*, 35(4), 763-775 <https://doi.org/10.1088/0952-4746/35/4/763>.
- Spannhake, E., Reddy, S., Jacoby, D., Yu, X.-Y., Saatian, B., & Tian, J. (2002, 110). Synergism between rhinovirus infection and oxidant pollutant exposure enhances airway epithelial cell cytokine production. *Environ Health Persp*, pp. 665-670.

- Sphera. (2022). *GaBi - Introduction to Water Use Assessment 2022*.
- Stranddorf, H., Hoffmann, L., & Schmidt, A. (2005). Update on Impact Categories, Normalisation and Weighting in LCA. Selected EDIP97-Data. *Environmental Project Nr. 995 2005*. Danish Environmental Protection Agency.
- Tavella, R. A., da Silva Júnior, F. M., Santos, M. A., Miraglia, S. G., & Pereira Filho, R. (2025). Review of Air Pollution from Petroleum Refining and Petrochemical Industrial Complexes: Sources, Key Pollutants, Health Impacts, and Challenges. *ChemEngineering*, 9, 13, <https://doi.org/10.3390/chemengineering9010013>.
- TENORM. (2025). *United States Environmental Protection Agency*. Retrieved 09 02, 2026, from <https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm>
- Terranova, D. B. (2021). Applicability assessment and sensitivity analysis of land-use impact models: Application of the LANCA model in site-specific conditions. *The International Journal of Life Cycle Assessment*, 2256–2272.
- TfS. (2024). *TfS PCF Guideline Version 3, The Product Carbon Footprint Guideline for the Chemical Industry*. Retrieved from Together for Sustainability AISBL: <https://www.tfs-initiative.com/app/uploads/2024/12/TfS-PCF-Guidelines-2024.pdf>
- Together for Sustainability AISBL. (2025, 09 01). *www.tfs-initiative.com*. Retrieved from [www.tfs-initiative.com](https://www.tfs-initiative.com/app/uploads/2025/09/TfS-PCF-Data-Model-1.pdf): <https://www.tfs-initiative.com/app/uploads/2025/09/TfS-PCF-Data-Model-1.pdf>
- U.S. Department of Energy (DOE). (1999). *Occupational radiation protection record-keeping and reporting guide*. Retrieved from DOE G 441.1-11: <https://www.directives.doe.gov/directives-documents/400-series/0441.1-EGuide-11>
- U.S. Department of Energy (DOE). (2026). *10 CFR Part 835 – Occupational Radiation Protection*. Retrieved from <https://www.ecfr.gov/current/title-10/chapter-III/part-835>
- U.S. Environmental Protection Agency (EPA). (1987). Lime and cement industry particulate emissions: Source category report. Volume II – Cement industry. EPA/600/S7-87/007, Research Triangle Park: Air and Energy Engineering Research Laboratory.
- U.S. Environmental Protection Agency (EPA). (2015). A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution; EPA 820-F-15-096; Office of Water: Washington, DC; p 110. Online (epa.gov/sites/default/files/2015-04/documents/nutrient-economics-report-2015.pdf),.
- U.S. Environmental Protection Agency (EPA). (2025). *40 CFR Part 190 – Environmental Radiation Protection Standards for Nuclear Power Operations*. Retrieved from <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-F/part-190>
- U.S. Environmental Protection Agency (EPA). (2025). Final Reconsideration of the National Ambient Air Quality Standards for Particulate Matter (PM), <https://www.epa.gov/pm-pollution/final-reconsideration-national-ambient-air-quality-standards-particulate-matter-pm>, accessed 11.03.2026.

- U.S. Environmental Protection Agency (EPA). (2025). *Particulate Matter (PM) Basics*. Retrieved from <https://www.epa.gov/pm-pollution/particulate-matter-pm-basics>
- U.S. Environmental Protection Agency (EPA). (2025, March 13). *Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM)*. Retrieved from Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM): <https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm>
- U.S. Environmental Protection Agency (EPA). (2026). *40 CFR Part 192 – Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings*. Retrieved from <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-F/part-192>
- U.S. Geological Survey. (2026). *Mineral commodity summaries 2026*. Retrieved from <https://doi.org/10.3133/mcs2026>
- U.S. Geological Survey. (2026). *Mineral commodity summaries 2026*. Reston: U.S. Geological Survey.
- U.S. Nuclear Regulatory Commission (NRC). (2016). *Regulatory Guide 8.10: Operating philosophy for maintaining occupational and public radiation exposures as low as reasonably achievable (ALARA)*. Retrieved from <https://www.nrc.gov/docs/ML1610/ML16105A136.pdf>
- U.S. Nuclear Regulatory Commission (NRC). (2024). *Radiation protection and environmental monitoring program manual*. Retrieved from <https://www.nrc.gov/docs/ML2427/ML24278A016.pdf>
- UN. (1982). *Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea*. Retrieved 03 19, 2026, from United Nations: https://www.un.org/depts/los/convention_agreements/texts/agreement_part_xi/agreement_part_xi.htm
- UNECE. (2012). *Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long-range Transboundary Air Pollution (as amended on 4 May 2012); United Nations Economic Commission for Europe (UNECE)*. Retrieved from https://unece.org/sites/default/files/2021-10/ECE.EB_.AIR_.114_ENG.pdf
- UNEP. (2017). *Mine tailings storage: Safety is no accident. UNEP/GRID-Arendal*. Retrieved 08 20, 2026, from United Nations Environment Programme: <https://www.grida.no/publications/383>
- UNEP. (2019). *Global Resources Outlook*. Retrieved 08 2026, from United Nations Environment Programme: <https://www.unep.org/news-and-stories/press-release/un-calls-urgent-rethink-resource-use-skyrockets>
- UNEP. (2020). *Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer, fourteenth ed. Ozone Secretariat, Nairobi*.
- UNEP. (2024). *Minamata Convention on Mercury*. Retrieved 03 19, 2026, from United Nations Environment Programme: https://minamataconvention.org/sites/default/files/documents/information_document/Minamata-Convention-booklet-Oct2024-EN.pdf
- UNEP/SETAC. (2017). *USEtox(R) 2.0 Documentation*. online.

- UNEP-SETAC Life Cycle Initiative. (2009). *Guidelines for social life cycle assessment of products*.
- UNEP-SETAC Life Cycle Initiative. (2016). *Global guidance for life cycle impact assessment indicators and methods (GLAM)*. Paris: United Nations Environment Programme. Retrieved from <https://eplca.jrc.ec.europa.eu/EFtransition.html>
- United Nations (UN). (2026). *Sustainable Development Goals*. Retrieved from <https://sdgs.un.org/goals>
- United Nations Economic Commission for Europe (UNECE). (2021). *Life Cycle Assessment of Electricity Generation Options*. Geneva: United Nations.
- United Nations Economic Commission for Europe (UNECE). (n.d.). *Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*. Retrieved from https://unece.org/environmental-policy/air/protocol-abate-acidification-eutrophication-and-ground-level-ozone?utm_source=chatgpt.com
- United Nations Environment Programme, SETAC Life Cycle Initiative. (2016). *Global Guidance for Life Cycle Impact Assessment Indicators, Volume 1. Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM) - Life Cycle Initiative*.
- US CWA. (1972). United States Clean Water Act (PL 92-500), Public Law 92e500, 1972.
- USEtox. (2026). *The USEtox model*. Retrieved from <https://usetox.org/model>
- Van Jaarsveld, J., Van Pul, W., & De Leeuw, F. (1997). Modelling transport and deposition of persistent organic pollutants in the European region. *Atmospheric Environment* 7, pp. 1011-1024.
- Van Oers, L. G. (2016). *The Abiotic Depletion Potential: Background, Updates, and Future, Resources*. Retrieved from doi:10.3390/resources5010016
- Van Oers, L. G. (2020). Abiotic resource depletion potentials (ADPs) for elements revisited: updating ultimate reserve estimates and introducing time series for production data. *The International Journal of Life Cycle Assessment*, 294–308. doi:<https://doi.org/10.1007/s11367-019-01683-x>
- Van Oers, L., De Koning, A., Guinée, J., & Huppes, G. (2002). *Abiotic resource depletion in LCA. Improving characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA handbook*. RWS-DWW: Delft, The Netherlands, 2002. Retrieved from http://www.leidenuniv.nl/cml/ssp/projects/lca2/report_abiotic_depletion_web.pdf
- Van Zelm, R., Huijbregts, M. A., Van Jaarsveld, H. A., Reinds, G. J., De Zwart, D., Struijs, J., & Van de Meent, D. (2007). Time horizon dependent characterisation factors for acidification in life-cycle impact assessment based on the disappeared fraction of plant species in European forests, *Environ Sci Technol*, 41(3), 922-927.
- Van Zelm, R., Huijbregts, M., Den Hollander, H., Van Jaarsveld, H., Sauter, F., Struijs, J., . . . Van de Meent, D. (2008). European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. *Atmospheric Environment*, 441-453.
- Van Zelm, R., Preiss, P., Van Goethem, T., Van Dingenen, R., & Huijbregts, M. (2016). Regionalized life cycle impact assessment of air pollution on the global scale: damage to human health and vegetation. *Atmospheric Environment* 134, 129-137.

- Vidal-Legaz, B., Sala, S., Antón, A., & Milà i Canal, L. (2016). Land-use related environmental indicators for life cycle assessment: A review and methodological proposal. *Journal of Cleaner Production*, 304–317. Retrieved from Journal of Cleaner Production.
- Vidal-Legaz, B., Sala, S. A., Maia de Souza, D., Nocita, M., Putman, B., Teixeira, & R.F.M. (2016). Land-use related environmental indicators for Life Cycle Assessment. *European Commission Joint Research Centre, EUR 27609*.
- Wang, Z., Xu, H., Gu, Y., Feng, R., Zhang, N., Wang, Q., . . . Cao, J. (2022). Chemical characterization of PM_{2.5} in heavy polluted industrial zones in the Guanzhong Plain, northwest China: Determination of fingerprint source profiles, *Science of The Total Environment*, 840, <https://doi.org/10.1016/j.scitotenv.2022.156729>.
- Wei, W., Ren, Y., Lan, J., Yi, J., Wang, M., Zhang, Y., . . . Li, J. (2026). Ionising radiation: molecular mechanisms, biological effects, and therapeutic targets, *Mol Biomed*;7(1):3. doi: 10.1186/s43556-025-00358-4. PMID: 41507636; PMCID: PMC12783457.
- Weidema, B. P. (2013). *The ecoinvent Centre (publ.): Overview and methodology. Data quality guideline for the ecoinvent database version3*.
- WMO. (2022). (World Meteorological Organization) Scientific Assessment of Ozone Depletion. *GAW Report No. 27*, p. 509.
- World Health Organisation (WHO). (2021). WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.
- World Health Organization (WHO). (2014). *Metrics: Disability-adjusted life year (DALY)*. Retrieved from <https://www.who.int/data/gho/indicator-metadata-registry/imr-details/158>
- World Health Organization (WHO). (2023). *Chemical Safety and Health*. Retrieved from <https://www.who.int/europe/news-room/fact-sheets/item/chemical--safety>
- World Health Organization (WHO). (2023). *Ionising radiation and health effects*. Retrieved from <https://www.who.int/news-room/fact-sheets/detail/ionising-radiation-and-health-effects>
- Yang, Y., Ok, Y. S., Kim, K., Kwon, E. E., & Tsang, Y. F. (2017). Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: A review. *Science of The Total Environment*, 303-320.
- Zampori, L. a. (2019). Suggestions for updating the Product Environmental Footprint (PEF) method,. *EUR 29682 EN, Publications Office of the European Union*.
- Zampori, L., & Pant, R. (2019). Suggestions for updating the Product Environmental Footprint (PEF) method, EUR 29682 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76- 00654-1, doi:10.2760/424613, JRC115959 + List of characterization factors for download av.
- Zhang, Y., Li, J., Tan, J., Li, W., Singh, B. P., Yang, X., . . . Wang, H. (2023). An overview of the direct and indirect effects of acid rain on plants: Relationships among acid rain, soil, microorganisms, and plants. *Science of the Total Environment*, <https://doi.org/10.1016/j.scitotenv.2023.162388>.

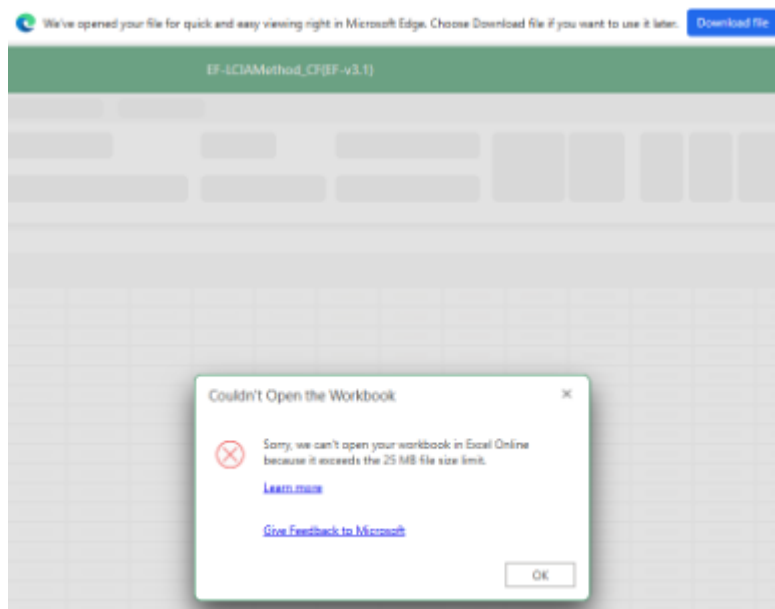
Bos, U. M. (2020). A GIS based method to calculate regionalized land use characterization factors for life cycle impact assessment using LANCA®. *Sustainable Food Production and Consumption*, 1259-1277.

21. Appendix

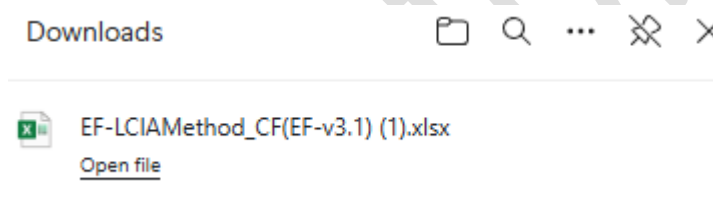
21.1. Downloading EF 3.1

The full list of LCI flows (incl. respective CFs) can be found under the following link: [EF 3.1](#).

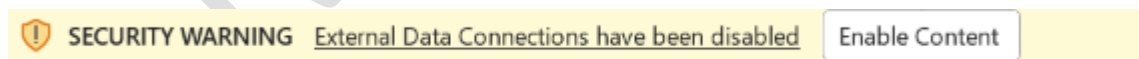
To check the full LCI flows, please click on the link [EF 3.1](#) and select “Download file”.



Then check your downloads and open the file.



Click on “Allow content”.



Then, you will be able to select the impact category in the excel file and see all related flows and their CF:

H159023 Emissions to air

FLOW_uid	FLOW_name	LCIAMethod_uid EF3.1	LCIAMethod_name	CF EF3.1	LCIAMethod_location
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	4.0E	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.035 RU	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.535 FI	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.12 IT	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.015 GR	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	4.451 SE	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.151 HR	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.12 IT	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	4.451 SE	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.082 CS	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.04 BG	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	4.451 SE	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.124 RO	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	4.414 NL	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.015 GR	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.568 LT	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.405 EE	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	1.059 IE	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.04 BG	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.455 HU	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.428 LV	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.27 SI	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.076 ES	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.455 HU	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.151 HR	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	3.655 CZ	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	2.347 DK	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.125 MD	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.021 MK	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.124 RO	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.058 PT	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.568 LT	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	2.501 GB	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.088 BA	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	1.054 SE	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.428 LV	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	3.02	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.058 PT	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.023 MK	
08a91e70-36d4-11d4-96a6-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	2.501 GB	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	1.72 AT	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.747 CH	
2905c4e-6556-11d4-a88b-0800200c9a66	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	2.347 DK	
08a91e70-36d4-11d4-a2a9-0050c2490048	ammonia	b5c611c5-def3-11e6-b001-4655135034f3	Acidification	0.405 EE	

21.2. Resource Use, fossils

21.2.1. Other LCIA methods: Resource Use, fossil

An overview of existing midpoint methods is given in Table 49. (Drielsma, et al., 2016) have compared the definitions used by the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) with definitions of reserves as used in the ADP (Resource use, fossils) (Van Oers, De Koning, Guinée, & Huppes, 2002).

Table 49: Overview of Midpoint assessment methods

ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European context First edition

Midpoint method	Underlying model	Reference
Swiss Ecoscarcity (energy and gravel)		Frischknecht <i>et al.</i> (2008)
Exergy	CEENE: Cumulative exergy extraction from the natural environment	Dewulf <i>et al.</i> (2007)
CML2002	Guinée and Heijungs, 1995	Guinée <i>et al.</i> (2002)
EDIP1997 (2004 update)	EDIP 1997 (Nedermark)	Hauschild (1998, updated in 2004)
MEEUP (water)		Kemna <i>et al.</i> (2005)
Swiss Ecoscarcity (water)		Frischknecht <i>et al.</i> (2006b)
Endpoint method		
Eco-indicator 99 (EI99)	Müller-Wenk (1998b)	Müller-Wenk (1998b) and Goedkoop (1999)
EPS2000		Steen (1999)
IMPACT 2002+	Fossil fuels: IMPACT2002+; Minerals as in EI99	Jolliet (2003)
ReCiPe		Goedkoop and De Schryver (2008), De Schryver and Goedkoop (2009c)

Exergy

This method is based on (Dewulf, et al., 2007). They used Exergy as a key element in their assessment. Exergy, often referred to as "available energy" or "useful work potential", is a fundamental concept in the field of thermodynamics and engineering. It plays a crucial role in understanding and quantifying the quality of energy within a system and its potential to perform useful work. Exergy analysis has widespread applications in various fields, including energy engineering, environmental science, and industrial processes. Exergy values have been determined for a list of resources covering fossil fuels, minerals, nuclear energy, land resources, renewable resources (e.g. wind power and hydropower), atmospheric resources and water resources. The method addresses several shortcomings of earlier exergy methods, like double counting in bio-based fuels and confusing exergy loss in ores with exergy loss in the minerals that contain the metals being exploited.

Although this method involves the exergy concept thoroughly, it does not reflect the scarcity of resources. Exergy is a thermodynamic concept and simply put, it's used to measure the quality or usefulness of energy or materials. As such, for instance, fossil resources have high exergy values and release plenty of useful energy. Nevertheless, it doesn't mean these resources are abundant or easily accessible. Even if this concept is interesting, we decided to follow the EF of the European Commission in sense of harmonization.

EDIP 1997

This method was updated in 2004 and includes non-renewable resources (fossil fuels and minerals). The amount of resources extracted is divided by the 2004 global production of the resource and weighted according to the quantity of resources in economically exploitable reserves. Effectively, this means that global annual production drops out, so that the

characterization model is based on the economic reserves only. The CFs are expressed in person-reserve, meaning the quantity of the resource available to an average world citizen. That is not very often used in many LCA, so we do not use this method either. Furthermore, it is a normalized figure and not a clear midpoint-related approach. That does not fit with the other recommended methods. Due to harmonization, this method is not recommended to be used.

21.3. Resource Use, minerals and metals

21.3.1. Current Scientific Discussion

The Joint Research Centre (JRC) has acknowledged several limitations of the assessment of Resource Use, minerals and metals in both scientific literature and methodological discussions (JRC, 2020). As a result, alternative approaches based on resource dissipation have been proposed and are currently under evaluation.

Nevertheless, Resource Use, minerals and metals using CML characterization factors remains the method currently recommended by both the European Commission and the United Nations Environment Programme (UNEP) Task Force on Mineral Resources.

Although the Product Environmental Footprint (PEF) methodology generally defines characterization factors only for elemental resources, the JRC recognizes that certain borderline cases exist where assigning a characterization factor of zero or simply summing elemental characterization factors may not adequately represent resource use. Sodium chloride is one example of such a case. However, no universally accepted guidance is currently available for handling these situations.

Consequently, the reviewed JRC publications provide valuable context regarding the limitations of current methods but offer limited practical guidance for resolving individual modelling cases.

21.3.2. Aggregates and Mineral Resources in Life Cycle Inventory Modelling

The UNEP-SETAC Life Cycle Initiative defines mineral resources broadly, allowing different interpretations within Life Cycle Assessment studies. This flexibility is reflected in current Life Cycle Inventory (LCI) practice.

For example, a mineral such as chalcopryrite (CuFeS_2) may be represented as:

- the mineral itself,
- its constituent elements (Cu, Fe, and S),
- or both.

Each representation may be considered valid because the mineral and its constituent elements can provide value to the technosphere (Berger M., 2020).

Current databases reflect different modelling philosophies. In ecoinvent, metal extraction is generally recorded based on the quantity of target metal contained within the ore (Weidema, 2013). However, where a mineral or aggregate has value in its own, such as gypsum, sand, or sodium chloride, the mineral or aggregate itself may be considered the relevant elementary flow in LCA (Berger M., 2020).

21.3.3. Proposed Hierarchical Decision Hierarchy

To improve consistency when assessing aggregates and compounds, the following hierarchy is proposed:

1. **Pure elements:** Use the characterization factor provided in EF 3.1.
2. **Modelled secondary datasets available:** Use a representative secondary dataset from an established LCA database. The dataset source, assumptions, and modelling approach should be documented.
3. **Aggregates and compounds without suitable datasets:** Calculate the characterization factor from the sum of the constituent elemental characterization factors. However, this approach is not compliant to the EF 3.1 methodology.
4. **No suitable data available:** Apply a scientifically justified proxy and clearly document the rationale and limitations.

Where multiple approaches are available, the use of the most conservative and transparent value is recommended to avoid underestimating the potential depletion of abiotic resources.

Scientifically justified proxies could be, e. g., characterization factors derived from comparing global reserves of mineral commodities to the global reserves of antimony which can be extracted from the (U.S. Geological Survey, 2026) which are exemplarily outlined in Table 50:

Table 50: Approach to derive CFs from global mineral reserves stated in (U.S. Geological Survey, 2026) in comparison to CFs given in EF 3.1 and CML 2016

Element		Reserves (metric tons)	USGS factor related to Sb reserves (kg Antimony/ kg element)	EF 3.1 CF (kg Sb-eq./kg)	CML 2016 CF (kg Sb-eq./kg)
Antimony	Sb	2,000,000	1.00E+00	1.00E+00	1.00E+00
Nickel	Ni	140,000,000	1.43E-02	6.53E-05	6.53E-05
Sulfur	S	~ almost unlimited (no quantification, gypsum and anhydrite given as potentially unlimited sources for sulfur)		1.93E-04	1.93E-04

Although, the usage of characterization factors derived from (U.S. Geological Survey, 2026) may close some gaps as the report also contains high commodity minerals such as bauxite or minerals like lime, sand, and gravel, there remain gaps as elements like sulfur, chlorine or oxygen. It should be mentioned that USGS addresses reserves that are mainly determined by economic factors and influences. The figures can change over time, depending on uses of the reserves and influenced by market changes. The CML and EF 3.1 figures are based on availabilities in the earth crust with a much higher (theoretical) availability of the element compared to economically used materials.

21.4. Water Scarcity

21.4.1. Example 1: Water scarcity impact for product with value chain in different countries

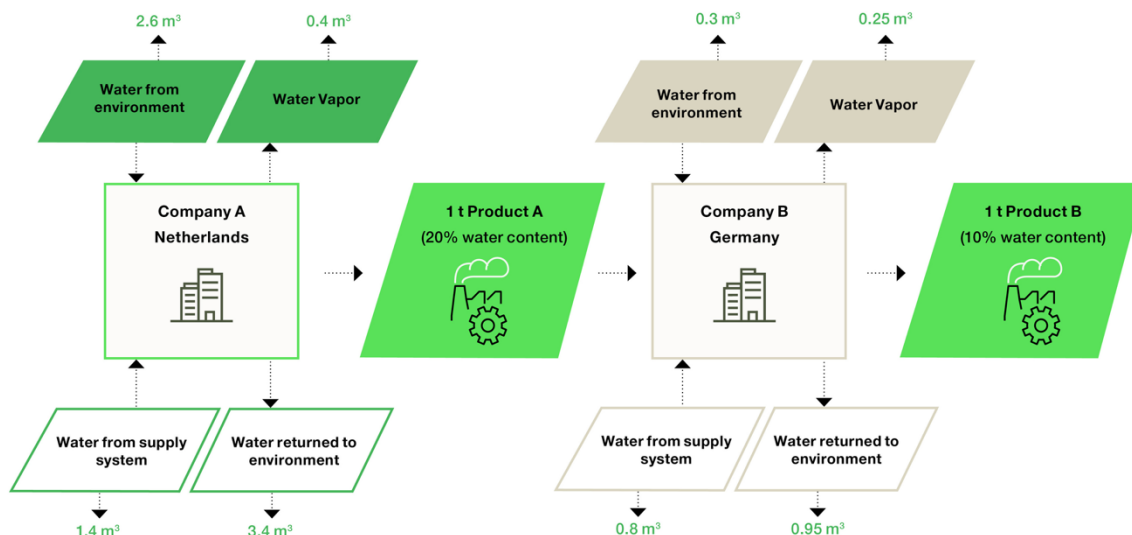


Figure 22: Example 1: Water scarcity impact for product with value chain in different countries.

Total Water Input Company A = $2.6 + 1.4 = 4 \text{ m}^3$

Total Water Output Company A = $3.4 + 0.4 + (0.2 \times 1) = 4 \text{ m}^3$

Water Balance: Checked!

Consumptive Water Company A = $4 - (3.4) = 0.6 \text{ m}^3$

CF (NL) = $1.17 \text{ m}^3 \text{ world eq./m}^3$

Water scarcity Impact Product A = $0.6 \times 1.17 = 0.702 \text{ m}^3 \text{ world eq. / ton}$

Total Water Input Company B = $(0.2 \times 1) + 0.3 + 0.8 = 1.3 \text{ m}^3$

Total Water Output Company B = $0.25 + 0.95 + (0.1 \times 1) = 1.3 \text{ m}^3$

Water Balance: Checked!

Consumptive Water Company B = $1.1 - (0.95) = 0.15 \text{ m}^3$

CF (DE) = $1.36 \text{ m}^3 \text{ world eq./m}^3$

Water scarcity Impact Product B = $0.702 + (0.15 \times 1.36) = 0.906 \text{ m}^3 \text{ world eq.}$

21.4.2. Example 2: Water scarcity impact when input water country of origin is different from output water

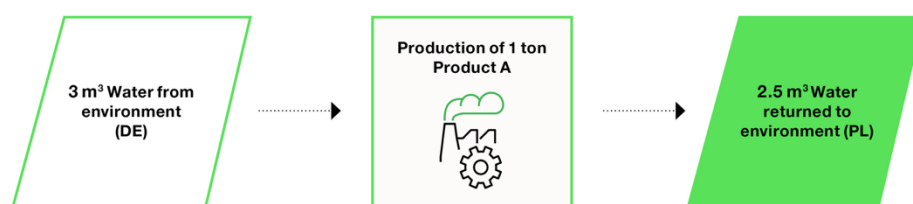


Figure 23: Example 2: Water scarcity impact when input water country of origin is different from output water.

$$CF_1 (DE) = 1.36 \text{ m}^3 \text{ world eq./m}^3$$

$$CF_2 (PL) = 1.96 \text{ m}^3 \text{ world eq./m}^3$$

$$\text{Water scarcity impact} = (\text{Total water inputs} \times CF_1) - (\text{Total water returned to environment} \times CF_2) = (3 \times 1.36) - (2.5 \times 1.96) = -0.82$$

In this case, the water scarcity impact is negative because transferring the water from Germany to Poland even if not fully returned, it causes a credit due to different water stress level.

21.4.3. Examples on Corrective Considerations for Surplus Water Outputs

Table 51 represents the water inventory obtained after data collection.

Table 51: Input-output process water inventory before water balance correction (example 4)

Input			Output		
Raw materials	10	ton	Product	9	ton
Cooling materials	5	m ³	Steam condensate	1.5	m ³
Water for steam generation	2	m ³	Process water to WWTP	0.9	m ³
Process water	1	m ³	Cooling water returned to environment	5.5	m ³
			Water loss (evaporation)	1.6	m ³

$$\text{Total Water Input} = 5 + 2 + 1 = 8 \text{ m}^3$$

$$\text{Total Water Output} = 1.5 + 0.9 + 5.5 + 1.6 = 9.5 \text{ m}^3$$

$$\text{Water Output Surplus} = 9.5 - 8 = 1.5 \text{ m}^3$$

- After confirming the water content of raw materials, 10% water content has been estimated to be included in raw materials.
- It has been also confirmed that due to having open facilities, rainwater has been entered into the network and returned into environment along with the cooling water. Therefore, the rainwater amount should be deducted from inventory based on the water imbalance.

The updated inventory is as follows:

Table 52: Input-output process water inventory after water balance correction (example 4)

Input			Output		
Raw materials (dry)	9	ton	Product	9	ton
Water content in raw materials	1	ton	Steam condensate	1.5	m ³
Cooling water	5	m ³	Process water to WWTP	0.9	m ³
Water for steam generation	2	m ³	Cooling water returned to environment (rainwater excluded ⁵)	5	m ³
Process water	1	m ³	Water loss (evaporation)	1.6	m ³
			Rainwater to be deducted!	0.5	m ³

Total Water Input = $5 + 2 + 1 + 1 = 9 \text{ m}^3$

Total Water Output = $1.5 + 0.9 + 5.5 + 1.6 - 0.5 = 9 \text{ m}^3$

Water Balance: Checked!

21.4.4. Examples on Corrective Considerations for Surplus Water Inputs

Table 53 represents the water inventory obtained after data collection.

Table 53: Input-output process water inventory before water balance correction (example 5)

Input			Output		
-------	--	--	--------	--	--

Raw materials (dry)	10	ton		Product	9	ton
Process water	4	m ³		Solid waste to incineration	2	ton
Water for steam generation	2	m ³		Steam condensate	1.5	m ³
				Process Water to WWTP	3	m ³

Total Water Input = 4 + 2 = 6 m³

Total Water Output = 1.5 + 3 = 4.5 m³

Water Input Surplus = 6 – 4.5 = 1.5 m³

- After confirming the water content of solid waste, 50% water content has been estimated to be included in the solid waste.
- The water loss due to evaporation also has been confirmed for the steam. Therefore, evaporated water has been added to output flows based on the water imbalance.

The updated inventory is as follows:

Table 54: Input-output process water inventory after water balance correction (example 5)

Input		
Raw materials (dry)	10	ton
Process water	4	m ³
Water for steam generation	2	m ³
Output		
Product	9	ton
Solid waste to incineration	1	ton
Water content in the solid waste	1	m ³
Steam condensate	1.5	m ³
Water loss (evaporation)	0.5	m ³
Process water to WWTP	3	m ³

Total Water Input = 4 + 2 = 6 m³

Total Water Output = 1 + 1.5 + 0.5 + 3 = 6 m³

Water Balance: Checked!

21.5. Acidification Potential

21.5.1. Other LCIA methods: Acidification Potential

In the ILCD Handbook (Hauschild, et al., 2011) different LCIA methods containing different models on midpoint level assessing the AP have been described and evaluated:

- **TRACI APs** are derived from (Norris, 2003) model, which offers generic, spatially differentiated CFs for the U.S. It employs the ASTRAP fate model to connect emissions to land deposition, accounting for AP across all land and inland water areas, regardless of soil and ecosystem sensitivity. The model's dose-response curve is set to 1. While TRACI effectively evaluates acidifying chemicals, it is limited to terrestrial acidification in the U.S. and does not fully address soil sensitivity to acidifying deposition. Enhancing environmental relevance could involve adding soil fate factors to differentiate sensitive from non-sensitive areas. Additionally, the ASTRAP model used for atmospheric fate is considered outdated. (Hauschild, et al., 2011)
- **MEEUP** (Kemna, Van Elburg, W., & Van Holsteijn, 2005) is aligned with European legislation and the Gothenburg protocol, focusing on AP based on H⁺ releases. It does not consider the chemical fate of emissions in air and soil, treating all emissions and depositions as equal in generating AP, with an implicit dose-response curve of 1. The method lacks environmental relevance due to its disregard for atmospheric fate and soil sensitivity, and it does not allow for regional differentiation (Hauschild, et al., 2011).
- **CML 2002** employs the Hazard Index (HI) method (Huijbregts, Verkuijlen, Heijungs, & Reijnders, 2001) to provide spatially specific CFs for acidifying and eutrophying air pollutants in Europe. These CFs indicate the marginal change in the hazard index across European ecosystems by comparing actual loads to critical loads, weighted by ecosystem and region. The European RAINS model (Amann, Cofala, Heyes, Klimont, & Schöpp, 1999) is used to assess atmospheric transport and deposition. The HI method assumes a dose-response slope that is inversely proportional to the critical load. While CML 2002 offers a solid

evaluation, it is less current and holds less stakeholder relevance compared to other methods. (Hauschild, et al., 2011)

- **ReCiPe** is a midpoint-endpoint method that utilizes the Base Saturation method developed by (Van Zelm R. , et al., 2007) to assess atmospheric fate using the EUTREND model (Van Jaarsveld, Van Pul, & De Leeuw, 1997), focusing solely on terrestrial ecosystems. It employs the SMART 2 simulation model (Kros, 2002) to evaluate soil sensitivity at the midpoint level through changes in soil base saturation, with data currently available only for Europe. ReCiPe provides a solid foundation for future acidification methods based on the Base Saturation factor, offering an alternative to critical load approaches. However, the concept needs to be expanded to include ecosystems beyond forests, and further exploration is required to create consistent CFs for other continents, including potential proxies for effect factors. (Hauschild, et al., 2011)
- **LIME** (Hayashi, Okazaki, Itsubo, & Inaba, 2004) is a midpoint-endpoint method that uses the Atmospheric Deposition Factor to express the SO₂ equivalency, indicating an increase in H⁺ deposition per unit area due to additional acidifying emissions. The fate of these emissions is assessed using an atmospheric transport model or empirical data, depending on the chemical, and it focuses solely on terrestrial ecosystems. While LIME generally meets scientific criteria at the midpoint level, its selected indicator lacks sufficient environmental relevance, as it only models the cause-effect chain up to the deposition of acid equivalents without considering sensitive and non-sensitive areas. (Hauschild, et al., 2011)
- **Payet** (2006) proposed a dose-effect relationship to evaluate changes in pH concentration in non-buffered water bodies, focusing on the fraction of affected or lost species, as part of the European NOMIRACLE project and IMPACT 2002+ developments. This method has not been operationalized or validated with field measurements and requires a fate model for further development. However, it could provide a valuable foundation for assessing the impact of acidifying chemicals on aquatic ecosystems. (Hauschild, et al., 2011)
- **ImpactWorld+** enhances existing regional modeling capabilities by extending them to a global scale, enabling consistent evaluation of regional life cycle emission inventories within the framework of a global economy (Jungbluth, 2025). This methodology serves as an update to the IMPACT 2002+, LUCAS, and EDIP methods. ImpactWorld+ employs a midpoint-damage framework that offers four complementary perspectives to illustrate an LCIA profile: (1) midpoint impacts, (2) damage impacts, (3) damages affecting human health, ecosystem quality, and resource & ecosystem service areas of protection, and (4) damages related to water and carbon concerns. The assessment of terrestrial and freshwater acidification impacts combines global atmospheric source-deposition relationships with the sensitivity of soil and water ecosystems at a resolution of 2° × 2.5° (latitude × longitude) (Bulle C. , et al., 2019). By utilizing more scientifically robust and advanced models, ImpactWorld+ delivers more accurate and environmentally relevant LCA results. Additionally, it incorporates uncertainties related to CFs and impact categories, employing cutting-edge characterization modeling. Notably, it is the first global regionalized method that allows for the assessment and differentiation of the same emission occurring in various geographical locations worldwide (Jungbluth, 2025).

21.6. Ozone Depletion Potential

21.6.1. Other LCIA methods: Ozone Depletion Potential

In a review of (Oever, et al., 2024) 15 LCIA methods covering ODP as impact category have been reviewed. An overview is shown in the following table:

Table 55: Description of the 15 LCIA methods selected for this review. Legend: M = midpoint, E = endpoint, n.a. = not available (Oever, et al., 2024)

Impact assessment method	# of substances	N ₂ O included	Time horizon	Type	Endpoint effects included	Normalization	Weighting
TRACI 2.1 (Bare, 2011)	90	No	Infinite	M	No	US and Canadian ODS emission 2008	n.a.
EPS2015d (Steen, 2015)	101	No	Infinite	E	Skin cancer, cataract	n.a.	Willingness-to-pay
CML-IA baseline (Oers, L. van, 2016)	23	No	Infinite	M	n.a.	Per capita global ODS emissions 1995	n.a.
CML-IA non-baseline (Oers, L. van, 2016)	15	No	5,10,15,20,25,30,40 years	M	n.a.	Per capita global ODS emissions 1995	n.a.
ReCiPe 2016 - Individualist (Huijbregts et al., 2016)	22	Yes	20 years	M/E	Skin cancer (Hayashi et al., 2006)	n.a.	n.a.
ReCiPe 2016 - Hiérarchisch (Huijbregts et al., 2016)	22	Yes	100 years	M/E	Skin cancer (Hayashi et al., 2006)	n.a.	n.a.
ReCiPe 2016 - Egalitarian (Huijbregts et al., 2016)	22	Yes	Infinite	M/E	Skin cancer, cataract (Hayashi et al., 2006)	n.a.	n.a.
Environmental prices (De Bruyn et al., 2018)	25	No	100 years	M/E	Skin cancer, agricultural crops (Hayashi et al., 2006)	n.a.	Damage-costs
Impact World+ (Bulle et al., 2019)	25 (midpoint) 23 (endpoint)	No	Infinite	M/E	Skin cancer, cataract (Struijs et al., 2010) et al., 2010)	Global damage 2000	n.a.
LC-IMPACT all effects, infinite (Verones et al., 2020)	21	Yes	Infinite	E	Skin cancer, cataract (Hayashi et al., 2006)	n.a.	n.a.
LC-IMPACT all effects, 100 years (Verones et al., 2020)	21	Yes	100 years	E	Skin cancer, cataract (Hayashi et al., 2006)	n.a.	n.a.
LC-IMPACT certain effects, infinite (Verones et al., 2020)	21	Yes	Infinite	E	Skin cancer (Hayashi et al., 2006)	n.a.	n.a.
LC-IMPACT certain effects, 100 years (Verones et al., 2020)	21	Yes	100 years	E	Skin cancer (Hayashi et al., 2006)	n.a.	n.a.
Ecological scarcity 2021 (FOEN, 2021)	42	No	Infinite	M	n.a.	Swiss emissions 2021	Distance-to-target (Swiss emissions 2040)
Environmental Footprint 3.1 (Andreasi et al., 2023; Fazio et al., 2018)	23	No	Infinite	M	n.a.	Per capita global emissions 2010	Hybrid evidence-based and expert-judgement

For the DMP, only the midpoint categories are relevant. Therefore, the abovementioned endpoint including EPS 2015d and LC-IMPACT (incl. all the variations) will not be considered in the discussion.

The UNEP Handbook for the Montreal Protocol (UNEP, 2020) enlisted 93 CFs. Despite relying on relatively old data sources, the impact assessment method TRACI 2.1 contains the highest number of CFs with 90 substances, followed by Ecological Scarcity 2021 with 42 substances. While the majority of LCIA methods (e.g., CML-IA baseline, EF 3.1, Impact World+, ReCiPe 2016) only include 22 to 25 ODS.

(Oever, et al., 2024) discovered that of the 32 substances not regulated by the Montreal Protocol, which are instead reported in the WMO inventory (WMO, 2022), only 5 of them are very sparsely included in the LCIA (e.g., N₂O in ReCiPe). (Oever, et al., 2024) stated that up to now only the LCIA method EF version 3.1 (Bassi et al., 2023; Fazio, et al., 2018) provides the most recent factors based on a global inventory for 2010. The rest of the methods offer normalization factors, which mostly refer to global inventories dated before 2010. However, it should be noted that the completeness of the global emissions inventory underlying the EF 3.1 normalization factor for ozone depletion has been estimated at below 30%; consequently, normalized and weighted ODP results should be interpreted with considerable caution.

Completeness of the inventory used in EF 3.1 is estimated to be below 30% (Sala S., 2019). TRACI 2.1 contains normalization factors based on US and Canadian ODS emissions of 2008. (Oever, et al., 2024)

Three different weighting methods were presented in the review of Oever et al. (2024). Ecological Scarcity 2021 provides a distance-to-target weighting factors, which express the normalized results relative to the Swiss policy targets for 2040, which limits the geographic representativeness. EF 3.1 incorporates a combination of public and expert panel-based weighting factors. (Oever, et al., 2024)

Figure 24 illustrates the data sources and model assumptions for ODP considering the period of publication of the LCIA method. The graph shows EF 3.1. as the most recent methodology, which is based on (Goedkoop, et al., 2009; WMO, 2022).

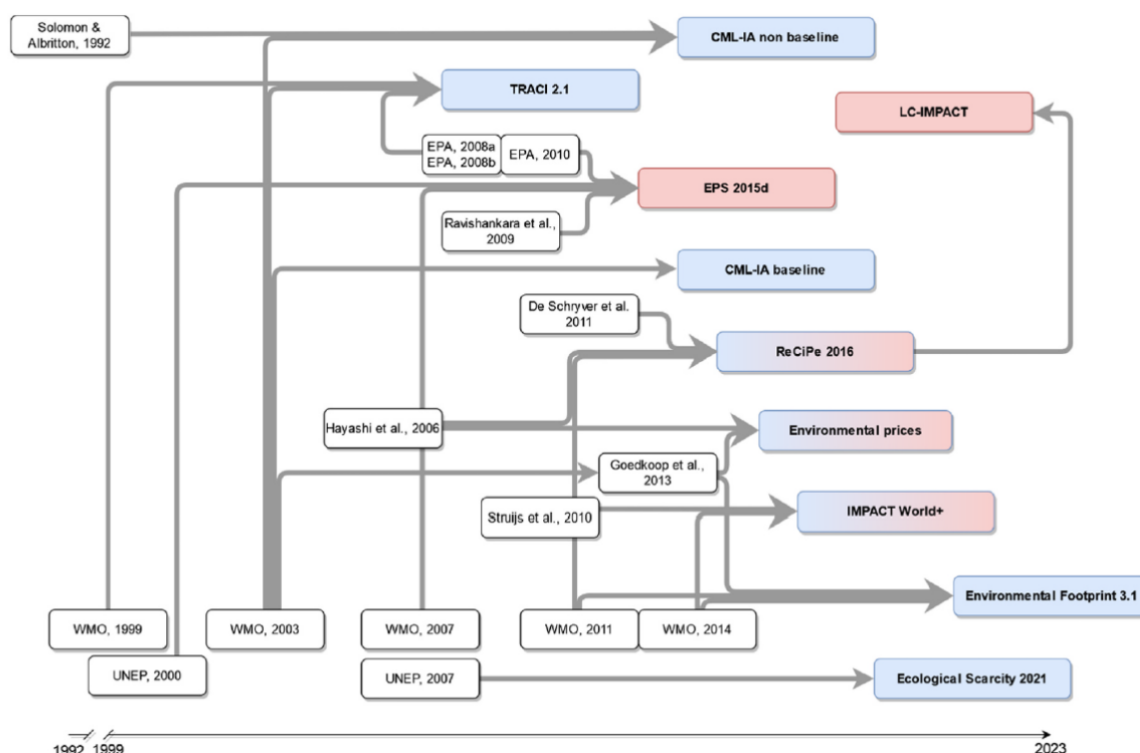


Figure 24: Overview of existing LCIA methods considering ODP in midpoint (blue ovals) and endpoint (red ovals) methods. White ovals represent data sources for ODP and model assumptions. (Oever, et al., 2024)

21.7. Photochemical Ozone Creation Potential

21.7.1. Other LCIA methods: Photochemical Ozone Creation Potential

Table 56 compares several existing methodologies for assessing POCP.

Table 56: Overview of LCIA methods for POCP

Method	Midpoint/ Endpoint	Unit	Spatial resolution	Chemicals	Coverage	Models	Reference
CML 2002	M	kg ethylene- eq. per kg emitted	Country, Europe	NO _x , POCP- factors		POCP	(Guinée et al., 2002)
ReCiPe 2016	M,E	Kg NO _x -eq	Europe but can be adapted for global	NO _x , NMVOC, N ₂ O	Terrestrial ecosystem, Human health	Global source- receptor model TM5- FASST	(Van Zelm, Preiss, Van Goethem, Van Dingenen, & Huijbregts, 2016)
TRACI 2.1	M	O ₃ equivalent	North America and Mexico			Maximum Incremental Reactivity (MIR) scale	Sphera LCA Database Modelling Principles 2024
EF 3.1	M	Kg NMVOC- eq. per kg	Europe	NO _x , NMVOC,	Human health	LOTOS- EUROS model	(Van Zelm R. , et al., 2008)
LIME	M,E	Kg ethylene eq. Into air per kg emitted	Japan	NO _x , NMVOC, POCP- factors	Human health, crops, wood and primary production		(Hayashi, Okazaki, Itsubo, & Inaba, 2004)

As shown in the table above, the methods use different reference unit to measure POCP, consider different groups of chemicals and utilize different underlying models. These differences result in large variation in POCP values. This is also evident in the study conducted by Joseph, B et al., 2024 to assess the POCP during composting using three methodologies: ReCiPe, EF 3.0 and IMPACT WORLD+ as depicted in Figure 25.

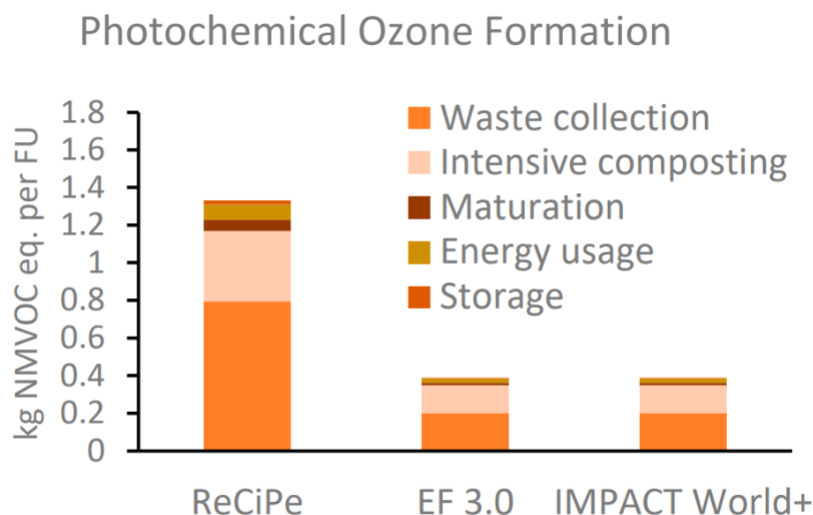


Figure 25: Comparison of photochemical ozone formation values (in kg NMVOC eq.) between the three methods: ReCiPe, EF 3.0 and IMPACT World+. (Joseph & Stichnothe, 2024)

Figure 26 highlights that the ReCiPe 2016 method yields the highest POCP value, while EF 3.0 and IMPACT WORLD+ methodologies results in a 76% lower value. As mentioned above, this is due to the differences in the characterization models used by the three methodologies. While LOTOS-EUROS model is used by EF 3.0 and IMPACT WORLD+ to characterize the impact of photochemical ozone formation, ReCiPe 2016 method uses global source-receptor model TM5-FASST. As a result, the coverage of the POCP causing substances has also varied. For instance, ReCiPe 2016 covers overall 134 substances, compared with 65 in EF 3.0 and 104 in IMPACT World+. Specifically looking at the individual NMVOC emissions, ReCiPe 2016 method covers nine ozone-forming substances compared to EF 3.0 and IMPACT World+, which covered only five and four substances, respectively.

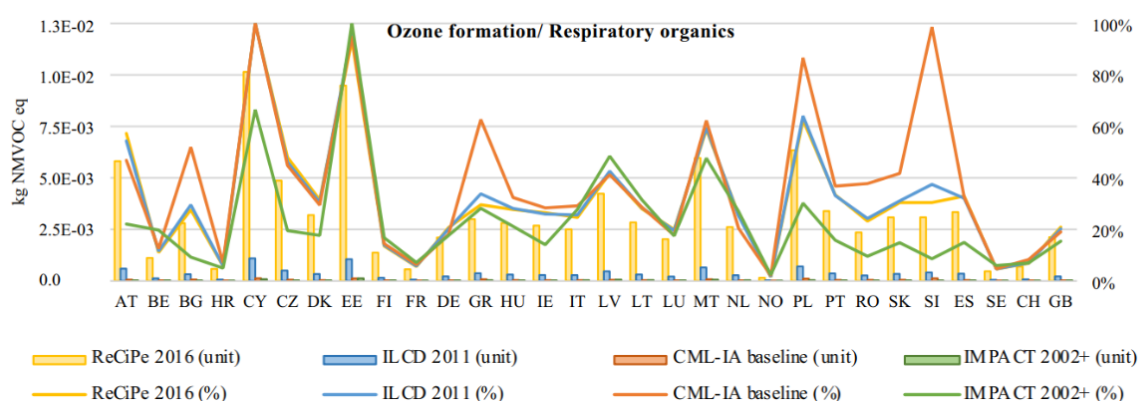


Figure 26: Comparison of photochemical ozone formation values (in kg NMVOC eq.) between the four methods: ReCiPe 2016, ILCD 2011, CML-IA baseline and IMPACT 2002+. (Rybczewska-Błażejowska & Jezierski, 2016)

Similar conclusion was also drawn by Rybczewska-Błażejowska and Jezierski (2024) where results from ReCiPe 2016, ILCD 2011, CML-IA baseline and IMPACT 2002+ were compared for

POCP at midpoint level of the electricity consumption mix across European countries (Rybaczewska-Błazejowska & Jezierski, 2016). Figure 26 clearly presents the visible trend across the European countries, with ILCD 2011, CML-IA baseline and IMPACT 2002+ methods showing ~90% lower value on average in comparison to ReCiPe 2016.

Not for review

21.8. Particulate Matter

Methodological approaches consider different approaches on how Disease Incidence is measured:

- **Epidemiological Data:** Measurement begins with the use of epidemiological studies that track the rates of diseases, such as respiratory or cardiovascular illnesses known to be associated with particulate matter exposure. These studies help establish baseline incidence rates in the general population (Pope, et al., 2002).
- **Exposure Assessment:** Advanced models estimate population exposure based on geographic proximity to emission sources, concentration of particulates in the air, and demographic factors (Fantke, et al., 2016).
- **Attribution of Cases:** Using dose-response relationships derived from epidemiological research, the EF method attributes a portion of disease incidence directly to particulate matter emissions. This involves calculating the increase in disease cases per kilogram of PM emitted, accounting for local conditions and population density (Fantke, et al., 2016).

Impact pathway and methodological approaches

The impact pathway describing health effects associated with exposure to $PM_{2.5}$ originating from emissions of primary particles or from secondary $PM_{2.5}$ precursors (gaseous substances) that are converted to $PM_{2.5}$ through oxidation builds on the general LCIA framework for air pollutant characterization developed by (De Haes, et al., 2002; Jolliet, et al., 2004), as shown in Figure 27. In this framework, the assessment of $PM_{2.5}$ -related health impacts begin with emissions of primary $PM_{2.5}$ or $PM_{2.5}$ -forming precursors into indoor or outdoor air, quantified as the mass released to the atmosphere. These emissions undergo transport and transformation processes within and between indoor and outdoor environments, as well as across urban and rural areas, resulting in a time-integrated $PM_{2.5}$ mass or concentration in air. A share of this accumulated $PM_{2.5}$ is inhaled by the exposed population, leading to an aggregated population-level health risk that can be expressed in terms of expected disease cases. In many applications, this cumulative risk is estimated directly from $PM_{2.5}$ air concentrations, assuming inhalation by the exposed population. Unlike numerous organic substances considered in LCIA, which are often modeled using linear dose-response relationships, $PM_{2.5}$ exhibits well-documented non-linear exposure-response relationships for key health outcomes. In the final step of the impact assessment as outlined in Figure 27, the estimated disease incidences are converted into damage indicators for the affected population by taking disease severity into account (Fantke, et al., 2016).

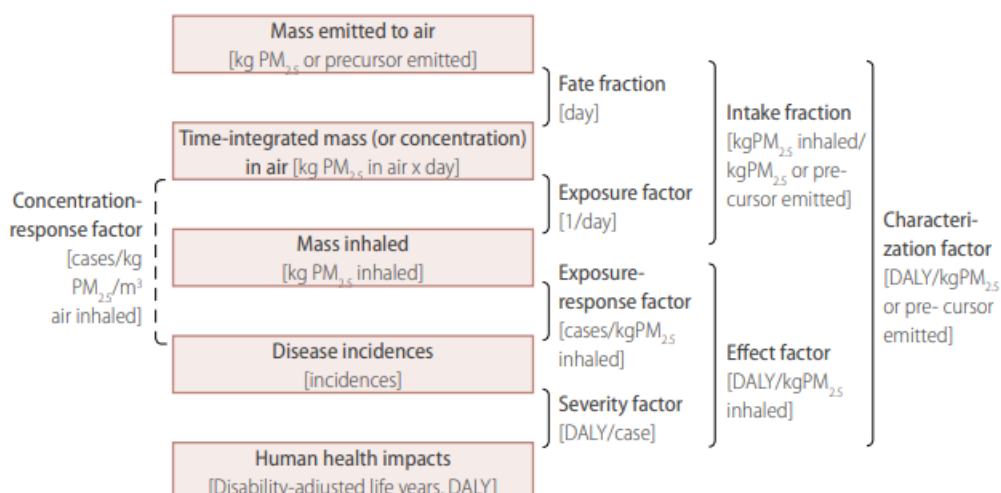


Figure 27: Impact pathway followed for assessing human health effects from particulate matter (PM) (Fantke, et al., 2016)

The PM score in EF 3.1 (Zampori & Pant, 2019) is calculated by characterizing emissions based on a disease incidence model. It quantifies the results as “disease incidence” due to the emissions of PM, focusing solely on human health effects from exposure to primary and secondary PM. It does not include ecosystem damage or climate change mechanisms within this category.

For the PM impact category, the calculation uses characterization factors (CF) for different substances, multiplying each substance's emission by its specific factor to represent its relative contribution to disease incidence.

Additional information on emission factors and characterization factors:

These factors are used to calculate PM emissions and are compiled by organizations like the U.S. EPA (EPA, 2026). Emission factors are specific to the source, pollutant, and activity, such as PM₁₀ or PM_{2.5} from burning different types of fuel or from animal feeding operations.

- **Pollutant-specific:** Emission factors are specific to the type of particulate matter being measured, such as PM₁₀ (inhalable particles) or PM_{2.5} (fine inhalable particles).
- **Activity-specific:** They are tied to the activity causing the emission, such as burning fuel, operating a boiler, or a specific agricultural activity.
- **Representative averages:** Emission factors are typically averages of available data and represent a population average for a source category, meaning roughly half of the real-world sources will have higher emissions and half will have lower emissions than the factor.
- **Source of factors:** Emission factors are compiled from various data sources, including source tests, material balance studies, and engineering estimates.
- **Vary by source:** Factors vary significantly depending on the source category. For example, the PM emission factor for a dairy facility will be different from that of a natural gas combustion unit.

Examples of emission factors

- **Fuel combustion:** The (Kansas Department of Health and Environment, 2026) provides examples like 1 pound of PM₁₀ per 1,000 gallons of fuel, and 0.25 pounds of PM_{2.5} per 1,000 gallons of fuel.
- **Animal feeding operations:** A study identified PM_{2.5} emission factors of 0.84kg per 1,000 animal days for a dairy and 8.09kg per 1,000 animal days for a feedlot during the summer.

The general approach for calculating the Air Quality Index (AQI) (EPA, 2026) for PM involves

1. Calculating a sub-index for PM based on its concentration using segmented linear functions,
 2. calculating other sub-indices for pollutants like ozone and nitrogen dioxide, and
 3. taking the highest of all the sub-indices as the overall AQI.
- For a more real-time score, the U.S. EPA uses a NowCast calculation, which involves a weighted average of recent PM readings.

The calculation needs to be performed for each sub-index for specific pollutants.

$$I = \frac{I_{hi} - I_{lo}}{BP_{hi} - BP_{lo}} (C - BP_{lo}) + I_{lo}$$

Formula 33: Equation for each sub-index for specific pollutants

Where:

- C is the concentration of the pollutant.
- BP_{hi} and BP_{lo} are the breakpoint concentrations that the value falls between.
- I_{hi} and I_{lo} are the AQI values corresponding to those breakpoints.

Calculate for all pollutants: Repeat this process for each pollutant (e.g., PM₁₀, O₃, CO, ...).

Take the maximum: The final AQI is the highest of all the individual sub-indices calculated.

Alternative NOWCAST method:

- **Calculate the range:** Find the minimum and maximum PM_{2.5} measurements over the past 12 hours and find the difference (the range).
- **Calculate the scaled rate of change:** Divide the range by the maximum measurement.
- **Determine the weight factor:** Subtract the scaled rate of change from 1. If the result is below 0.5, set it to 0.5. This factor must be between 0.5 and 1.
- **Calculate the weighted average:** Multiply each hourly measurement by the weight factor raised to the power of the number of hours ago it was measured. Then, sum these products and divide by the sum of the weight factor raised to the corresponding power for each hour.
- **Convert to AQI:** Use a concentration-to-AQI converter (available on the MET ONE website (MET 2026) to get the final score.

- How to Calculate AQI and NowCast Indices

21.9. Ionising radiation (human health)

Impact pathway and methodological approaches

The method proposed by Frischknecht *et al.* (Frischknecht, Braunschweig, Hofstetter, & Suter, 2000) (Figure 28) starts with releases at the point of emission, expressed as Becquerel (Bq), and calculates the radiative fate and exposure, based on detailed nuclear physics knowledge. The fate and exposure analysis are generalized from site-specific modelling of the French nuclear fuel cycle within the ExternE (“Externalities of Energy”) project, covering routine atmospheric and liquid discharges from all steps of the cycle (Dreicer, Tort, & Manen, 1995).

For human toxicity, the exposure analysis calculates the dose that a human actually absorbs, given the radiation levels that are calculated in the fate analysis. The measure for the effective dose is the Sievert (Sv), based on human body equivalence factors for the different ionising radiation types (α -radiation, neutrons: 1 Sv = 1 J/kg body weight). Data expressed in Sievert includes physical data on energy doses and biological data on the sensitivities of different body tissues. Man Sievert (Man-Sv) is the collective dose, calculated by multiplying the average individual dose representative of the population, by the number of people affected and integrating it over a specified time horizon. An intermediate stage in the calculations of doses is often expressed as Gray (Gy). This is the measure of absorbed dose without considering the different reaction types of body tissues. Impact pathways followed for assessing human health effects from ionising radiation are shown in Figure 28.

The following terms and units are used in the modelling:

- **Becquerel (Bq)** is the unit for measuring radioactive decay: 1 Bq is equivalent to one radioactive decay per second. Becquerel is a measure at the point of emission.
- **Gray (Gy)** is the measure of absorbed dose, not considering the different reaction types of body tissues. It is the energy absorbed per unit mass of the irradiated material (1 Gy = 1 J/kg mass) and is the fundamental dosimetric quantity in radiological protection.
- **Sievert (Sv)** is the unit for measuring the effective dose, based on human body equivalence factors for the different ionising radiation types (α -, β -, γ - radiation; neutrons). 1 Sv = 1 J/kg body weight. Sievert is a measure at the point of emission. Sv contains physical data on energy doses and biological data on the sensitivities of different body tissues. It is also used to quantify the committed effective dose (effective dose integrated over 50 years) and of the average individual dose (committed effective dose received by an average individual).
- **Man Sievert (man.Sv)** is the collective dose, calculated by multiplying the average individual dose representative of the population by the number of people affected and integrating it over a specified time horizon.

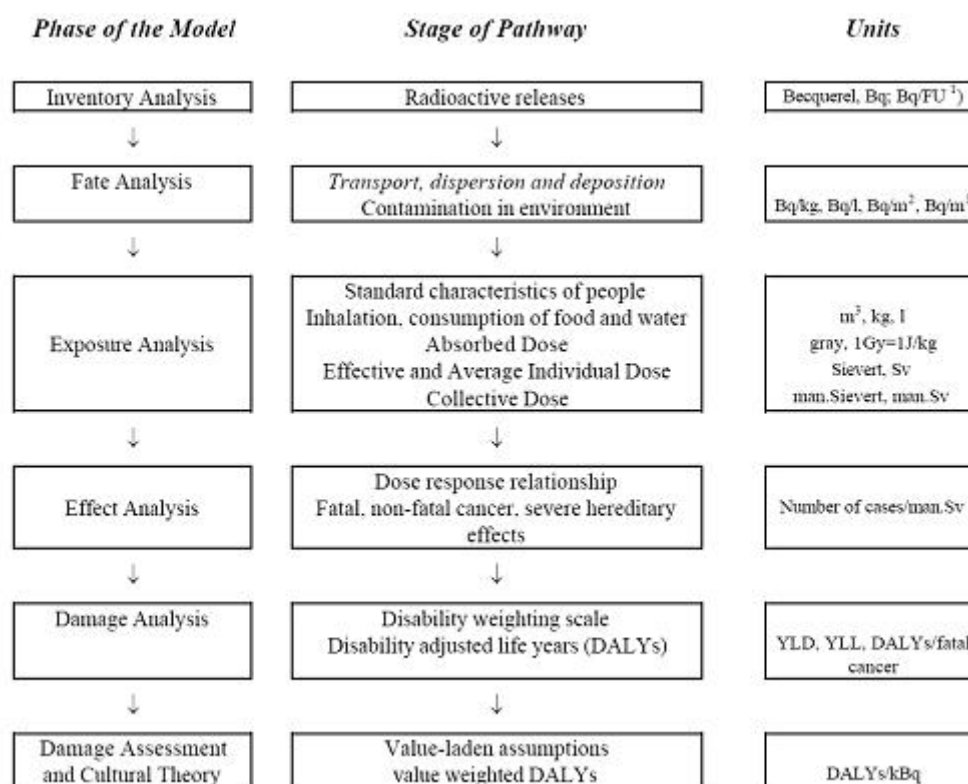


Figure 28: Impact pathway followed for assessing human health effects from ionising radiation (IR) (Frischknecht, Braunschweig, Hofstetter, & Suter, 2000).

21.10. USEtox for Human Toxicity assessment in LCA

Detailed Formula Derivation for Characterization factors can be found in the Annex 21.12

The CTU_h (Fantke, et al., 2017) calculation can be derived from the impact pathway logic used in USEtox: an emitted mass is distributed in the environment, a fraction of that mass reaches humans through exposure routes, and the resulting intake is translated into expected health effects. The derivation below uses generic notation and is intended to explain the calculation structure rather than reproduce all model-specific matrix equations.

Step 1: Start from the inventory emission. For substance *x* emitted to compartment *c*, the life cycle inventory provides the emitted mass per functional unit:

$$m_{x,c} \text{ [kg/FU]}$$

Step 2: Calculate the time-integrated environmental mass using the fate factor. USEtox estimates how long and where the chemical remains in the multimedia environment. For an emission to compartment *c* and a receiving or intermediate compartment *i*:

$$M_{x,i}^{\text{int}} = m_{x,c} \times FF_{x,c \rightarrow i}$$

- $M_{x,i}^{\text{int}}$ = time-integrated mass or presence of substance *x* in receiving compartment *i*.
- $FF_{x,c \rightarrow i}$ = fate factor linking emission to compartment *c* with persistence and distribution in compartment *i*.

In the full USEtox model, fate is represented by multimedia mass-balance relationships that account for partitioning, degradation, intermedia transport and removal. Conceptually, the fate factor is the proportionality term that converts a unit emission into time-integrated chemical presence in relevant compartments.

Step 3: Translate environmental presence into human intake using exposure factors. For exposure route r , such as inhalation, drinking water or food ingestion, the intake caused by the time-integrated environmental presence is:

$$I_{x,c,i,r} = m_{x,c} \times FF_{x,c \rightarrow i} \times XF_{x,i,r}$$

Where

- $I_{x,c,i,r}$ = human intake of substance x via route r after emission to compartment c .
- $XF_{x,i,r}$ = exposure factor translating chemical presence in compartment i into human intake through route r .

The product of fate and exposure is commonly summarized as the intake fraction:

$$iF_{x,c,r} = \sum_i FF_{x,c \rightarrow i} \times XF_{x,i,r}$$

Thus, total intake across compartments and routes can be written as:

$$I_{x,c} = m_{x,c} \times \sum_{i,r} FF_{x,c \rightarrow i} \times XF_{x,i,r} = m_{x,c} \times iF_{x,c}$$

Step 4: Convert intake into expected human health effect using the effect factor. The effect factor expresses the expected number of disease cases per unit intake:

$$E_{x,c} = I_{x,c} \times EF_x$$

Where

- $E_{x,c}$ = expected human toxicity effect for substance x emitted to compartment c , expressed in disease cases per functional unit.
- EF_x = human effect factor, expressed as disease cases per kg intake, derived from dose-response information.

Substituting the intake expression gives:

$$E_{x,c} = m_{x,c} \times \sum_{i,r} FF_{x,c \rightarrow i} \times XF_{x,i,r} \times EF_{x,r}$$

Step 5: Define the characterization factor. The term multiplying the emitted mass is the USEtox human toxicity characterization factor:

$$CF_{x,c} = \sum_{i,r} FF_{x,c \rightarrow i} \times XF_{x,i,r} \times EF_{x,r}$$

Step 6: Aggregate across all inventory flows. The total human toxicity midpoint score for the product system is obtained by summing all substance- and compartment-specific results:

$$CTU_{h,total} = \sum_{x,c} m_{x,c} \times CF_{x,c} = \sum_{x,c} m_{x,c} \times \sum_{i,r} FF_{x,c \rightarrow i} \times XF_{x,i,r} \times EF_{x,r}$$

Step 7: Optional endpoint derivation. If the analysis proceeds from midpoint to endpoint, the disease-case midpoint result may be multiplied by a severity factor:

$$\text{DALY}_{\text{total}} = \text{CTUh}_{\text{total}} \times \text{SF}$$

Here, SF is a severity factor expressed as DALY per disease case. This endpoint conversion is optional and adds additional assumptions about disease severity and duration. Endpoint calculations are not applied in this context of the document.

Table 57: Input factors for CTUh calculation in USEtox assessments

Derivation Term	Interpretation	Typical Unit
$m_{x,c}$	Mass of substance x emitted to compartment c per functional unit.	kg/FU
$\text{FF}_{x,c \rightarrow i}$	Time-integrated environmental presence in compartment i per kg emitted to compartment c.	kg·day/kg emitted or equivalent fate unit
$\text{XF}_{x,i,r}$	Human intake via route r per time-integrated environmental presence in compartment i.	kg intake/(kg·day) or equivalent exposure unit
$i\text{F}_{x,c}$	Fraction of emitted mass eventually taken in by humans across compartments and exposure routes.	kg intake/kg emitted
$\text{EF}_{x,r}$	Expected human health effect per kg intake via route r.	cases/kg intake
$\text{CF}_{x,c}$	Human toxicity characterization factor for substance x emitted to compartment c.	CTUh/kg emitted
$\text{CTUh}_{\text{total}}$	Total comparative toxic units for humans per functional unit.	CTUh/FU

Compact derivation: emission mass → time-integrated environmental presence → human intake → disease cases. In formula form: $m \times \text{FF}$ gives environmental presence; $m \times \text{FF} \times \text{XF}$ gives intake; $m \times \text{FF} \times \text{XF} \times \text{EF}$ gives CTUh. Summing over substances, emission compartments, receiving compartments and exposure routes gives the total CTUh result for the functional unit. Table 57 summarizes the data needed for a CTUh calculation.

21.11. ProScale for Human Toxicity assessment in LCA

21.11.1. General principles

ProScale (ProScale 2017) links chemical hazard with exposure conditions and mass flows, it can support product design, supplier engagement, material selection, safe and sustainable-by-design assessments, procurement decisions and chemical footprinting (Holmquist, et al., 2021) (Saling, Gelder, & Krüger, 2019). This makes it suitable for industries that may not have deep toxicological modelling expertise but do have access to safety data sheets, classification data, and use descriptions and process information (Lexen, 2021).

ProScale is not only relevant for chemical producers. Many other sectors use chemicals in products, materials, cleaning operations, coatings, electronics, construction products, textiles, packaging, agriculture, energy technologies and consumer goods. These industries also need to understand where hazardous substances create direct exposure potentials along the life cycle and where improvements can be made.

USEtox and ProScale should not be seen as direct substitutes in all cases. USEtox remains highly relevant when the objective is to quantify potential human toxicity and ecotoxicity impacts from emissions within a conventional LCA framework. ProScale uses the common approach of chemical industry when risks of chemicals to humans are evaluated. Based on the systematic of risk assessments, ProScale addresses human tox impacts. The objective is to assess and compare chemical exposure potentials in industrially realistic product systems, especially where direct human exposure, process conditions and risk management measures are decisive. This information can be used in LCA as well and harmonizes risk assessment work done for chemicals with LCA for consistent results in EF3.1 but as well in Safe and Sustainable by Design (SSbD) approaches of the EU commission. Based on this approach, data are generated to compare different products in an LCA. ProScale can be used in LCA following the mass flows of inputs and outputs and link them in the impact assessment with the ProScale results.

ProScale is a life-cycle-oriented method for assessing direct human toxicity potential associated with chemicals in product systems. It complements conventional life cycle assessment methods that mainly address indirect human toxicity from environmental emissions by focusing on near-field exposure of workers, professionals and consumers along the value chain. It was developed by a consortium of chemical companies together with IVL (IVL, 2026).

- **Life cycle thinking:** The assessment follows the product system and functional unit used in LCA, covering relevant unit processes from raw material extraction to production, use and, where relevant, end-of-life.
- **Hazard and exposure combined:** ProScale is risk-oriented rather than purely hazard-based. It combines intrinsic hazard with modelled exposure potential, time of exposure and substance mass flow.
- **Route-specific assessment:** Scores are calculated separately for inhalation, dermal and oral exposure routes where relevant.
- **Process specificity:** Exposure is linked to process conditions, operational controls, substance properties and use patterns.
- **Aggregation:** Chemical-level and process-level scores can be summed to obtain a product-system score for a functional unit.

- **Compatibility with LCA:** Results can be used alongside LCA indicators, Environmental Product Declarations, Product Environmental Footprints and Safe and Sustainable by Design assessments.

21.11.2. Procedure and workflow

The following text describes the workflow that is needed for the preparation of ProScale results including guardrails and assessment approaches (Rydberg, 2023).

1. **Define goal and scope:** Use the functional unit, system boundaries, life cycle stages, target audience, intended comparison and exposure routes to be considered as outlined for other environmental impact categories.
2. **Map the product system:** Identify all relevant unit processes and chemicals used, formed, emitted or present in mixtures during the life cycle.
3. **Collect substance hazard data:** Compile harmonised or self-classified GHS/CLP hazard statements, occupational exposure limits, derived no-effect levels or equivalent acceptable exposure levels.
4. **Assign the Hazard Factor:** Convert route-specific hazard information and potency information into a Hazard Factor.
5. **Model exposure:** Estimate exposure concentrations using ECETOC TRA or an equivalent tiered exposure model, applying process categories, substance properties, operational conditions and risk management measures.
6. **Determine person-hours:** Estimate the number of exposed person-hours per unit output of each process. In Chem X there was a list defined for the harmonized use of PHF, see Table 60.
7. **Determine mass flows:** Use the amount of each substance required per functional unit in each process.
8. **Calculate route-specific scores:** Multiply the four factors for each substance, process and exposure route.
9. **Aggregate and interpret:** Sum scores across substances and processes, identify hotspots, compare alternatives and document assumptions and uncertainties.

21.11.3. Procedural guardrails

For a meaningful calculation of ProScale results, some procedural guardrails were defined. The method is very flexible and can calculate many different types of products. For a harmonization in the Chem X context, these guardrails are helpful.

- **Avoid hazard-only conclusions:** A high hazard classification alone does not determine the ProScale result; exposure potential, person-hours and mass flow are also decisive.
- **Keep exposure route separation:** Do not combine inhalation, dermal and oral scores unless a clearly defined aggregation or weighting approach is used.
- **Use authoritative hazard data:** Prefer harmonised CLP classifications, REACH registration data, safety data sheets, DNELs and legally established OELs, documenting the hierarchy applied.
- **Respect applicability domains:** ECETOC TRA-style modelling is most appropriate for defined occupational, professional or consumer use conditions; special cases may require expert review.

- Document risk management measures:** Ventilation, containment, personal protective equipment, duration, concentration and process category assumptions should be transparent. In Chem X, risk management measures were defined for harmonization purposes. ProScale offers four levels of Local Exhaust Ventilation (LEV) influencing the inhalative pathway of toxic substances:
 - No,
 - Indoors with Local Exhaust Ventilation (LEV),
 - Indoors with Local Exhaust Ventilation (LEV) and good general ventilation,
 - Indoors with Local Exhaust Ventilation (LEV) and enhanced general ventilation.
 As proxy, Indoors with Local Exhaust Ventilation (LEV) is recommended to be used. In specific situations and with additional knowledge of the processes, other risk management measures may be applied.
- In addition,** ProScale offers four levels of dermal protection of workers influencing the dermal pathway of toxic substances:
 - No,
 - Gloves APF 5
 - Gloves APF 10
 - Gloves APF 20
- Do not interpret scores as actual disease cases:** ProScale provides comparative toxicity potential scores, not epidemiological incidence, absolute risk or regulatory compliance proof.
- Check data quality and sensitivity:** Identify dominant assumptions and test the influence of uncertain hazard factors, exposure estimates, person-hours and mass flows.

An overview of the elements of the assessment approach is given in Table 58.

Table 58: Summary of important key elements of ProScale assessments.

Assessment approach	Description	Typical use
Screening assessment	Uses readily available classifications, default exposure assumptions and generic person-hour factors.	Early hotspot identification, portfolio screening, data-gap prioritization.
Process-specific assessment	Uses process category, operational conditions, concentration, duration, ventilation, containment and risk management measures.	Product comparisons, improvement studies, internal decision support.
Route-specific assessment	Calculates separate scores for inhalation, dermal and oral exposure.	Identifying dominant exposure pathways and targeted risk reduction options.

Life-cycle aggregation	Sums substance-process-route scores across the product system per functional unit.	LCA integration, EPD or PEF-type communication, alternative comparison.
Hotspot and contribution analysis	Ranks contributions by substance, process, exposure route or life cycle stage.	Design of safer alternatives, supplier engagement, process optimization.

21.11.4. Core formulas

ProScale uses several formulas to calculate results, to aggregate results, and to support interpretation. The following text describes relevant formulas and their use.

The basic ProScale score for a substance in a unit process and exposure route is calculated as:

$$PSS_{s,p,r} = HF_{s,r} \times ECF_{s,p,r} \times PHF_p \times MF_{s,p}$$

Formula 34: Equation for “human toxicity” calculation in ProScale

Where:

- PSS: the ProScale Score,
- S: substance,
- P: unit process, usually open mixing, closed dosing, spraying, cleaning, formulation, use phase
- R: exposure route, usually inhalation, dermal, or oral exposure
- HF: Hazard Factor,
- ECF: Exposure Concentration Factor,
- PHF: Person-Hours Factor and
- MF: Mass Flow per functional unit

The route-specific score for a product system is calculated by summing all substance-process contributions. If all exposure routes are reported together, the aggregation should remain transparent:

$$PSS_{\text{product,total}} = \sum_r PSS_{\text{product},r}$$

Formula 35: Equation for aggregation of all exposure routes in ProScale

For contribution analysis, the share of a substance, process or route can be calculated as:

$$\text{Contribution (\%)} = PSS_i / PSS_{\text{product}} \times 100$$

Formula 36: Equation for the identification of a product result contribution compared to the overall result

In this sense the following definitions apply:

Hazard Factor: $HF_{s,r}$

The Hazard Factor represents the intrinsic toxicological concern of a substance for a specific exposure route.

It answers:

How severe or potent is the substance if exposure occurs by this route?

Typical inputs include:

- GHS/CLP hazard classifications
- H-statements
- route-specific toxicity information
- DNELs, OELs, or comparable threshold values
- chronic versus acute effects
- systemic versus local effects

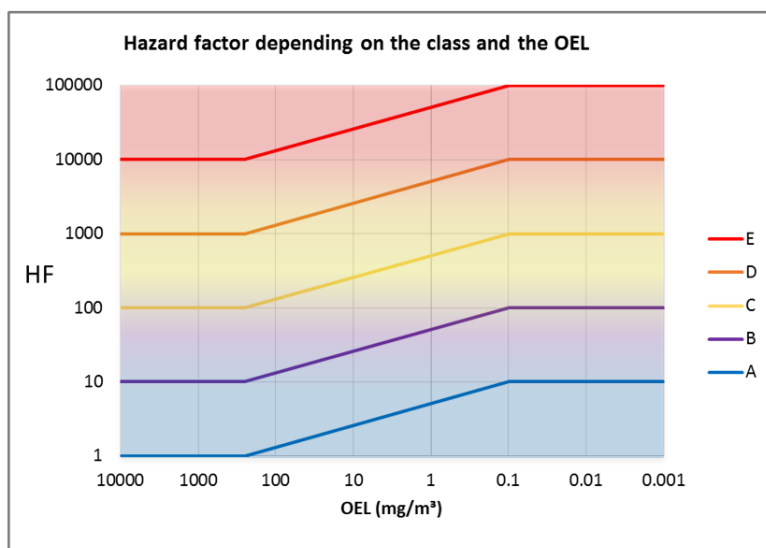
A higher HF means a substance is more hazardous or potent for that route.

Example:

- A carcinogenic volatile solvent may receive high inhalation HF.
- A low-toxicity additive may receive much lower HF.

The important point is that HF is route specific. A substance may have a high inhalation hazard but a lower dermal hazard, or vice versa.

In ProScale a scaling approach was developed, where H-phrases are linked with a numeric score. The classes defined have no overlap, the position of a substance in this scheme can be influenced by the DNEL getting in every band a lower number of a factor of 10 at max. With the influence of DNEL the classes cannot be switched.



- ➔ Unknown OEL => the ProScale Hazard Factor = =maximum of the class
- ➔ No H-phrase , but identified OEL or DNEL => Hazard class A
- ➔ No H-phrase and No OEL/DNEL => Hazard Factor "0".

Figure 29: Hazard classifications of H-phrases to numerical numbers and visualization of the influence of OEL/DNEL

H-phrases

classification

- ➔ H-phrases have been grouped in five ProScale hazard classes
- ➔ The H-phrase class of a substance is established separately for each exposure route
- ➔ The H-phrase that corresponds to the highest class is determining the class for a substance
- ➔ EUH specific H-phrase have been added (for EU only)

ProScale Hazard class	H-phrases according to GHS/CLP, grouped by exposure route
E 10 000 - 100 000 (highest hazard)	All routes : H340, H350, H360, H362
D 1000 - 10 000	Dermal : H310 Inhalation : H330, H334, EUH032 Oral : H300, All routes : H341, H351, H361, H372
C 100 - 1000	Dermal : H311, H314, H317, H318, EUH070 Inhalation : H331, EUH029, EUH031, EUH071 Oral : H301, H304 All routes : H370, H373
B 10 - 100	Dermal : H312, H315, H319, Inhalation : H332, H335 Oral : H302 All routes : H371
A 1 - 10 (lowest hazard)	Dermal : H313, H316, H320, EUH066 Inhalation : H333, H336 Oral : H303, H305,

Figure 30: Hazard classifications of H-phrases to ProScale Hazard classes and H-phrases

Exposure Concentration Factor: $ECF_{sp,r}$

The Exposure Concentration Factor represents the relative exposure potential for a substance in a specific process and route.

It answers:

Under the defined process conditions, how much exposure could occur?

Typical inputs include:

- physical state: gas, liquid, powder, solid
- vapor pressure

- dustiness
- concentration in the mixture
- process category
- temperature
- duration of handling
- open versus closed process
- ventilation
- containment
- personal protective equipment
- local exhaust ventilation
- consumer or professional use conditions

A higher ECF means the process creates a higher potential exposure.

Example:

- Open mixing of a volatile solvent may have a high inhalation ECF.
- Closed transfer with local exhaust ventilation may have a lower ECF.
- A dusty powder may have a relevant inhalation ECF.
- A non-volatile liquid in a closed system may have a low inhalation ECF.

The ECF is process-specific and route-specific, because the same substance can have very different exposure potentials depending on how it is used.

Person-Hours Factor: PHF_p

The Person-Hours Factor represents the amount of exposed human time allocated to one functional unit.

It answers:

How many person-hours of exposure are associated with producing or using one functional unit?

A simplified expression is:

$$PHF_p = \frac{N_p \times t_p}{Q_p}$$

Formula 37: Equation for “person hour factor” calculation in ProScale

Where:

- N_p = number of exposed persons in process p

- t_p = exposure time during the process
- Q_p = process output linked to the functional unit

Example:

If 2 workers are exposed for 1 hour while producing 100 functional units:

$$PHF_p = \frac{2 \times 1}{100} = 0.02 \text{ person-hours per FU}$$

Formula 38: Equation for “person hour factor” calculation of an example in ProScale

The PHF ensures that a brief, automated process is not treated the same as a labor-intensive process with long exposure duration.

Mass Flow: $MF_{s,p}$

The Mass Flow represents the amount of substance used, handled, or present in the process per functional unit.

It answers:

How much of the substance is associated with the functional unit?

A simplified expression is:

$$MF_{s,p} = m_{s,p} \text{ per FU}$$

Formula 39: Equation for “mass flow” calculation in ProScale

Where:

- $m_{s,p}$ = mass of substance used or present in process p
- FU = functional unit

For mixtures, the substance mass can be calculated as:

$$MF_{s,p} = MF_{mixture,p} \times c_s$$

Where:

- $MF_{mixture,p}$ = mass of the mixture per functional unit
- c_s = concentration or mass fraction of substance s in the mixture

Example:

If 2 kg of a mixture is used per functional unit and the substance concentration is 5%:

$$MF_{s,p} = 2 \times 0.05 = 0.10 \text{ kg/FU}$$

Formula 40: Equation for “mass flow” calculation example in ProScale

Mass flow is important because even a highly hazardous substance may contribute little if used in very small quantities, whereas a moderately hazardous substance may contribute strongly if used in large amounts.

Product-system score for one route

To calculate the overall scores in ProScale, the following formula applies:

$$PSS_{product,r} = \sum_p \sum_s H F_{s,r} \times ECF_{s,p,r} \times PHF_p \times MF_{s,p}$$

Formula 41: Equation for “Product System Score” in ProScale including HF, ECF, PHF and MF

This formula sums all individual substance-process scores for one exposure route.

It answers:

What is the total ProScale score for the product system via one exposure route?

For example, the inhalation score of a product system is obtained by summing:

- all substances
- in all relevant processes
- for the inhalation route

This allows hotspot analysis by:

- substance
- process
- life cycle stage
- exposure route
- supplier process
- improvement measure

Total product score across routes

$$PSS_{product,total} = \sum_r PSS_{product,r}$$

Formula 42: Equation for “Product System Score” in ProScale including different single results of PSS depending on the exposure route

This formula sums the route-specific product scores.

It answers:

What is the total ProScale score across all considered exposure routes?

For example:

$$PSS_{product,total} = PSS_{product,inh} + PSS_{product,derm} + PSS_{product,oral}$$

Formula 43: Equation for “Product System Score” in ProScale showing different single results of PSS depending on the exposure route

However, this aggregation should be handled carefully because inhalation, dermal, and oral exposure may differ in toxicological relevance, data quality, and modelling assumptions.

A good practice is to report route-specific results separately and only then provide an aggregated total.

21.11.5. Data needs and data generation

Meaningful data information is the foundation for calculation. The data will be transferred to the calculation tool and can be automatically processed, if they are in the right format and containing the required information. Table 59 summarizes the data needs.

Table 59: Overview of data input needed for ProScale including proposals for the use and further explanations behind the terms.

Data category	Examples	Purpose in ProScale
Substance identity	CAS number, EC number, substance name, mixture composition, concentration range.	Links chemical inventory to hazard, exposure and mass-flow data.
Hazard data	GHS/CLP H-statements, harmonized classifications, self-classifications, specific concentration limits.	Derives the Hazard Factor by exposure route.
Potency or acceptable exposure data	OELs, DNELs, derived acceptable levels, route-specific thresholds.	Refines hazard potency and supports route-specific scoring.
Physicochemical data	Vapour pressure, physical state, dustiness, molecular weight, water solubility where relevant.	Supports exposure modelling, especially inhalation and dermal exposure.
Process information	PROC category, operational temperature, duration, containment, ventilation, concentration in mixture, frequency of use.	Defines the Exposure Concentration Factor.
Risk management measures	Local exhaust ventilation, closed systems, gloves, respiratory protection, automation.	Adjusts modelled exposure potential.
Person-hour data	Number of workers, task duration, shift pattern, exposed population, output per time.	Determines the Person-Hours Factor.
Mass-flow data	Input amount per unit process, yield, concentration, losses, amount per functional unit.	Determines the Mass Flow and links the score to the functional unit.
Life cycle inventory data	Bill of materials, process flows, supplier data, use-stage quantities, recycling or disposal flows.	Enables aggregation across the product system.

The Person Hour factor can be generated from primary data, from statistics or other sources. They can be determined per specific product or factors out of the list as shown in Table 60 can be used as proxy figures.

Table 60: Overview of Person hour factors as averages from different productions

Person Hours Factors for industrial processes		
Type of production process	Working time (hr/ FTE*yr)	Person hour per kg (hr/kg)
Organic commodity chemicals manufacturing, large to medium size chemical plant		
Refinery, very large chemical plant	2000	1,57E-04
Naphtha cracker	2000	1,00E-03
Organic commodity chemicals manufacturing, small to medium size chemical plant		
Production of goods as lubricants, plasticizers, intermediates, etc.	2000	2,67E-03
Inorganic chemicals manufacturing, large to medium size chemical plant		
Inorganic production	2000	2,67E-03
Fine/specialty chemicals manufacturing, small to medium size chemical plant		
Manufacturing of fine organic chemicals such as pigments and dyes, flame retardants, plasticisers such as phtalate esters, pharmaceuticals etc	2000	3,39E-02
Plastics manufacturing		
Polymer manufacturing	2000	2,84E-03
Plastics processing		
Plastics extrusion etc	2000	1,28E-02
Mixing and blending batch processes, such as paint manufacturing		
Paint and varnish production	2000	3,43E-02
Waste management		
Incineration of municipal solid waste	2000	2,80E-04

To support the generation of data that is needed in the ProScale methodology, there were some testing initiatives initiated by the Chem X project partners. In this testing phase a prompt was developed to be used in AI search for relevant information. With the examples included in this prompt, harmonized data inputs were found by several testers.

The prompt is defined as the following. The products in the prompt are examples and must be replaced by those products a ProScale result is requested to be calculated.

Start the prompt

Substance 1: Benzene,

Substance 2: Ethanol,

Substance 3: Bisphenol A

For the following chemicals — Substance 1, Substance 2, Substance 3 — research and compile the following data fields for each chemical, strictly aligned with ECHA registered data (CLP Annex VI harmonised classifications, REACH dossiers, CMD Directive):

- **CAS number**
- **H-phrases** (harmonised, CLP Annex VI only)
- **OEL** (EU binding or indicative occupational exposure limit, 8h-TWA; include national values such as DE MAK or UK WEL where no EU harmonised OEL exists)
- **DNEL** (worker inhalation long-term systemic and general population inhalation long-term; sourced from ECHA dossiers / ECETOC / DECOS where available)
- **Vapour pressure** at 25 °C (in Pa)
- **Production process type** (e.g., petrochemical refining, fermentation, condensation reaction, agrochemical formulation)
- **Fugacity class** (dominant environmental compartment: air, water, soil/sediment, or reactive — based on Mackay Level I partitioning)
- **Typical risk management measures** (LEV, PPE, substitution requirements, regulatory restrictions, waste disposal — aligned with REACH/CLP obligations)

Then perform the following tasks in order:

Step 1 — Build the Product Input table: Convert all compiled data into a single ProScale-ready Excel summary table on one sheet, with one row per chemical and one column per data field listed above. Apply the following formatting:

- Auto-filter enabled on all columns
- Header row frozen (row 1)
- Colour-code cells to flag: ● no EU harmonised OEL, ● DNEL under review or contested (e.g., BPA endocrine disruptor status), and fugacity class colour-coded by dominant compartment (air / water / soil / reactive)
- Include a footer row with source citations and a colour legend

Step 2 — Populate the Calculation sheet and provide an Excel workbook (Benzene_ProScale_ATB2_testing.xlsx) containing a ProScale chemical exposure assessment tool. The Calculation sheet already has Benzene filled in as a fully worked example in column F, covering all manual input rows (CAS number, name, PROC, setting, state of substance, vapour pressure, LEV, respiratory protection, dermal PPE, OEL) and all formula rows (H-phrases lookup, OEL/DNEL lookup, exposure factors, hazard factors, and final ProScale scores for inhalation, dermal, and oral routes).

Using the data compiled in Step 1, fill in the Calculation sheet for the remaining 5 chemicals in columns G through K (Substance 1 → G, BPA → H, Substance 2 → I, Substance 3 → J), following the exact same structure as the Benzene template in column F:

- Populate all manual input rows (green cells) by mapping data from the Product Input table
- Adapt all formula rows from column F — replace every intra-column reference (e.g., F\$10) with the new column letter (e.g., G\$10, H\$10, etc.), leaving all cross-sheet references (e.g., 'HF-Scoring'!\$K\$4) unchanged
- Where specific inputs (e.g., exact PROC number, LEV status, PPE level) are not explicitly listed, infer them from the chemical's physical/hazard properties (state: solid vs. fluid; vapour pressure → volatility class; H-phrases → LEV/PPE requirement) and the supporting sheets in the workbook (H-Phrase-Database, OEL-Database, ECF-Modification, etc.)
- Copy cell formatting (font, fill, border, alignment, number format) from column F to each new column

Step 3 — Validate and deliver:

- Run formula validation across all populated columns — confirm zero errors
- Save the final output as a single Excel file containing both the Product Input summary table and the fully populated Calculation sheet
- Deliver the file ready for immediate use in ProScale assessments

Step 4 - Build the Product Input table in Word

Stop of the prompt

Results coming out from the Prompt research look like the example shown in Table 61. The data were transferred to the ProScale calculation tool and were used to generate the final ProScale scores as shown in Table 62.

Table 61: Prompt results for Benzene used as input information for ProScale calculation.

ProScale Chemical Reference Table ECHA-Aligned Data (CLP Annex VI · REACH Dossiers · CMD Directive) June 2026									
Chemical Name	CAS No.	H-Phrases (CLP Annex VI – harmonised)	OEL (EU, 8h-TWA)	DNEL Worker Inh. LT (mg/m ³)	DNEL Gen. Pop. Inh. LT (mg/m ³)	Vapour Pressure @ 25 °C (Pa)	Production Process Type	Fugacity Class	Risk Management Measures
Benzene	71-43-2	H225; H304; H315; H319; H340; H350; H372	1 ppm = 3.25 mg/m ³ (BOELV, CMD Dir. 2004/37/EC)	0.80 mg/m ³ (0.25 ppm, 8h- TWA; DECOS 2014 / LOA dossier)	0.26 mg/m ³ (24h)	12,690	Petrochemical refining; industrial manufacture; intermediate / solvent	Air dominant (~95% air; Mackay Level I)	LEV (mandatory, CMR); closed systems; RPE half-mask + OV cartridge; nitrile gloves; biological monitoring (S- PMA / TTMA); substitution (SVHC / Annex XIV); waste incineration

Table 62: ProScale calculation and results derived from data from prompt search and integration into ProScale calculation tool.

OS	Dermal Exposure	Dermal Personal Protective Equipment (PPE)		Gloves APF 5
		Final Dermal Exposure	mg/(kgBW*day)	6,86E-03
	Oral Exposure	Final Oral Exposure	mg/(kgBW*day)	
		Inhalative	-	1,18E-01
	Exposure Concentration Factors	Dermal	-	1,34E-06
		Oral (consumer only)	-	0,00E+00
HE	Existing OEL in sheet 'List OELs'?			no
	If no, enter OEL manually or leave empty to use default value (1E-3)			
	OEL => Hazard Factors modification: green: lower bound orange: log-lin interp. between low/high red: upper bound		mg/m³	1,0E-03
	Hazard Factors	Inhalative	-	1,00E+05
		Dermal	-	1,00E+05
		Oral	-	1,00E+05
PS	Total			
	ProScale tota results	Inhalative		7,85E+04
		Dermal		8,94E-01

21.11.6. Interpretation of results

High ProScale scores indicate combinations of high hazard, high modelled exposure, long exposure time and/or large substance mass flow. The result is most useful for comparing alternatives, identifying hotspots and testing improvement options such as substitution, exposure reduction, process redesign, lower concentration, automation or reduced mass flow.

Results should be communicated as toxicity potentials within a defined assessment context (Kärnman, 2024). They should not be interpreted as proof of unsafe use, legal non-compliance or quantified health damage. Robust reporting should include data sources, modelling assumptions, route-specific results, contribution analysis, uncertainty discussion and sensitivity checks.

21.11.7. Assessment examples

Many examples of ProScale applications were worked out, some of them are published (Saling et al 2021) (Holmquist, et al., 2021) (Kärnman, 2024) (Lexen, 2021)

The following simplified example illustrates how a ProScale-type calculation can be structured. The numbers are hypothetical and are used only to demonstrate the calculation logic; they are not substance-specific regulatory values and should not be used for compliance or safety decisions.

Example situation: A product system requires two chemicals in one manufacturing step to produce one functional unit. Substance A is a volatile solvent handled in an open mixing process, while Substance B is a low-volatility additive handled in a mostly closed dosing step. Only inhalation exposure is considered in this simplified example shown in Table 63.

Table 63: Example process calculation of results in ProScale

Parameter	Substance A: volatile solvent	Substance B: low-volatility additive	Comment
Exposure route	Inhalation	Inhalation	Simplified route-specific example
Unit process	Open mixing	Closed dosing	Different exposure situations
Hazard Factor, HF	100	10	Illustrative factor derived from route-specific hazard and potency information
Exposure Concentration Factor, ECF	0.50	0.05	Illustrative relative exposure potential after considering process conditions and risk management measures
Person-Hours Factor, PHF	0.20 h/FU	0.10 h/FU	Exposed working time allocated to one functional unit
Mass Flow, MF	0.80 kg/FU	0.20 kg/FU	Amount of substance used per functional unit

Step 1: Calculate the inhalation score for Substance A

$$PSS_{A,mixing,inh} = HF \times ECF \times PHF \times MF = 100 \times 0.50 \times 0.20 \times 0.80 = 8.0$$

Substance A receives a relatively high score because all four drivers point in the same direction: high hazard factor, open handling with higher exposure potential, relevant working time and comparatively large mass flow.

Step 2: Calculate the inhalation score for Substance B

$$PSS_{B,dosing,inh} = HF \times ECF \times PHF \times MF = 10 \times 0.05 \times 0.10 \times 0.20 = 0.01$$

Substance B receives a much lower score because the hazard factor, exposure potential, exposure time and mass flow are all lower than for Substance A.

Step 3: Aggregate the product-system inhalation score

$$PSS_{product,inh} = PSS_{A,mixing,inh} + PSS_{B,dosing,inh} = 8.0 + 0.01 = 8.01$$

The product-system inhalation score is therefore dominated by Substance A in the open mixing step.

Step 4: Calculate contribution shares

$$Contribution_A = 8.0 / 8.01 \times 100 = 99.9\%$$

$$Contribution_B = 0.01 / 8.01 \times 100 = 0.1\%$$

This contribution analysis shows that almost the entire inhalation toxicity potential comes from Substance A. Improvement efforts should therefore first focus on reducing the score for Substance A rather than optimizing Substance B.

Step 5: Test an improvement option

Assume that the open mixing process for Substance A is replaced by a closed system with improved local exhaust ventilation, reducing the Exposure Concentration Factor from 0.50 to 0.10 while all other factors remain unchanged.

$$\text{Improved PSS}_{A,\text{mixing,inh}} = 100 \times 0.10 \times 0.20 \times 0.80 = 1.6$$

$$\text{Improved PSS}_{\text{product,inh}} = 1.6 + 0.01 = 1.61$$

$$\text{Reduction} = (8.01 - 1.61) / 8.01 \times 100 = 79.9\%$$

In this example, improved containment and ventilation reduce the product-system inhalation score by approximately 80%. This illustrates how ProScale can support hotspot analysis and compare risk-management or design options within a life-cycle framework.

Here is a detailed explanation of the formulas already included in the document.

Interpretation logic

Because the four factors are multiplied, a high score can result from different combinations:

$$\text{High PSS} = \text{High HF} \times \text{High ECF} \times \text{High PHF} \times \text{High MF}$$

This means a hotspot may be caused by:

- very hazardous substance
- high exposure potential
- long worker exposure time
- large mass flow
- or a combination of these

Improvement options therefore include:

- substituting a less hazardous substance, reducing HF
- improving containment or ventilation, reducing ECF
- reducing manual task duration or automation, reducing PHF
- reducing substance amount or concentration, reducing MF

The formula is powerful because it shows not only where a hotspot occurs, but also which lever can reduce it.

Formaldehyde production example

The following table uses illustrative default factors. HF values are route-integrated screening values reflecting the most relevant occupational health classifications and potency indicators. ECF and PHF are relative factors representing closed industrial operation with limited routine exposure and higher exposure potential during transfers, handling, sampling, and maintenance. The results are shown in Table 64.

Table 64: Example process calculation of Formaldehyde production with ProScale

Life-cycle stage	Substance	Main exposure route	MF per FU	HF	ECF	PHF	Score contribution
Methanol production	Methane / natural gas	Inhalation, flammability-related handling	310 kg	10	0.01	0.002	0.062
Methanol production and transfer	Carbon monoxide in synthesis gas	Inhalation	120 kg-equivalent handled internally	1,000	0.005	0.002	1.200
Methanol production, storage, transfer	Methanol	Inhalation and dermal	420 kg	1,000	0.02	0.004	33.600
Formaldehyde synthesis and absorption	Formaldehyde	Inhalation and dermal	370 kg	10,000	0.03	0.004	444.000
Product handling	37% formalin solution	Inhalation and dermal during loading/sampling	1,000 kg	5,000	0.02	0.004	400.000

Total screening ProScale score: 878.9 relative ProScale units per tonne of 37% formalin.

In Figure 31 the contributions of all hazardous compounds to the final score are shown. The formaldehyde production and handling are the most significant contributions. The PROC 4 was applied in this process in the ECF calculation.

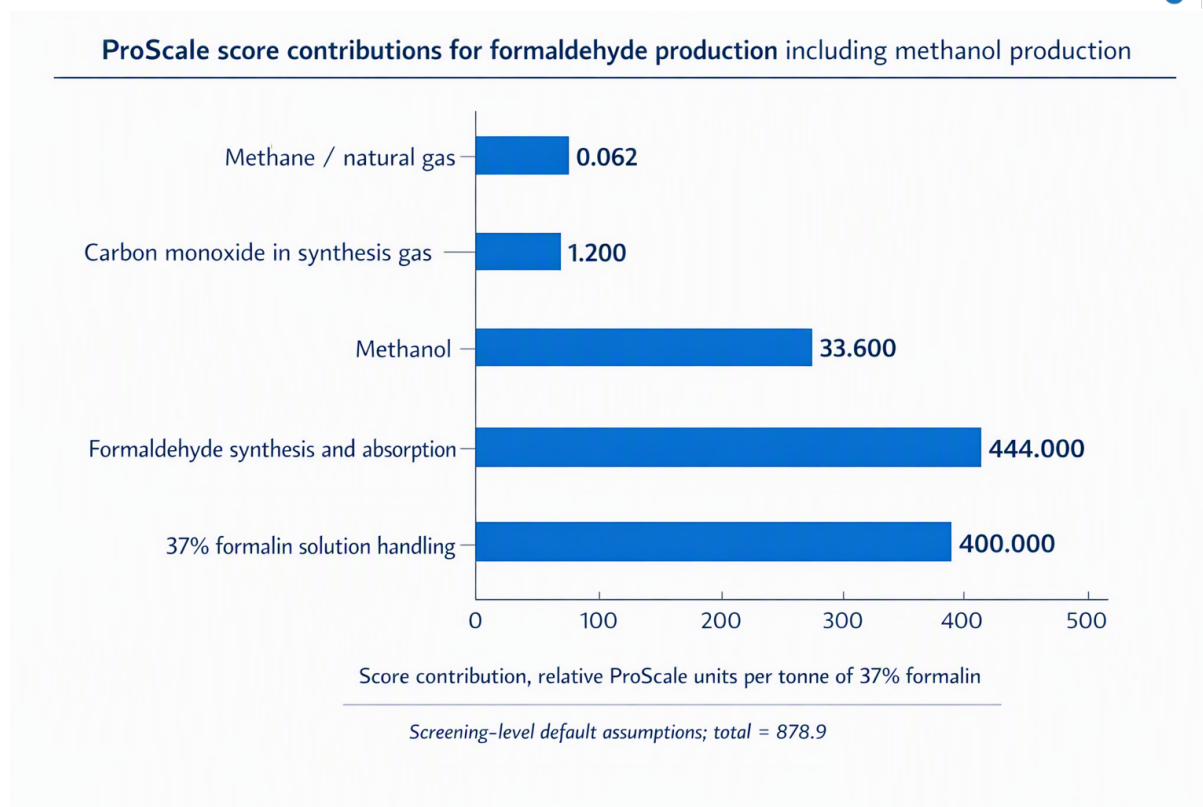


Figure 31: Contributions to materials to the overall result of Formaldehyde production with ProScale

Results from ProScale can be linked with other LCA impact categories, even if ProScale data are not available from commonly used LCA data bases. That introduction can be done via normalization of the single results to a complete LCA. Normalization factors were developed for usage in LCA. About 60 globally important processes with respect to their global production were assessed in this development (Rydberg, 2023).

Figure 32 shows, how these results can be integrated in the interpretation of an LCA to a single score, with or without weighting.

Overall approaches addressing several impacts

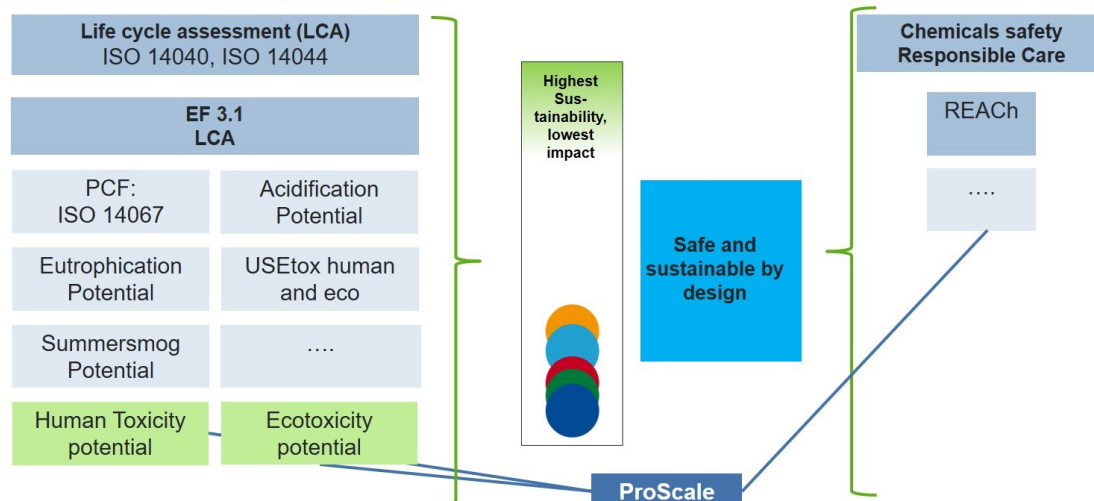


Figure 32: Integration of ProScale results based on REACH data and integration in overall LCA results interpretation

21.12. ProScaleE for Eco-Toxicity assessment in LCA

Purpose. This annex summarizes the current conceptual basis of ProScale-E as an ecotoxicity potential scoring approach for chemical footprinting, life cycle assessment, and Safe and Sustainable by Design screening. ProScale-E extends the ProScale logic from direct human toxicity potential toward environmental toxicity potential by combining substance-level ecotoxicity hazard information with simplified fate or degradation information.

Introduction

ProScale-E is a screening-level ecotoxicity potential method for comparing substances, mixtures, processes, and product systems in a life-cycle perspective. It combines an ecotoxicity hazard factor based primarily on CLP aquatic hazard classification and potency information with a degradation factor reflecting persistence or degradability. The resulting characterization factor can be multiplied by mass flows and summed across the product system. The method is intended for chemical footprinting, LCA-compatible comparison, SSbD screening, and prioritization of data collection or substitution options. It should be interpreted as a relative potential indicator and not as a site-specific ecological risk assessment.

21.12.1. General Principles

ProScale-E is intended to be transparent, pragmatic, regulatory-aligned, and compatible with life-cycle thinking. The method uses data generated in regulatory and product stewardship practice, especially CLP environmental hazard classifications, REACH registration information, M-factors for aquatic toxicity potency, and biodegradation or persistence-related information. It is not a substitute for detailed fate, exposure, and effect modelling such as USEtox. Instead, it provides a conservative and practical screening indicator for cases where early-stage comparison, chemical footprinting, or prioritization is needed.

- Assess ecotoxicity potential consistently across substances, mixtures, processes, and product systems.

- Use regulatory data and classifications rather than requiring extensive additional testing.
- Provide an LCA-compatible characterization factor that can be multiplied by mass flows or inventory flows.
- Allow conservative screening, comparison of alternatives, and identification of ecotoxicity risk drivers.
- Support chemical footprinting and SSbD assessments at early design stages.

21.12.2. Core Procedure

1. **Assign ecotoxicity hazard information.** Collect CLP environmental hazard statements, harmonized classifications where available, self-classifications where justified, and M-factors.
2. **Assign degradation or persistence information.** Use ready biodegradability, inherent biodegradability, hydrolysis, persistence indicators as e.g. high degradation rates, or other relevant fate information.
3. **Calculate substance-level ProScale-E factors.** Combine hazard and degradation factors according to the ProScale-E formula.
4. **Calculate product-system scores.** Multiply each substance factor by the corresponding mass flow and aggregate across the defined system.
5. **Interpret results.** Identify substances, processes, and life-cycle stages that dominate the score and evaluate improvement options.

Assessment Approaches

Substance-level screening. The simplest application uses the ProScale-E characterization factor to rank individual substances according to their ecotoxicity potential. This is useful for early design, alternatives assessment, and prioritization of data collection.

Product-system assessment. For life cycle or chemical-footprint applications, the characterization factor is multiplied by the relevant mass flow and summed across substances and life-cycle stages. This enables identification of dominant substances and stages and supports comparison of alternatives with similar technical performance.

Tiered assessment. ProScale-E can be used as a Tier 1 or screening method. If the score is high, uncertain, or decision-critical, the assessment should be refined with better substance data, more specific degradation information, measured ecotoxicity data, or complementary LCIA modelling.

21.12.3. Data Quality and Uncertainty

Data quality should be evaluated before interpreting the score. Key uncertainty drivers include missing or conflicting hazard classifications, missing M-factors, incomplete (bio)degradation information, new ecotoxicity and fate information, uncertain mass flows, and differences between supplier SDS data and public regulatory data. For screening applications, conservative assumptions are recommended when information is missing. For decision-critical comparisons, uncertainty should be reduced by checking primary sources, documenting the selected

classification basis, and testing the sensitivity of the score to alternative hazard or degradation factors.

The calculation sections below translate the method description into practical application. They should be read as implementation guidance; the numerical factors in the worked example are illustrative and must be replaced by the selected ProScale-E factor scheme in real assessments.

Formulas and Units

Substance characterization factor: $CF_{E,i} = HF_{E,i} \times DF_i$

M-factor adjusted hazard factor: $HF_{E,i} = HBS_i \times M_i$

where HBS_i is the base hazard score derived from the CLP aquatic hazard category and M_i is the applicable acute or chronic M-factor for substance i . If no substance-specific M-factor is available, M_i should be set to 1 or replaced by a documented conservative default, depending on the selected ProScale-E implementation rule.

The M-factor is not an additional mass or fate parameter; it is a potency multiplier used in CLP to give greater weight to substances that are very toxic to aquatic organisms at low concentrations. In ProScale-E, this means that two substances with the same aquatic hazard category can receive different hazard factors if one of them has a higher acute or chronic M-factor. A higher M-factor therefore increases the ecotoxicity hazard factor and can make a substance dominate the product-system score even when its mass flow is small.

Substance contribution: $Score_i = MF_i \times CF_{E,i}$

Product-system score: $Score_{system} = \sum (MF_i \times HF_{E,i} \times DF_i)$

Expanded product-system score with M-factor: $Score_{system} = \sum (MF_i \times HBS_i \times M_i \times DF_i)$

Total system score

$$Score_{system} = \sum_i Score_i$$

Formula 44: Equation for assessing the score results in ProScaleE including different single results of PSS depending on the exposure route

Where:

- MF_i = the mass flow of substance i per functional unit,
- $HF_{E,i}$ = the ecotoxicity hazard factor, and
- DF_i = the degradation factor. The score is relative and should be interpreted comparatively within a consistent goal and scope
- $CF_{E,i}$ = the ProScale-E ecotoxicity characterization factor for substance i .
- $Score_i$ = the Substance-level contribution to the product-system ProScale-E score.
- HBS_i = the Base hazard score for substance i , derived from the selected CLP aquatic hazard category before applying the M-factor.

- M-factor = the CLP multiplying factor used to reflect very high aquatic toxicity potency. In ProScale-E, it scales the base hazard score upward before the degradation factor and mass flow are applied.

Graphic description for the M-factor example. The following visual is intended to make the amplifying effect of the M-factor intuitively understandable by comparing the calculation with and without this multiplier. The graphic should present the calculation as a simple left-to-right flow. It starts with the base hazard score $HBS_A = 10$. This value is then multiplied by the M-factor $M_A = 10$, resulting in an adjusted hazard factor $HF_{E,A} = 100$. In the next step, $HF_{E,A}$ is multiplied by the degradation factor $DF_A = 3$, giving $CF_{E,A} = 300$. Finally, $CF_{E,A}$ is multiplied by the mass flow $MF_A = 0.20 \text{ kg/FU}$, resulting in $Score_A = 60$. A grey comparison path should show the same calculation without the M-factor, ending at $Score_A = 6$. This contrast makes the main message clear: the M-factor causes a tenfold increase in the final score.

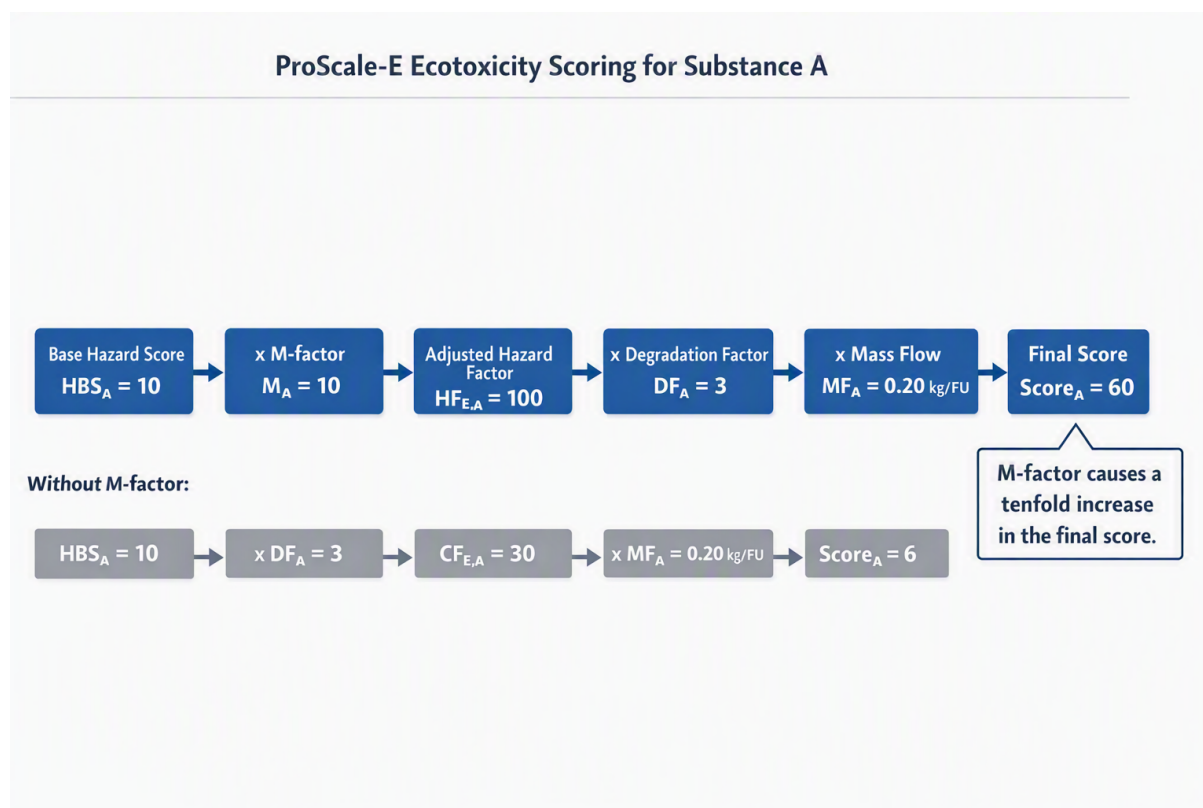


Figure 33: Stepwise illustration of the M-factor effect in the Substance A example. The blue path includes the M-factor and results in $Score_A = 60$; the grey comparison path omits the M-factor and results in $Score_A = 6$.

Legend. Blue boxes and arrows show the calculation path including the M-factor. Grey boxes and arrows show the reference calculation without the M-factor. HBS_A is the base hazard score, M_A is the M-factor, $HF_{E,A}$ is the M-factor adjusted hazard factor, DF_A is the degradation factor, $CF_{E,A}$ is the characterization factor, MF_A is the mass flow, and $Score_A$ is the final substance contribution.

Example application of the M-factor. Assume Substance A has the base hazard score $HBS_A = 10$ based on its CLP aquatic hazard category and an acute or chronic M-factor $M_A = 10$. The M-factor adjusted hazard factor is therefore $HF_{E,A} = HBS_A \times M_A = 10 \times 10 = 100$. With a degradation factor $DF_A = 3$, the characterization factor becomes $CF_{E,A} = HF_{E,A} \times DF_A = 100 \times 3 = 300$. If the mass flow is $MF_A = 0.20 \text{ kg/FU}$, the substance contribution is $Score_A = 0.20 \times 300 = 60$. Without the M-factor, the same calculation would give $HF_{E,A} = 10$, $CF_{E,A} = 30$, and $Score_A = 6$. The M-factor therefore

increases the contribution by a factor of 10 and explains why highly potent aquatic toxicants can dominate the result even at low mass flows.

21.12.4. Data Needs

Meaningful data information is the foundation for calculation. The data will be transferred to the calculation tool and can be automatically processed, if they are in the right format and containing the required information. Table 65 summarizes the data needs.

Table 65: Data needs and overview of source for the generation of inputs information in ProScaleE

Data category	Typical data elements	Preferred sources
Substance identity	CAS number, EC number, substance name, composition, impurities	SDS, supplier data, REACH registration, internal inventories
Hazard classification	H400, H410, H411, H412, H413 and related CLP environmental hazard information	CLP Annex VI, ECHA dissemination, SDS, company classifications
Potency information	M-factors for acute or chronic aquatic toxicity, concentration limits where relevant	CLP Annex VI, ECHA, SDS, dossier information
Degradation and fate	Ready biodegradability, inherent biodegradability, persistence screening, hydrolysis, biodegradation half-lives where available	ECHA, OECD test reports, IUCLID summaries, literature
Mass flow	Amount of each substance per functional unit, process input, output, emission, or product composition	Bill of materials, LCI data, process engineering data, supplier data
Context information	Life-cycle stage, process type, use pattern, release relevance, intended comparison	Goal and scope definition, process maps, LCA model

For HF values, use sources that describe ecotoxicity hazard and potency:

- CLP Annex VI harmonized classification: Preferred source where available; use aquatic hazard categories such as Aquatic Acute 1 and Aquatic Chronic 1–4.
- ECHA dissemination / REACH registration dossiers: Use for registered classifications, ecotoxicity endpoints, and supporting dossier information.
- Safety Data Sheets (SDS): Useful for supplier classifications, H-statements, and mixture-relevant information; check consistency against ECHA/CLP.
- M-factors: Use officially assigned acute or chronic M-factors where available to reflect high aquatic toxicity potency.
- Expert/company classification: Use only when public/harmonized data is missing or conflicting and document the rationale.

For DF values, use sources that describe degradation, persistence, and environmental fate:

- ECHA / REACH registration data: Preferred source for ready biodegradability, inherent biodegradability, hydrolysis, and persistence assessment information..
- OECD (bio)degradation test reports: Especially OECD

- ready biodegradability, inherent biodegradability and transformation in water/soil/sediment tests.
- IUCLID summaries: Useful for structured endpoint summaries from registration dossiers.
- Peer-reviewed literature: Use when regulatory data are missing or when additional fate information is needed.
- Persistence screening information: Use conservative DF assumptions when degradation data are missing, conflicting, or uncertain.

A concise hierarchy would be:

1. Harmonized regulatory data
2. ECHA/REACH dossier data
3. Supplier SDS and company classifications
4. OECD test reports / IUCLID endpoint summaries
5. Peer-reviewed literature
6. Documented conservative assumptions

In the template, the Source/comment column should record which source was used for both HF and DF, including any assumptions or uncertainty flags.

Guardrails, Data Hierarchy and Conservative Rules

- Use harmonized CLP classifications where available and document any deviation.
- Where multiple classifications exist, apply the most relevant and conservative classification unless there is a justified reason to use another value.
- Do not treat absence of classification as absence of ecotoxicity; flag data gaps explicitly.
- Use M-factors to reflect potency where available; where missing, apply a documented default or conservative assumption.
- Use conservative degradation factors where biodegradation or persistence data are missing or conflicting.
- Keep the scope consistent between alternatives; differences in mass flows, boundaries, or omitted substances can dominate results.
- Use ProScale-E as a comparative screening indicator, not as a site-specific ecological risk assessment.

Prioritize data collection

Focus additional data gathering on substances with:

- High mass flow
- High preliminary score
- Missing M-factor
- Missing degradation information

- Conflicting classifications
- Run a sensitivity check

Test how the result changes using low, medium, and conservative HF/DF assumptions.
This is especially important if the substance contributes strongly to the total score.

21.12.5. Assessment examples

The following illustrative example shows how ProScale-E can be calculated for a simplified product system containing three substances. The numerical values are hypothetical and are used only to demonstrate the calculation logic. The example assumes that higher hazard factors and degradation factors indicate higher ecotoxicity potential. The inputs are shown in Table 66.

Table 66: Data needs and overview of source for the generation of inputs information in ProScaleE for three different substances

Substance	Illustrative CLP basis	MF _i mass flow per functional unit (kg)	HF _{E,i} hazard factor	DF _i degradation factor	CF _{E,i} = HF _{E,i} × DF _i	Score _i = MF _i × CF _{E,i}
Substance A	Very toxic to aquatic life with long-lasting effects; M-factor considered	0.20	100	3	300	60
Substance B	Toxic to aquatic life with long-lasting effects	1.50	10	2	20	30
Substance C	Harmful to aquatic life with long-lasting effects; readily degradable assumption	5.00	1	0.5	0.5	2.5
Total		6.70				92.5

In this example, Substance A dominates the result even though its mass flow is relatively small. This happens because its illustrative hazard factor and degradation factor are high. Substance B contributes less despite a higher mass flow, while Substance C has the largest mass flow but a low contribution because the assumed hazard and degradation factors are low. The calculation therefore highlights why contribution analysis should consider mass flow, classification severity, potency, and degradability together.

Example calculation. For Substance A, $CF_{E,A} = 100 \times 3 = 300$. The substance contribution is then $Score_A = 0.20 \text{ kg} \times 300 = 60$. The total product-system score is the sum of all substance contributions: $60 + 30 + 2.5 = 92.5$.

Template Table for Real Substances

The simplified template below in Table 67 captures only the essential fields needed for a first ProScale-E calculation. Additional documentation such as EC number, detailed M-factor source, degradation test reference, and sensitivity scenarios can be kept in a separate Excel sheet or data appendix.

Table 67: Simplified template below captures only the essential fields needed for a first ProScale-E calculation.

Substance	CAS No.	Mass flow MF_i (kg/FU)	CLP aquatic classification	$HF_{E,i}$	DF_i	$CF_{E,i}$	Score i	Source / comment
Substance A	Illustrative	0.20	Aquatic Acute 1 / Aquatic Chronic 1	100	3	300	60	Illustrative row; replace with real CAS number, classification source, and ProScale-E factor scheme.
Substance B	Illustrative	1.50	Aquatic Chronic 2	10	2	20	30	Illustrative row; assumed chronic aquatic hazard and moderate degradation factor.
Substance C	Illustrative	5.00	Aquatic Chronic 3	1	0.5	0.5	2.5	Illustrative row; assumed lower aquatic hazard and readily degradable behaviour.

Total	6.70	92.5	Total reflects the three filled illustrative rows.
--------------	-------------	-------------	--

Summary of total scores. The three illustrative rows result in a total mass flow of 6.70 kg/FU and a total ProScale-E score of 92.5. Substance A contributes 60 score units, corresponding to approximately 65% of the total score; Substance B contributes 30 score units, corresponding to approximately 32%; and Substance C contributes 2.5 score units, corresponding to approximately 3%. The result shows that the dominant ecotoxicity contribution is driven mainly by the combination of hazard and degradation factors, not by mass flow alone.

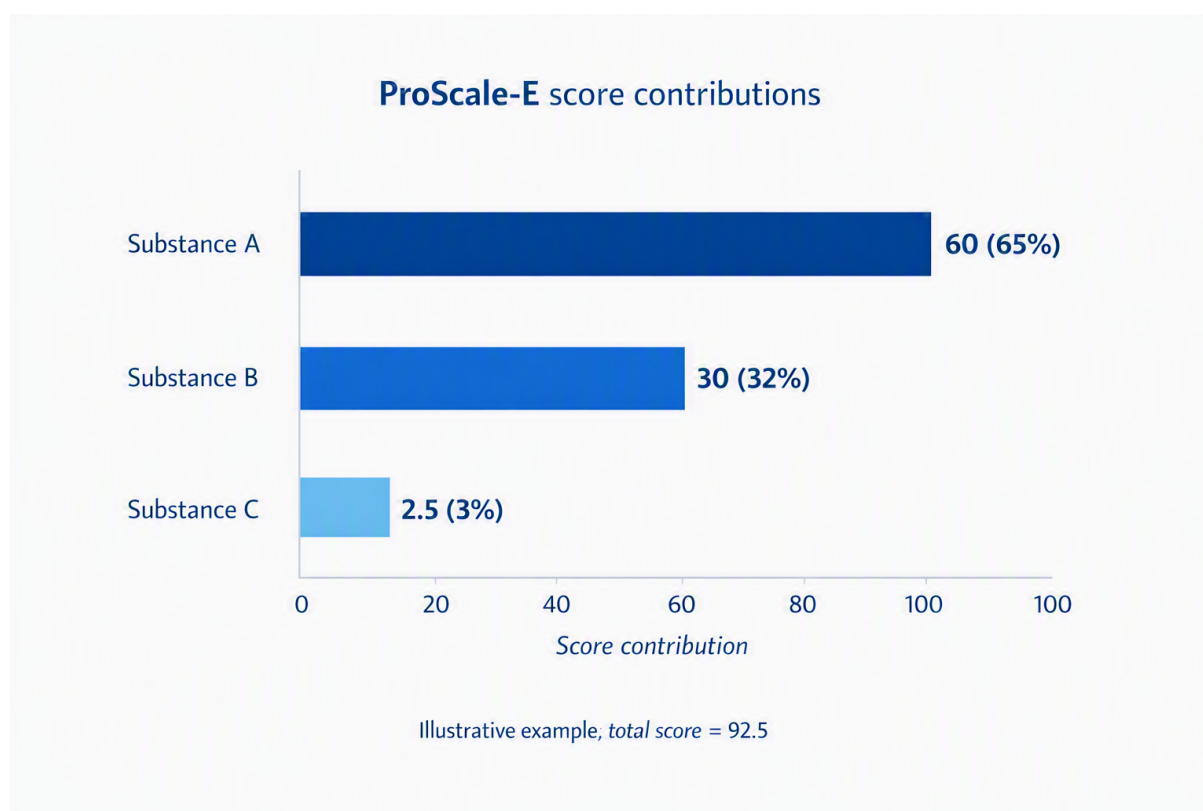


Figure 34: Illustrative ProScale-E score contributions for Substance A, Substance B, and Substance C. The total score is 92.5.

Chart interpretation. The chart makes the contribution pattern visible: Substance A is the dominant driver of the total ProScale-E score, even though it has the lowest mass flow in the example. This indicates that its high hazard factor and degradation factor outweigh the effect of quantity. Substance B is the second-largest contributor because its higher mass flow partly compensates for a lower characterization factor. Substance C contributes only marginally despite the largest mass flow, because its assumed hazard and degradation factors are low. For improvement analysis, the first priority would therefore be to review Substance A, followed by Substance B, before focusing on Substance C.

Recommended use. Enter the substance identity, mass flow, and CLP aquatic classification first. Then assign $HF_{E,i}$ and DF_i , calculate $CF_{E,i} = HF_{E,i} \times DF_i$, and calculate $Score_i = MF_i \times CF_{E,i}$. Use the source/comment column to record key assumptions and data quality issues.

Use of results

A high ProScale-E score indicates that one or more substances combine relevant ecotoxicity hazards, high potency, low degradability, and/or large mass flows. Interpretation should focus on contribution analysis: identify which substances dominate the score, whether the score is driven by classification severity, M-factor potency, degradation assumptions, or mass flow, and whether improvement options exist through substitution, reduced loading, improved containment, or better data.

Limitations

ProScale-E is a simplified ecotoxicity potential indicator. It does not provide site-specific environmental concentrations, ecosystem-specific risk quotients, or full multimedia fate and exposure modelling. It should therefore be understood as complementary to detailed LCIA methods such as USEtox and to regulatory environmental risk assessment. The method is most suitable for comparative screening, early-stage product development, chemical footprinting, and identification of priorities for substitution or further assessment.



tfs-initiative.com
chem-x.de

© BASF SE, coac GmbH, Cofinity-X GmbH, Covestro Deutschland AG, DAW SE, Henkel AG&Co. KGaA, Merck KGaA, SAP SE, Siemens AG, Spherity GmbH, Wacker Chemie AG, Catena-X e.V., Evonik Industries AG, Sika Services AG, Together for Sustainability, 2026

Funded by the European Union – NextGeneration EU. The views and opinions expressed are solely those of the authors and do not necessarily reflect the views of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Funded by the Federal Ministry of Economic Affairs and Energy BMWF



**Funded by
the European Union**
NextGenerationEU

Supported by:



Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag