Description of life cycle impact assessment methods

Supplementary information for tenders

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UID: CHE-112.959.660
Commercial registry by the canton of Schaffhausen: CHE-112.959.660
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Schaffhausen, 28. June 2024

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Imprint

Citation	Niels Jungbluth (2024) Description of life cycle impact assessment methods. ESU-services Ltd., Schaffhausen, Switzerland, https://esu-services.ch/address/tender/
Contractor	ESU-services Ltd., fair consulting in sustainability Vorstadt 10, CH-8200 Schaffhausen www.esu-services.ch Phone 0041 44 940 61 32 jungbluth@esu-services.ch
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Version	28.06.24 11:27 https://esuservices-my.sharepoint.com/personal/jungbluth_esu-services_ch/Documents/ESU-intern/000 Wichtige Dateien/Vorlagen/ESU-Description-of-LCIAmethods.docx

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1 Overview

An essential aspect of life cycle assessment is the combination of different environmental impacts (such as the greenhouse effect or eutrophication) into one indicator. Various evaluation methods are available for this purpose, which differ in scope and procedure for characterisation and weighting.

Tab. 1.1 shows a comparison of different indicators for evaluation. Methods such as cumulative energy demand, water footprint or CO_2 footprint only consider one selected environmental area at a time. On the other hand, fully aggregated methods such as the ecological scarcity method (eco-points) combine a large number of different environmental impacts into a single score (see Jungbluth et al. 2011a; Jungbluth et al. 2011b for further explanations).

On the following pages we present different life cycle impact assessment (LCIA) methods as part of life cycle assessment. If you would like to collaborate with us, you can book the date for a first meeting. You should receive an email with a calendar invitation and Teams link after choosing the time and date. Please check your Spam folder if you do not receive such an invitation or contact us by Email.

Tab. 1.1 Overview of LCIA methods

	© ESU-services Ltd. (2021)	One environmental issue				Several issues					
	LCIA method: Impact category	Cumulative Energy Demand	MIPS	Water Footprint	Carbon footprint	Ecological footprint	Ecological scarcity	ReCiPe	Environmental Footprint (PEF)	ImpactWorld+, Midpoint	Planetary Boundaries
Resources	Energy,non-renewable	√	√	∅	∅	∅	√	√	√	√	∅
	Energy, renewable	√	√	∅	∅	∅	√	∅	∅	∅	∅
	Ore and minerals	∅	√	∅	∅	∅	√	√	√	√	∅
	Water depletion	∅	√	√	∅	∅	√	√	√	√	√
	Biotic resources	∅	√	∅	∅	∅	√	∅	∅	∅	∅
	Land occupation	∅	∅	∅	∅	√	√	√	√	√	√
	Land-transformation	∅	∅	∅	∅	∅	∅	√	√	∅	∅
Emissions	Only CO_2	∅	∅	∅	∅	√	∅	∅	∅	∅	∅
	Climate change incl. CO_2	∅	∅	∅	√	∅	√	√	√	√	√
	Ozone depletion	∅	∅	∅	∅	∅	√	√	√	√	√
	Human toxicity	∅	∅	∅	∅	∅	√	√	√	√	∅
	Particulate matter formation	∅	∅	∅	∅	∅	√	√	√	√	∅
	Photochemical ozone formation	∅	∅	∅	∅	∅	√	√	√	∅	∅
	Ecotoxicity	∅	∅	∅	∅	∅	√	√	√	√	∅
	Acidification	∅	∅	∅	∅	∅	√	√	√	√	√
	Eutrophication	∅	∅	∅	∅	∅	√	√	√	√	√
	Persistant organic pollutants	∅	∅	∅	∅	∅	√	∅	∅	∅	∅
	Odours	∅	∅	∅	∅	∅	∅	∅	∅	∅	∅
	Noise	∅	∅	∅	∅	∅	√	∅	∅	∅	∅
	Ionising radiation	∅	∅	∅	∅	∅	√	√	√	√	∅
	Endocrine disruptors	∅	∅	∅	∅	∅	√	∅	∅	∅	∅
Others	Accidents	∅	∅	∅	∅	∅	∅	∅	∅	∅	∅
	Wastes	∅	∅	∅	∅	∅	√	∅	∅	∅	∅
	Littering	∅	∅	∅	∅	∅	∅	∅	∅	∅	∅
	Salinisation	∅	∅	∅	∅	∅	∅	∅	∅	∅	∅
	Biodiversity loss	∅	∅	∅	∅	∅	∅	∅	∅	∅	√
	Erosion	∅	∅	∅	∅	∅	∅	∅	∅	∅	∅
Framework	Reference	GLO	GLO	GLO	GLO	GLO	CH	GLO	RER	GLO	GLO
	Publication	2007	1996	2018	2013	1996	2021	2016	2018	2019	2009
	Damage assessment	∅	∅	√	∅	√	∅	√	∅	partly	∅
	Normalization	∅	∅	∅	∅	GLO	CH	GLO	GLO	∅	∅
	Weighting	√	∅	∅	∅	∅	√	√	√	∅	∅

2 Single issues

2.1 Global Warming Potential (GWP)

2.1.1 IPCC 2021

Global Warming Potential (GWP), commonly referred to with the popular term carbon footprint (CF), calculates the radiative forcing over different time horizon. It assesses the potential impact of different gaseous emissions on climate change (IPCC 2021).

Climate change is a global problem that leads to several different direct and indirect effects on human health, man-made infrastructures and environmental damages such as:

- warmer or colder temperatures at certain places and times
- changes in the amount, annual distribution and magnitude of rainfalls and snowfalls
- changes in the magnitude of wind velocities
- melting of glaciers leading to disappearance of permafrost areas, higher sea level and changes in salinity
- acidification of oceans due to higher concentration of carbonic acid
- changes in local or global climate phenomena such as the gulf stream, monsoon seasons, etc.

There is no mechanism to clean up this damage and these emissions. Emissions today will lead to long lasting changes in the climate system of the earth.

The residence time of the substances in the atmosphere and the expected immission design are considered to determine the global warming potentials. The potential impact of the emission of one kilogram of a greenhouse gas is compared to the potential impact of the emission of one kilogram CO_2 resulting in kg CO_2-equivalents (kg CO_2-eq).

The gases with the greatest global warming impact are CO_2, CH_4 (methane) and N_2O (nitrous oxide). In addition, various chlorinated and fluorinated hydrocarbons (CFCs, HCFCs, HFCs, PFCs) and SF6 have a direct radiative forcing effect. While the global warming impact of the latter substances per kilogram can be several thousand times greater than that of CO_2, their contribution to the overall emissions inventory is often small.

Global warming potentials can be determined applying different time horizons (20, 100 and 500 years). The short integration period of 20 years is relevant because a limitation of the gradient of change in temperature is required to secure the adaptation ability of terrestrial ecosystems. The long integration time of 500 years is about equivalent with the integration until infinity. This allows monitoring of the overall change in temperature and thus the overall sea level rise, etc.

Most studies present results for a time horizon of 100 years. For our studies, we show results for time horizon of 20 and 100 years is chosen. This seems to be necessary as there are urging challenges in the short time perspective to avoid irreversible damage to the climate system on the earth.

There are specific effects of emissions in high altitude, which lead to a higher contribution of aviation to climate change than just due to the emission of CO_2 from burning aviation fuels. The exact relevance is subject to scientific debate, but there is a consensus that aircrafts have an impact that is higher than just their contribution due to the direct CO_2. The gap between this scientific knowledge on the one side and the absence of applicable GWP (global warming potential) factors on the other side is an important shortcoming for life cycle assessment or carbon footprint studies which aim to cover all relevant environmental impacts of the services or products investigated (Jungbluth & Meili 2019).

For our studies a factor for the RFI (radiative forcing index) is included. This represents the state of the art concerning the accounting of specific aircraft emissions. For the time being an RFI of 1.7 and 4 for GWP 100a and 20a, respectively is applied on the total aircraft CO_2 (Lee et al. 2021).

Tab. 2.1 shows typical reference values for products and services causing an global warming potential of 1 kg CO_2-eq. The IPCC Method with the RFI Factor was used.

Tab. 2.1 Reference values for products and services causing 1kg CO_2-eq

GWP 20a	GWP 100a	1 kg CO2-eq equals...
3'131.2	3'594.7	litres of tapwater from Switzerland
6.5	8.7	centimeters road, used for one year
1.0	1.0	kilograms of fossil CO2, directly emitted
0.012	0.034	kilograms of fossil methane, directly emitted
0.93	1.76	litres crude oil produced, with transport to the refinery
2.9%	3.4%	of a person's private daily consumption in Switzerland, 2018
2.8%	3.3%	the daily consumption of a person in Switzerland
1.9	4.2	km transport of one person by plane
4.2	5.1	km transport of one person by car (occupancy 1.6 persons)
104.9	124.6	km transport of one person by bicycle
8.2%	10.2%	of a vegetarian menu with 4 courses
4.2%	6.5%	of a meaty 3-course menu
11.9%	18.6%	of the daily food consumption of a person in Switzerland, 2018
26.8	26.8	plastic carrier bags (production, distribution and disposal)
0.109	0.109	cotton T-Shirts
0.47%	0.47%	of the production of a laptop
40%	53%	of daily consumption for hobbies/leisure activities in Switzerland, 2018
77%	97%	of daily consumption of furniture and household appliances in Switzerland, 20

2.1.2 Accounting for biogenic carbon

One question that arises in carbon footprint is how to account for the bio-based vs. the fossil resource-based materials in terms of CO_2 emissions. There are different approaches on how to compare the environmental impacts of such products (Pawelzik et al. 2013). Sometimes these approaches are driven by singular interests, and all encounter some subjectivity. In the end, any chosen approach must be consistent with allocation choices applied in the foreground and background data.

This section describes possible approaches that can be applied.

2.1.2.1 Carbon neutral

In this approach, CO_2-emissions from burning materials derived from biomass feedstock are assumed to be carbon neutral. Thus, they are labelled as biogenic in the inventory and are not considered when calculating the global warming potential. The same holds true for the burning of wastes from biomaterial.

For ESU this is the most common approach to be applied in LCA.

2.1.2.2 Biofeedstock-storage approach

In this option the biogenic carbon content in the biomass is considered as a negative emission for the biomass production process. The approach is sometimes labelled as “Biofeedstock-storage approach” (Pawelzik et al. 2013). This can be considered by applying the LCIA method IPCC 2021 GWP 100a (incl. CO_2 uptake) in SimaPro which takes uptake and biogenic emissions into account. Often there are large uncertainties in this approach as the uptake and emissions recorded in the background data are not fully equalized e.g. due to allocation or incomplete inventories. Therefore, this approach is not recommended to be applied without a thorough and detailed control of the correctness of the LCI over different life cycle stages.

2.1.2.3 Biomaterial storage approach

This approach is sometimes labelled as “Biomaterial storage approach” (Pawelzik et al. 2013). It is like the biofeedstock-storage approach, but only gives credit for the biogenic carbon stored in the final product. Biogenic carbon emissions during end-of-life must therefore be considered as well. This approach makes a full balance of the life cycle but avoids complicated issues due to allocation and other modelling choices in the background database used and is also not used in this study.

2.1.2.4 Other options (not followed)

Beside these options further modelling choices are possible but are not considered in this study.

One approach could be to subtract emissions of biomethane (e.g. due to leakage in a landfill) that might be prevented due to the use of waste for biogas production. To be consistent, it must be clarified if this would result in a reduction of the global warming potential for the original product “A” (where the waste occurred, or as credit for the process using the waste. However, some studies take this into account in a system expansion. Often, no reliable information about all the types of waste used in bioproduct (e.g. biogas) and alternatives for their use (e.g. as compost, fertilizer, etc.) or disposal (incineration, landfill, etc.) are known. Thus, the theoretical alternative fate of the different waste types is often not known and thus difficult to analyse.

To maintain the full mass balance of physical properties, such as the biogenic carbon content, it would be possible to allocate impacts of biomass growing e.g. by mass between the main product and the by-product (bio-waste). But, detailed knowledge about the prices paid is often not available.

2.1.3 Offsetting / compensation of CO_2-emissions

Today many companies use carbon offsetting, compensation, or neutralization as a means of environmental management. They even claim to be carbon neutral.

A carbon offset is a reduction in emissions of carbon dioxide or other greenhouse gases made to compensate for emissions made elsewhere. Offsets are measured in tonnes of carbon dioxide equivalent. One tonne of carbon offset represents the reduction of one tonne of carbon dioxide or its equivalent in other greenhouse gases.

There are service providers and projects on the market that allow offsetting of greenhouse gas emissions related to e.g., travel by air, car, or any other activity. It is tempting to simply pay a small amount of money to offset all the emissions related to one’s own activities and claim that the business is carbon neutral.

However, in our point of view this is a misleading approach that lacks purpose. It is also not supported by the underlying standards applied for e.g. an LCA or EPD.

We, as a global community, not only need to reduce greenhouse gas emissions to net zero, but also must immediately capture climate gases that are already in the atmosphere. This is not possible if each company or individual implements simple and cheap solutions or even tries to pass on the responsibility for their own shortcomings to others by purchasing offsets.

To slow down climate change, it is not sufficient to just burn fossil fuels more efficiently, it is necessary to completely stop using and burning them.

Further possible shortcomings of offsetting are:

- The reduction is achieved in the future and not today. So, it does not support the prevention of tipping points in climate change. Furthermore, it might be difficult to ensure that the future capture is really achieved. So, for example, a forest fire can destroy a newly planted tree and then no carbon capture will be achieved. Certificates once sold cannot be taken back if later analysis shows an overestimation of the reductions to be achieved.
- The reduction is a theoretical value assuming that the compensation partner would have done business as usual (e.g., installing a natural gas heating instead of moving alone to an innovative technology like heat pumps or buying a fossil-driven car instead of a Tesla). But, this often does not reflect reality were also other incentives or politics would ask for such a change and the compensation money is just taken as one additional benefit.
- Some compensation schemes promise to protect forest from cutting, but later on it has been shown that there were false assumptions regarding the real cutting activities in the areas.
- The storage time of carbon needs to be several thousands of years to avoid overstepping certain climate goals. Carbon capture and removal projects cannot always guarantee such a long-time frame.
- The owner of a heat pump, electric car or PV panel sells the declaration right to a compensation partner, but still profits from the green image of the installations in their premises (or might forget about accounting for the bought CO_2-pollution). Some users of products or services even might not know that emission reduction have already been sold to third parties.
- Rebound effects are not considered. A compensated cruise seems to be fine for the climate and thus more people tend to buy a fully unsustainable holiday package.
- The income from selling climate certificates cannot be spent immediately and compensation measures are initiated much later than the initial emission to be compensated took place. This is another thread for tipping points to be reached without taking immediate action on reducing greenhouse gas emissions.

With the option to offset, we tend to only improve the internal situation where the costs are higher than for the offset, e.g., by opting for a flight and missing the opportunity to travel by train, powered by green electricity. But, with climate compensation, the maximum reduction of total CO_2-emissions is limited to 50% which is not sufficient to reach climate goals.[1]

We think, paying money to other companies or individuals can be done as a voluntary measure, e.g., by supporting so-called Gold Standard projects that also bring social benefits. But, carbon offsets or climate certificates are not suitable as a substitute for one's own actions and should not be claimed in LCA or carbon footprint. And such partners need to be trustworthy which is often difficult to know.

If emissions already occurred, it is helpful if these previous emissions are offset. However, if a decision must be made regarding future emissions: No climate certificate can undo one emitted ton of CO_2, regardless of if you offset it once, twice, or as many times as you want.

Many of the critics on carbon compensations are shared by other stakeholders.[2] With these points in mind, ESU-services does not engage directly in carbon compensation measures, but we do our best to reduce our emissions as far as possible and help our customers to do the same.

We also do not factor in compensation in our LCA or carbon footprint studies.

[1] https://www.esu-services.ch/fileadmin/download/jungbluth-2009-DF37-7.pdf

[2] See e.g. https://www.worldwildlife.org/publications/wwf-position-and-guidance-on-voluntary-purchases-of-carbon-credits, https://www.weforum.org/agenda/2021/09/greenpeace-international-carbon-offsetting-net-zero-pledges-climate-change-action/, https://climatenetwork.org/wp-content/uploads/2022/11/CAN-Positon_Carbon-offsetting_Nov-2022.pdf

2.2 Indicators for water use and consumption (water footprint)

2.2.1 Definitions

A range of different terms is used in the context of water use and water consumption. As a base for the following methodical discussions, some basic terms are listed, and their definition is harmonised in Tab. 2.2.

The distinction between water consumption and water use is important. While the water use includes the water input and all types of water uses (e.g. cooling, turbinating, irrigation etc.), water consumption describes only the amount of water that is lost to a watershed because of the production of a good or the cultivation of crops. Water consumption is sometimes also called "net water use" or "net water withdrawal". Water consumption itself can be specified according to the type and origin of the water source. It is sometimes differentiated into blue, green and grey water. The definition of these types of water can vary slightly among the different studies and according to their scope and system boundaries.

The analysis of water consumption concentrates mainly on the quantity of the water. The degradation of the water quality is assessed in LCA in separate impact categories (e.g. ecotoxicity or eutrophication). Despite that, grey water consumption is an indicator of the harmfulness of the substances emitted, although not damage oriented.

Tab. 2.2 Definition of different terms concerning the water use and water consumption (based on Hoekstra et al. 2011; Milà i Canals et al. 2009; Pfister et al. 2009).

Water use	All types of water use; in industrial and agricultural processes, households, including in-stream processes (e.g. turbinated water in hydropower).
	=
Water borrowing	Part of the water use that is released back into the same water shed without a change in water quality. E.g. turbinated water in hydropower. The water is unrestrictedly available for further use.
	+
Water degradation	Part of the water use that is released back into the same water shed but with a changed water quality (chemically or physically), e.g. waste water, cooling water
	+
Water consumption	Part of the water use that is not released into the same water shed due to evaporation, evapotranspiration, product incorporation, discharge into another water shed. The water is "lost" to the watershed and it is no more available to ecosystems and humans.
	=
Blue water consumption	Part of the consumed water that derives from surface water and groundwater. It is available to ecosystems and humans.
	+
Green water consumption	Part of the consumed water. Rain water that is stored as soil moisture and lost by the evaporation through the soil and the uptake through the plants.
	+
Grey water	If not counted separately as water degradation, part of the consumed water. It describes the amount of water needed to dilute the load of pollutants to reach natural background concentrations. This is a virtual water consumption.

The evolution of water footprint indicators is pictured in Fig. 2.1. The first water footprints looked at the total withdrawal or use of water. Then water consumption became the focus of the assessment. Afterwards the demand in a certain area was also included in the assessment. Since about 2015, water demand and availability are considered in the assessment.

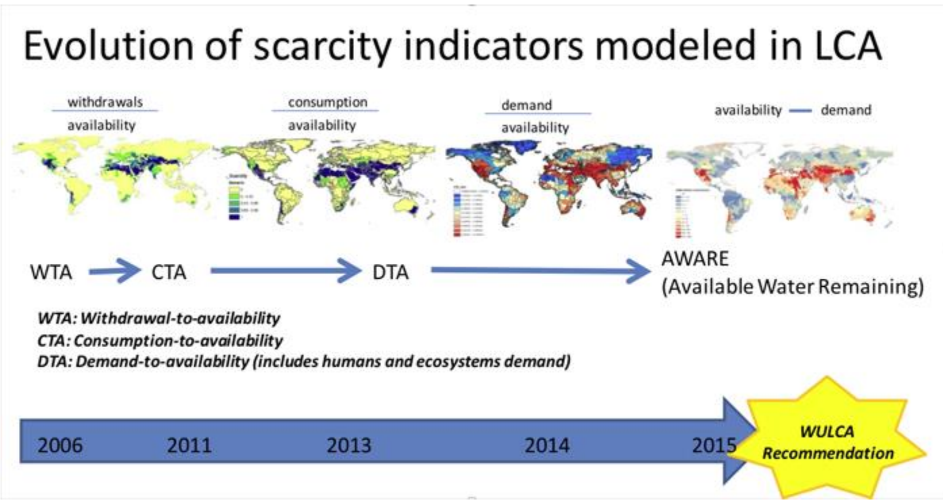

Fig. 2.1 Evolution of scarcity indicators modelled in LCA[3]

2.2.2 AWARE-method (2018)

The AWARE (Available WAter REmaining) is the outcome of a 2-year consensus building process by "Water Use in Life Cycle Assessment" (WULCA), a working group of the UNEP-SETAC Life Cycle Initiative. This group developed a water scarcity midpoint method for use in LCA and for water scarcity footprint assessments. The AWARE method is endorsed by the Joint Research Centre and will eventually become a part of ILCD recommendation.

The characterization model for water scarcity footprints is applied for assessing impacts of water consumption. The method is based on the quantification of the relative available water remaining per area once the demand of humans and aquatic ecosystems has been met. It assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived (Núñez et al. 2016).

It is answering the question "*What is the potential to deprive another user (human or ecosystem) when consuming water in this area?*" The resulting characterization factor (CF) ranges between 0.1 and 100 and can be used to calculate water scarcity footprints as defined in the ISO standard (Boulay et al. 2018). Importantly, the users looked at are both humans and ecosystems (see Fig. 2.2).

[3] https://www.wulca-waterlca.org/aware.html

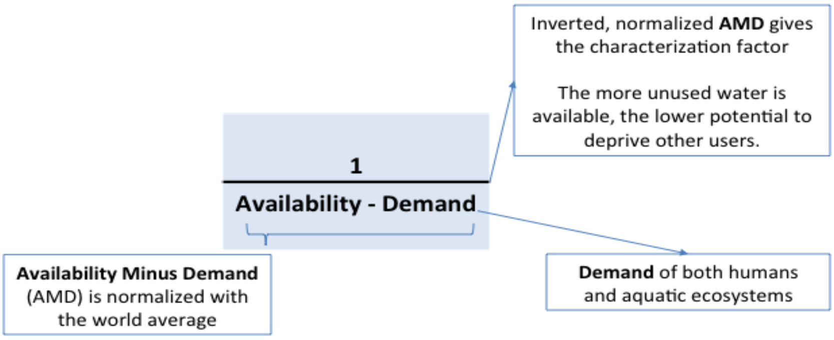

Fig. 2.2 Descriptive model of the AWARE indicator[4]

The characterisation factors are first calculated as the water Availability Minus the Demand (AMD) of humans and aquatic ecosystems and is relative to the area (m^3/m^2/month). In a second step, the value is normalized with the world average result (AMD = 0.0136 m^3/m^2/month) and inverted. The characterisation factor than represents the relative value in comparison with the average m^3 consumed in the world (the world average is calculated as a consumption-weighted average). Once inverted, 1/AMD can be interpreted as a surface-time equivalent to generate unused water in this region. The indicator is limited to a range from 0.1 to 100, with a value of 1 corresponding to the world average, and a value of 10, for example, representing a region where there is 10 times less available water remaining per area than the world average. The map below shows the factors at annual level per watersheds (normal average over 12 months).

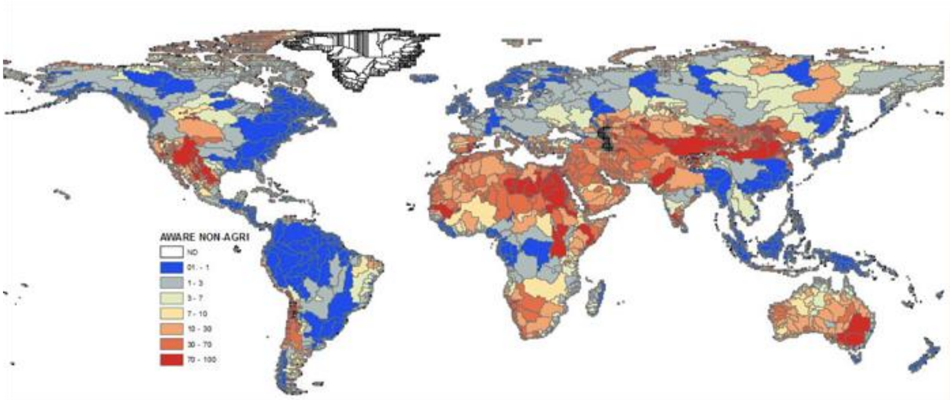

Fig. 2.3 Map of AWARE factors for non-agricultural activities (normal average over 12 months) Interpretation – Spatio-temporal scale

The indicator was calculated at the sub-watershed level and monthly time-step, and then aggregated in SimaPro to country and annual resolution. This aggregation can be done in diverse ways to better represent an agricultural use or a domestic/industrial use, based on the time and region of water use. Characterization factors for agricultural and non-agricultural use are provided in the method, as well

[4] https://simapro.com/2017/whats-new-simapro-8-3/, 05.03.2018

as default (“unknown”) ones if the activity is not known. The interpretation of results can be seen relative to the world average.[5]

It must be noted that an aggregated value at country/annual level based on consumption:

- Does not represent the “average picture” of the country/year. It may completely exclude large regions where no/very low consumption occur (i.e. deserts, most of Canada, etc.).
- Is strongly influenced by agricultural water use (in both “unknown” and “agri” values).
- Represents where/when water is most consumed: often in dryer months/regions.

For use with the ESU database (ESU-services 2024a, b), some special features must be taken into account. The AWARE factors in SimaPro (for the ecoinvent v3 database) also evaluate the water quantity for water turbines and cooling. However, the databases based on v2 do not include the corresponding return flows into the catchment area. Therefore these contributions are ignored. This is in line with the procedure used in FOEN studies (Jungbluth & Meili 2018).

2.2.3 Former assessment methods

Different LCIA methods are available for the assessment of water use and consumption (e.g. Milà i Canals et al. 2009; Pfister et al. 2009 or Hoekstra et al. 2011). In this section we provide an overview and we motivate the choice of the method applied in this study. Data availability is considered too.

The **ReCiPe method** (Goedkoop et al. 2009) quantifies the water use on a mid-point level but it is not considered in the end-point indicators. The category of the water depletion (WD) includes the water use from lakes, rivers, wells and unspecific natural origin.

The **Water Footprint** (Hoekstra et al. 2011) is a widely known and applied method to quantify the water consumption. The Water Footprint quantifies the blue, green and grey water of the direct (foreground system) and indirect (background system) water consumption. The water returned to the same watershed is not considered whereas the inter-basin water transfer is defined as consumption. The Water Footprint does not measure or asses the related environmental impacts of the water consumption. The blue and green water consumption is defined by the crop water use (m^3/ha) and the yield. The grey water consumption is calculated from the chemical application rate to the field (kg/ha), the leaching-run-of fraction as well as the maximum acceptable and the natural concentration for the most important pollutant, i.e. the pollutant that yields the highest grey water volume. This approach cannot be applied in a life cycle assessment because it requires unit process specific calculations instead of generic characterisation factors.

The approach of **Milà I Canals et al.** (2009) focuses on two impact pathways of the freshwater consumption: the freshwater ecosystem impact (FEI) and the freshwater depletion (FD). The FEI describes the effects on the ecosystem quality due to changes in the freshwater availability and in the water cycles as a result of land use changes. For the FEI, a water stress index ($WSI_{Milà}$) for different river basins is defined and used as mid-point characterisation factor. It is the ratio of the water withdrawal to the water available for human use after subtracting the needed amount of water for ecosystems (Smakhtin et al. 2004). The method of Milà I Canals et al. considers blue and indirectly green water consumption. The blue water is differentiated between flow (rivers and lakes), fund (aquifers) and stock (fossil).The discharge of used water to another watershed is not considered as water consumption. Concerning the consumption of green water, Milà I Canals et al. (2009) argue that it does not have a direct impact on the environment and as a consequence it should not be considered

[5] It should be noted that a characterisation factor value of 1 is not equivalent to the factor for the average water consumption in the world, i.e. the world average factor to use when the location is not known. This value is calculated as the consumption-weighted average of the factors, which are based on 1/AMD and not AMD, hence the world consumption-based average has a value of 43 for unknown use and 20 and 46 respectively for non-agricultural and agricultural water consumption respectively. https://www.wulca-waterlca.org/aware.html, 05.03.2018.

in the LCIA. It is rather the change in land use that should be assessed as it affects the infiltration and the evapotranspiration and consequently the availability of freshwater to other users. Following the land occupation categories of ecoinvent, land use effects are quantified. This factor and the $WSI_{Milà}$ result in the FEI. Seasonal fluctuations and regional differences along the river are not considered.

The reduced long-term availability of groundwater due to its use is described by the FD. The baseline method for abiotic resources depletion in the CML 2001 guidelines (Guinée et al. 2001b) is adapted for the development of characterisation factors for the FD. As the groundwater reserves are seldom quantified this approach is characterised with high uncertainties.

In the approach of **Pfister et al.** (2009) mid-point and end-point characterisation factors are provided for the assessment of the environmental impact of the water consumption. The method is adapted to the Eco-indicator-99 impact assessment method (Goedkoop & Spriensma 2000a). The focus lies on three areas of protection: human health, ecosystem quality and resources. The effects of water consumption on human health is characterised by the lack of water for irrigation, which consequently leads to malnutrition. The reduced availability of freshwater in ecosystems eventually leads to a diminished vegetation and biodiversity; and consequently, to a reduced ecosystem quality. The damages to resources described by Pfister et al. (2009) follow the concept of the abiotic resource depletion applied in EI99 (Goedkoop & Spriensma 2000a), where the "surplus energy" (MJ) needed to make the resource available in the future is used as indicator. In the context of water consumption, the energy use for desalination of seawater might be applied as a worst-case assumption (maximum estimation).

The approach of Pfister et al. (2009) considers only the consumption of blue water. It is defined as water that is no longer available to the water shed. Green water is not included directly but it is mentioned that with the lack of blue water the availability of green water might eventually be reduced too. A water stress index ($WSI_{Pfister}$) relates the water consumption to the water scarcity and serves as mid-point characterisation factor. The $WSI_{Pfister}$ accounts for the spatial variability in precipitation as well as the effects of strong regulations of flows. Even though the index is applicable to any spatial scale, the authors recommend to assess the water consumption on the water shed level.

The **eco-scarcity method** (Frischknecht et al. 2009) defines the scarcity of freshwater according to the water stress index of OECD (2004): Share of consumption to the available water resource (precipitation + inflows – evaporation). Based on national levels of water consumption and the acceptable water stress index defined by the OECD (2004), eco-factors are defined for the OECD-countries, the average of the OECD-countries and for six different levels of water scarcity. Furthermore, eco-factors are available on a watershed level[6]. The eco-factors are applicable to all types of water uses or consumptions except for the in-stream water use in hydroelectric power plants. The eco-factor can be applied on the (net) water withdrawal of drinking water supply, irrigation, industrial processes (incl. cooling water), etc. If fossil (non-renewable) water is consumed, the eco-factors of the most severe water stress category are to be applied. The water consumption is assessed on the midpoint as well as on the endpoint level. The European research institute DG-JRC in Ispra recommends the ecological scarcity approach for the assessment of water use and consumption as a mid-point indicators in LCIA (European Commission et al. 2011).

There are no requirements and guidelines for the assessment and reporting of water footprints yet published by the **International Organization for Standardization (ISO)**[7]. As a basis for the assessment of the methods presented and as a supporting information for the choice of one or more methods, the latest working draft (ISO 14046.3, International Organization for Standardization (ISO) 2011) is summarised shortly: According to this ISO draft, not only the amount of water consumption is to be considered but also the change in water quality. It is stated though that double-counting of the change in water quality (e.g. in combination with other impact categories) shall be avoided. The form

6 https://www.esu-services.ch/projects/ubp06/google-layer/
7 https://www.iso.org/iso/home.html

of water use considered is the water consumption according to the definition described above in Tab. 2.2. According to the ISO draft (2011), the applied assessment method should take into account the change in water availability for humans and other species, the different water sources (e.g. groundwater, surface water, sea water) as well as the quality of the water returned. The assessment should furthermore include regional conditions. A multi impact categories approach should at least differentiate between impacts on ecosystems, human health and on resources.

In Tab. 2.3 the main characteristics of the presented methods are summarized.

While the Water Footprint simply summarizes the water consumption and does not assess its environmental impact, the other three specified methods include at least one characterisation step. The Water Footprint may serve as a good guideline in the data collection but not as assessment method.

Pfister et al. (2011) as well as Frischknecht et al. (2009) have developed methods which assess the impact of the consumption of water resources. Both methods offer a midpoint as well as an endpoint indicator. While the assessment of the water use is part of the eco-scarcity method (Frischknecht et al. 2009), the method of Pfister et al. (2011) is easily combinable with the Eco-Indicator 99 (Goedkoop & Spriensma 2000a). This allows for the comparison of products and services on an endpoint level. This is not possible with the approach of Milà I Canals et al. (2009). Nevertheless, its consideration of the land use change might be very interesting for certain specific questions and comparisons.

The impacts of water use and consumption of the product systems under study are consequently assessed with the LCIA methods developed by Pfister et al. (2011) as well as the method proposed by Frischknecht et al. (2009).

Tab. 2.3: Overview of different approaches to quantify and assess the impacts of water consumption.

Method	Impact pathways	Available data	Required data/if specific calculations are requested	Integration in existing LCI / LCIA	Indicator
Water Footprint (Hoekstra et al. 2011)	-	-Product water footprint (e.g. global ethanol from sugarcane, maize and other crops) -Water footprint of crop production at national, sub-national and river basin level -water footprint of rain-fed and irrigated agriculture for maize, sugarcane and other crops	-Crop water use (green and blue water) -Chemical application rate -Leaching-run-of fraction -Max. acceptable concentration -Natural concentration	-ecoinvent data (used in the background system) are <u>not</u> compatible. -required data: blue and/or green water consumption of the foreground and background system	Water consumption (m^3)
Milà I Canals et al. (Milà i Canals et al. 2009)	-Freshwater ecosystem impact -Freshwater depletion	-Water stress index (WSI) for the world's main river basins -Land use effects	-Blue water consumption (crop evaporation requirement, effective rainfall, irrigation) -Land use occupation and transformation processes -Water resource (WR) -Environmental water requirement (EWR) -Evaporative and non-evaporative uses of fossil water and aquifers -Extraction rate of resource -Regeneration rate of resource -Ultimate reserve of resource		Water use impacts: ecosystem-equivalent water (m^3) Abiotic depletion potential (kg Sb eq)
Enhanced Eco-indicator 99 (Pfister et al. 2009)	-Human health -Ecosystem quality -Resources	WTA by WaterGAP2 Water stress index (WSI) Damage to human health (DALY) Ecosystem damage Damage to resources (MJ) LCA impact factors (EI99):Human health, ecosystem quality, resources and aggregated on watershed level	-Blue water consumed -Freshwater withdrawals -Hydrological availability -more parameters if the mid-point characterisation factors need to be calculated		Characterisation by WSI possible. Midpoint: Impact on human health (DALY), ecosystem quality ($PDF*m^2a$) and resources (MJ surplus) due to water consumption. Endpoint: EI99HA points (Can be integrated in the Eco-indicator 99 method)
Ecological scarcity method (Frischknecht et al. 2009a)	-Water scarcity, proxy indicator for impacts related to water use or consumption	Eco-factors 2006 based on the water stress index (WSI) of all countries in the world, for different scarcity situations and on watershed level	-Blue water use or consumption -National/regional level of water consumption -Available water resources (from FAO CropWat database)	- ecoinvent data (used in the background system) can easily be integrated if water use is assessed - required data: total water use or consumption of the foreground system	Eco-points (UBP)

2.3 Cumulative Energy Demand (CED)

CED (implementation according to Frischknecht et al. 2007b) describes the consumption of fossil, nuclear and renewable energy sources along the life cycle of a good or a service. This includes direct use as well as indirect or grey energy consumption due to the use of, e.g. plastic or wood as construction or raw materials. This method was developed in the early seventies after the first oil crisis and has a long tradition (Boustead & Hancock 1979; Pimentel 1973). A CED assessment can be a good starting point in an assessment due to its simplicity in concept and its comparability with CED results in other studies. In this study, the CED indicator is used as a resource indicator.

The following two CED indicators are calculated:

- CED, total
    - CED, non-renewable (MJ-eq.) – fossil and nuclear
    - CED, renewable (MJ-eq.) – hydro, solar, wind, geothermal, biomass

2.4 Cumulative Exergy Demand

The cumulative exergy demand (CExD) is based on the method developed for the ecoinvent database (Bösch et al. 2007; European Commission et al. 2010; Frischknecht et al. 2007b). The cumulative exergy demand is split into different subcategories to discriminate between different types of renewable and non-renewable origins. They are listed in Tab. 2.4.

Tab. 2.4 Explanation for the sub-categories of the cumulative exergy demand

Sub-category	Explanation
Non-renewable, fossil	Exergy content of fossil resources like coal, crude oil, natural gas, peat and others (chemical energy)
Non-renewable, nuclear	Energy from uranium converted in the technical system (nuclear energy)
Renewable, kinetic (wind)	Energy from wind converted in the technical system (kinetic energy)
Renewable, solar	Energy from the sun converted in the technical system (radiative energy)
Renewable, potential (water)	Energy from hydropower reservoir (potential energy)
Non-renewable, primary forest	Exergy content of wood from primary forests (chemical energy)
Renewable, biomass	Exergy content of other wood sources (chemical energy)
Renewable, water	Exergy content of extracted fresh water minus released water (chemical energy)
Non-renewable, metals	Exergy content of metal resources (chemical energy)
Non-renewable, minerals	Exergy content of mineral resources (chemical energy)

2.5 Acidification

Acidification describes a change in acidity in the soil due to atmospheric deposition of sulphates, nitrates and phosphates. Major acidifying substances are NO_X, NH_3, and SO_2. This covers all relevant substances as in the foreground system no emissions of other acidifying substances as HCl, HF, etc occur.

2.6 Eutrophication

Eutrophication can be defined as nutrient enrichment of the aquatic environment. In inland waters eutrophication is one of the major factors that determine its ecological quality.

2.7 Photochemical oxidation

Also known under “summer smog”. Photo-oxidant formation is the photochemical creation of reactive substances (mainly ozone), which affect human health and ecosystems. This ground-level ozone is formed in the atmosphere by nitrogen oxides and volatile organic compounds in the presence of sunlight.

2.8 Land competition

Not all types of land occupation have the same effect on the biodiversity.

3 European environmental footprint method (EF 3.1, 2023)

The Environmental Footprint (EF) method is developed and recommended by the EF Initiative of the European Commission for assessing the environmental impacts of products and organisations. It has thus already been developed for future use in consumer information. This method and its impact categories are also used for B2B communication in the context of environmental declarations in Europe (European Committee for Standardisation (CEN) 2022). The implementation in SimaPro is based on EF method 3.1. It includes normalization and weighting.

In the European context EF3.1 is often considered as state of the art because it has been updated recently, includes latest IPCC 2021 characterisation factors and is the method of choice for PEF and EPD studies. EF 3.1 is a political consensus. EF is not so much used in the US.

3.1 Characterisation

The characterization methods are described in one document (Andreasi Bassi et al. 2023). A description of the impact categories considered can be found in Tab. 3.1.

The indicators robustness and reliability are additionally described where I indicates good robustness and reliability and III indicates the lower robustness. The robustness is dependent on different factors. As example one indicator is described in terms of their robustness (Zampori & Pant 2019:Table 2).

The EF method for particulate matter characterises the emissions in terms of disease incidence due to the emission of particulate matter according to the model developed by Fantke et al. 2016. The representation of relevant substances in the background data is good and modelling generates reliable results.

Tab. 3.1 Midpoint impact categories used in this study (Andreasi Bassi et al. 2023)

Impact category	Impact assessment model	Indicator unit	Source	Robust-ness
Climate change	The Global Warming Potential (GWP) calculates the radiative forcing over a 100 year time horizon. It assesses the potential impact of different gaseous emissions on climate change.	kg CO_2 eq	IPCC 2021 + JRC adaptions	I
Ozone depletion	The Ozone Depletion Potential (ODP) calculates the destructive effects on the stratospheric ozone layer over a time horizon of 100 years. The stratospheric ozone layer reduces the amount of UV-radiation that reaches the ground, and which can cause damages for humans, animals, plants and materials.	kg CFC-11 eq	EDIP model based on the ODPs of WMO 2014 + integrations from other sources	I
Ionizing radiation	This category estimates the effect of radioactive emissions on human health. Most radiation stems from normal operation of nuclear power plants including the nuclear fuel production and treatment of radioactive wastes (accidents are not included). Quantification of the impact of ionizing radiation on the population is made with reference to Uranium 235.	kg U^{235} eq	Frischknecht et al. 2000	II
Photochemical ozone formation	This category calculates the effect of summer smog on human health. Ozone and other reactive oxygen compounds are formed as secondary contaminants in the troposphere (close to the ground). Ozone is formed by the oxidation of the primary contaminants VOC (Volatile Organic Compounds) or CO (carbon monoxide) in the presence of NOx (nitrogen oxides) under the influence of light. Expression of the potential contribution to photochemical ozone formation close to the ground. The method used includes spatial differentiation and is only valid for Europe. Considering a marginal increase in ozone formation, the LOTOS-EUROS spatially differentiated model averages over 14000 grid cells to define European factors.	kg NMVOC eq	Van Zelm et al. 2008 as applied in ReCiPe	II
Human toxicity, non-cancer	The unit “CTUh” (Comparative Toxic Unit for Humans) expresses the estimated increase in morbidity in the total human population due to different types of emissions entering into the environment. The calculation is based on USEtox® 2.1, which is a model that describes chemical fate, exposure, effect and optionally severity of emissions. No spatial differentiation beyond continent and world compartments. Specific groups of chemicals require further works (cf. details in other sections). Impact indicator: Comparative Toxic Unit for human (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram).	CTUh	Fantke et al. 2017 Rosenbaum et al. 2008 as in Saouter et al. 2018	III
Human toxicity, cancer	Based on USEtox 2.1 model, see above	CTUh	Fantke et al. 2017 Rosenbaum et al. 2008 as in Saouter et al. 2018	III
Acidification	This impact category describes potential impacts on soil and freshwater that becomes more acid due to the deposition of certain pollutants from air: The “Accumulated Exceedance” model characterizes the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.	molc H+ eq	Posch et al. 2008 Seppälä et al. 2006	II
Particulate matter	This category estimates the potential effect of fine dust emissions on human health: The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level. Exposure model based on archetypes that include urban environments, rural environments, and indoor environments within urban and rural areas.	Disease incidence	Fantke et al. 2016	I

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European environmental footprint method (EF 3.1, 2023)

Impact category	Impact assessment model	Indicator unit	Source	Robust-ness
Eutrophication, freshwater	Expression of the degree to which the nutrients emitted in Europe reach the freshwater and lead to the problem of eutrophication. Only phosphorus emissions are evaluated since it is considered as the limiting factor in freshwater. EUTREND model used to model atmospheric emissions. Impact indicator: Phosphorus equivalents: European validity. Averaged characterization factors from country dependent characterization factors.	kg P eq	Struijs et al. 2009 as implemented in ReCiPe	II
Eutrophication, marine	Expression of the degree to which nutrients emitted in Europe reach the oceans and lead to eutrophication. Only nitrogen emissions evaluated since it is considered as the limiting factor in marine water. EUTREND model used to model atmospheric emissions. Impact indicator: Nitrogen equivalents.	kg N eq	Struijs et al. 2009 as implemented in ReCiPe	II
Eutrophication, terrestrial	Eutrophication means that too many nutrients reach ecosystems and harm the plants and animals living in sensitive systems: The “Accumulated Exceedance” model characterizes the change in critical load exceedance of the sensitive terrestrial area, to which eutrophying substances (“excess nutrients”) deposit. It is European-country dependent which is not considered with the LCI data used in this study.	molc N eq	Posch et al. 2008 Seppälä et al. 2006	II
Ecotoxicity, freshwater	Measurement of environmental toxicity in freshwater due to emissions: The unit “CTUe” (Comparative Toxic Unit for ecosystems) is an expression of an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg). Specific groups of chemicals require further works. USEtox consensus model (multimedia model). No spatial differentiation beyond continent and world compartments. Specific groups of chemicals requires further works.	CTUe	Fantke et al. 2017 Rosenbaum et al. 2008 as in Saouter et al. 2018	III
Land use	Land use refers here to the amount and quality deficit of land occupied or transformed. This model is based on soil quality index as in LANCA model. CFs set was re-Calculated by JRC starting from LANCA® v 2.5 as baseline model. Out of 5 original indicators (Erosion resistance, Mechanical filtration, Physicochemical filtration, Groundwater regeneration, Biotic production) only 4 have been included in the aggregation (Physicochemical filtration was excluded due to the high correlation with the mechanical filtration). Biodiversity impacts are not covered in this method.[8]	Pt	De Laurentiis et al. 2019; Horn et al. 2018	III
Water use	Assessment of the water use related to local scarcity of water in different countries. Relative Available WAter REmaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met.	m^3 deprived	Boulay et al. 2018	III
Resource use, fossils	Abiotic resource depletion fossil fuels (ADP-fossil); based on lower heating value	MJ eq	van Oers et al. 2002	III
Resource use, minerals and metals	Ultimate reserves model. The model takes both the annual production as well as the availability of the resource into account. (CML 2002 model). ADP for energy carriers, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016). Depletion model based on use-to-availability ratio. Full substitution among fossil energy carriers is assumed.	kg Sb eq	van Oers et al. 2002	III

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8 The LCIA method in SimaPro has assigned characterisation factors for elementary flows of land use in the ocean „benthos“. These factors have been removed after consulting the authors of the method as they are not meaningful.

3.2 Long-term emissions

Some indicators are strongly dependent on long-term emissions. Such long-term emissions can only be modelled in a quite unreliable way. Some databases such as ecoinvent investigate long-term emissions of heavy metals and other pollutants (Frischknecht et al. 2007a). These emissions can take place in a time frame of 100 to 60'000 years from now. They mainly stem from waste disposal in landfills and deposits made during mining of metals.

If these long-term-emissions are included in the LCIA they can make up a considerable amount of the total impacts in the ILCD impact categories. The analysis of e.g. heating options shows that in five categories, a considerable part of total impacts solely stems from the long-term emissions if they are included in the LCI:

- Human toxicity, non-cancer effects: 50 to 80%
- Human toxicity, cancer effects: 4 to 80%
- Ionizing radiation HH: around 70% for all datasets
- Freshwater eutrophication: 30 to 90%
- Freshwater ecotoxicity: 40 to almost 100%

If long-term emissions are included in the assessment, background data on e.g. machinery become very relevant, but it is nearly impossible to check the appropriateness of this data.

An extensive discussion about the pros and cons of including long-term emissions in LCIA can be found in the Ecoinvent report on LCIA methods (Frischknecht et al. 2007b).

In the authors' view, other aspects also speak against assigning a high weight to long-term emissions in the LCA assessment (cf. the detailed discussion in Frischknecht et al. 2007b). ESU-services recommends excluding long-term emissions in the life cycle impact assessment because of the high uncertainties involved.

3.3 Adjustments for water use

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For the impact category water use, the available, country-specific scarcity factors are used. The determination and application of region-specific factors for water extraction would make the study and interpretation considerably more complex. However, the observation can be helpful in estimating the influence of unnecessarily extracted water. The difference between water withdrawal and return is relevant for the evaluation (and thus the removal of water from a region). This is often only roughly estimated in the data used and this indicator is thus considered relatively uncertain.

With the update to ecoinvent 3.10 new leachate treatment processes were introduced to land-fill datasets (FitzGerald et al. 2023). Since these datasets do not consider the rainwater in-put, but the water released to a waterbody after treatment, their water balance is not closed. Hence, the deprived water indicator is negative if calculated with the original EF 3.1/EN15804+A2 impact assessment method. To avoid these incorrect results, an additional deprived water indicator was added following the implementation of water use indicators in ecoinvent. Ecoinvent states: "The issue with water is similar to the carbon imbalance: allocation dis-torts the balance and simply applying positive [characterisation factors] to water consumptions and negative [characterisation factors] to water emission back to water would lead to unreliable water scores. However, ecoinvent rigorously reports water evaporation to air. This quantity represents the water that leaves the ecosystem without being available for its usual function, so the general approach is to apply (positive) [characterisation factors] only to those [elementary flows]." (Sonderegger & Stoikou 2023, p. 22) The adjusted water use indicator considers only the water evaporation flows using the regionalised characterisation factors of the original methods for water withdrawals from unspecified natural origin.

For use with the ESU database (ESU-services 2024a, b), some special features are considered. The AWARE factors in SimaPro (for the ecoinvent v3 database) also evaluate the water quantity for water turbines and cooling. However, the databases based on ecoinvent v2 do not include the corresponding return flows into the catchment area. Therefore, these contributions are ignored.

3.4 Normalization and Weighting

The normalization and weighting factors are shown in Tab. 3.2

- Normalization (Crenna et al. 2019).
- Weighing factors (Sala et al. 2018)

Tab. 3.2 Normalization and weighting factors applied for the EF method in SimaPro

Impact category	Normalization	Weighting
Climate change	0,0001324	21,1%
Ozone depletion	19,10	6,3%
Ionising radiation	0,000237	5,0%
Photochemical ozone formation	0,02447	4,8%
Particulate matter	1680	9,0%
Human toxicity, non-cancer	7768	1,8%
Human toxicity, cancer	57961	2,1%
Acidification	0,018	6,2%
Eutrophication, freshwater	0,6223	2,8%
Eutrophication, marine	0,05116	3,0%
Eutrophication, terrestrial	0,005658	3,7%
Ecotoxicity, freshwater	0,00001763	1,9%
Land use	0,00000122	7,9%
Water use	0,00008719	8,5%
Resource use, fossils	0,00001538	8,3%
Resource use, minerals and metals	15,72	7,6%

3.5 Reliability of impact categories indicator results

One issue that arises when using methods such as the EF method is the interpretation of possible trade-offs between different impact categories. In several cases in this study, different processing alternatives were determined to be more favourable depending on the indicators. One solution to this is normalisation and weighting, which determines which indicators are considered more or less important and summarises all environmental impacts in one dimensionless indicator (single score).

Normalisation refers to calculating the magnitude of category indicator results relative to reference information. In many cases, total emissions and the resource use of one person over the course of a year in a certain area e.g. Switzerland, Europe, or worldwide are used as a reference. Weighting refers to converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices. The weighting factors applied express the relative importance of different environmental indicators for decision making. This can be based on the environmental relevance, but also on other aspects such as reliability of the indicator. Single scores are calculated by adding the results of all category indicators multiplied by the normalisation factor and the weighting factor for each category (International Organization for Standardization (ISO) 2006). The world population was used to calculate the normalisation factors and the weighting system developed by Sala et al. 2018 was applied in the Environmental Footprint method.

Climate change is often in the forefront of public debate on environmental issues and during the development of the weighting approach for the EF method, surveys of the general population and LCA experts revealed that climate change was one of the top three concerns in all three categories considered (human health, natural environmental, and natural resources) for both survey groups (Sala et al. 2018). The IPCC models show that global warming is likely to happen to an extent that can be considered dangerous, and the scenarios of 2013 show more global warming compared to the scenarios from 2007, indicating that the problem is intensifying. Therefore, this problem is generally considered important for the interpretation of LCA results.

The assessment of the impact on ozone depletion is based on sound modelling. However, much of the impact stems from background data. The emissions of ozone depleting substances were reduced considerably in the past years since the Montreal protocol regulates the phasing out of the use of these substances. Which means the age of data sources often determines the ozone depletion result (and not the real impact). Therefore, the results in this impact category do not provide much informative value and this indicator should not be given priority when comparing the environmental impacts.

The category ionising radiation reflects the use of nuclear power. Since market mixes were used, the share of nuclear power is reflected in the impacts in this category. This category is therefore important if different energy-generation systems are being compared, for example the comparison of cultivation approaches partly powered by photovoltaics vs. conventional electricity.

According to the previously-mentioned survey of LCA experts, particulate matter was considered to be the second most worrisome category in terms of human health, after only human toxicity, cancer (Sala et al. 2018). The EF method characterises the emissions in terms of disease incidence due to the emission of particulate matter according to the model developed by Fantke et al. 2016. The representation of relevant substances in the background data is good and modelling generates reliable results.

Nitrogen oxides play a key role in the impact categories photochemical ozone formation, acidification, and marine and terrestrial eutrophication. As a result, there is a certain degree of correlation between these impact categories and the overlap should be considered in the interpretation. Freshwater eutrophication on the other hand is dominated by phosphorous emissions.

In terms of human health, both experts and members of the general public consider human toxicity, cancer to be the most worrisome impact category and the general public rated both types of human toxicity as relevant (Sala et al. 2018). While these impact categories are deemed important, they are, along with freshwater ecotoxicity, among the least robust indicators included in the method (Sala et al. 2018: Table 30).

Land use and water use were considered relevant in the survey of LCA experts (Sala et al. 2018), and land use in particular is an important factor to be considered when comparing biogenic products. Although both methods have been updated since the ILCD, these impact categories are not considered highly robust (Sala et al. 2018: Table 30).

Resource use, fossils is driven using fossil fuels and feedstocks and thus often shows a similar tendency as the climate change indicator. The category resource, minerals and metals is often dominated by one single substance, with a characterisation factor, which should be taken into account when considering this impact category.

3.6 Reference values and examples

Tab. 3.3 shows typical reference values for this impact assessment method.

Tab. 3.3 Reference values for products and services causing one thousandth EF points

EF3.1	One milli-eco-point equals ...
24.206,7	litres of tapwater from Switzerland
0,9	centimeters road, used for one year
35,9	kilograms of fossil CO2, directly emitted
1,2	kilograms of fossil methane, directly emitted
11,13	grams copper input into agricultural soil
10,8	litres crude oil produced, with transport to the refinery
0,20	grams pesticide application in agriculture
25%	of a person's private daily consumption in Switzerland, 2018
24%	the daily consumption of a person in Switzerland
100,7	km transport of one person by plane
62,5	km transport of one person by car (occupancy 1.6 persons)
1.536,3	km transport of one person by bicycle
102%	of a vegetarian menu with 4 courses
63%	of a meaty 3-course menu
136%	of the daily food consumption of a person in Switzerland, 2018
2,1	plastic carrier bags (production, distribution and disposal)
0,18	cotton T-Shirts
1,2%	of the production of a laptop
335%	of daily consumption for hobbies/leisure activities in Switzerland, 2018
595%	of daily consumption of furniture and household appliances in Switzerland, 20

4 EN 15804 + A2 (2022) for environmental product declaration

This standard covers Environmental Product Declarations (EPDs) of Construction Products. The 2019 EN 15804 + A2 revision of this standard has aligned their methodology with the Environmental Footprint method, except for their approach on biogenic carbon.

This list of characterisation models and factors is used also in other EPDs for the default environmental impact categories. This recommendation is updated on a regular basis. It is based on the latest developments in LCA methodology and ensuring the market stability of EPDs.

According to the EN 15804, biogenic carbon emissions cause the same amount of Climate change as fossil carbon but can be neutralized by removing this carbon from the atmosphere again.

EF 3.1 normalization and weighting values, published in July 2022, are used.

The source and version of the characterisation models and the factors used shall be reported in the EPD. Alternative regional life cycle impact assessment methods and characterisation factors are allowed to be calculated and displayed in addition to the default list. If so, the EPD shall contain an explanation of the difference between the different sets of indicators, as they may appear to the reader to display duplicate information.

4.1 Use of resources

Tab. 4.1 Indicators for the use of resources

Use of resources			
PARAMETER			UNIT
	Use as energy carrier	PERE	MJ, net calorific value
	Used as raw materials	PERM	MJ, net calorific value
Primary energy resources – Renewable	TOTAL	PERT	MJ, net calorific value
	Use as energy carrier	PENRE	MJ, net calorific value
	Used as raw materials	PENRM	MJ, net calorific value
Primary energy resources – Non-renewable	TOTAL	PENRT	MJ, net calorific value
Secondary material		SM	kg
Renewable secondary fuels		RSF	MJ, net calorific value
Non-renewable secondary fuels		NRSF	MJ, net calorific value
Net use of fresh water		FW	m3

4.2 Waste production and output flows

Tab. 4.2 Indicators for waste production and output flows

Waste production		
PARAMETER		UNIT
Hazardous waste disposed	HWD	kg
Non-hazardous waste disposed	NHWD	kg
Radioactive waste disposed	RWD	kg
Output flows		
PARAMETER		UNIT
Components for reuse	CRU	kg
Material for recycling	MFR	kg
Materials for energy recovery	MER	kg
Exported energy, electricity	EE	MJ
Exported energy, thermal	EE	MJ

4.3 Additional indicators

To better characterise the environmental performance of a product category, the PCR shall indicate the mandatory or voluntary use of other indicators of potential impacts. All environmentally relevant indicators for the product category shall be included. Examples of such environmental impact categories to include in the PCR are:

- emission of ozone-depleting gases, in SimaPro 'Ozone layer depletion (ODP) (optional)'
- land use and land use change.

Tab. 4.3 Mandatory environmental indicators according to PCR 2019 (v1.2.3)

Impact category as named in PCR 2024 v1.2.3	Impact category as named in EN 15804+A2 in SimaPro	Unit
Climate change - total	Climate change	kg CO2 eq
Climate change - fossil fuels	Climate change - Fossil	kg CO2 eq
Climate change - biogenics	Climate change - Biogenic	kg CO2 eq
Climate change - land use and land use transformation,	Climate change - Land use and LU change	kg CO2 eq
Ozone depletion	Ozone depletion	kg CFC11 eq
Acidification	Acidification	mol H+ eq

Impact category as named in PCR 2024 v1.2.3	Impact category as named in EN 15804+A2 in SimaPro	Unit
Freshwater eutrophication	Eutrophication, freshwater	kg P eq
Marine aquatic eutrophication	Eutrophication, marine	kg N eq
Terrestrial eutrophication	Eutrophication, terrestrial	mol N eq
Photochemical ozone formation	Photochemical ozone formation	kg NMVOC eq
Abiotic resource depletion - elements or resource depletion - metals and minerals	Resource use, minerals and metals	kg Sb eq
Abiotic resource depletion - fossil fuels or resource depletion – fossils	Resource use, fossils	MJ
Water requirement	Water use	m3 depriv.

Tab. 4.4 Optional environmental indicators according to PCR 2024 v1.2.3

Impact category as named in PCR 2024 v1.2.3	Impact category as named in EN 15804 A2 in SimaPro	Unit
Emission of fine particles	Particulate matter	disease inc.
Ionizing radiation, human health	Ionising radiation	kBq U-235 eq
Ecotoxicity (fresh water)	Ecotoxicity, freshwater	CTUe
Human toxicity, carcinogenic effects	Human toxicity, cancer	CTUh
Human toxicity, non-carcinogenic effects	Human toxicity, non-cancer	CTUh
Impacts related to land use/soil quality	Land use	Pt

5 Swiss Ecological Scarcity Method 2021 (eco-points 2021)

The ecological scarcity method (BAFU 2021) evaluates the inventory results on a distance to target principle. The calculation of the eco-factors is based on one hand on the actual emissions (actual flow) and on the other hand on Swiss environmental policy and legislation (critical flow). These goals are:

- Ideally mandatory or at least defined as goals by the competent authorities,
- formulated by a democratic or legitimised authority, and
- preferably aligned with sustainability.

The weighting is based on the goals of the Swiss environmental policy; global and local impact categories are translated to Swiss conditions, i.e. normalised. The method is applicable to other regions as well. Eco-factors were also developed for the Netherlands, Norway, Sweden (Nordic Council of Ministers 1995, Tab. A22 / A23), Belgium (SGP 1994), Germany (Ahbe et al. 2014) and Japan (Miyazaki et al. 2004). The ecological scarcity method allows for an optimisation within the framework of a country's environmental goals.

The environmental and political relevance is essential for the choice of substances. The environmental policy does by far not define goals for all substances. Thus, the list of eco-factors is limited. This particularly applies to substances with low or unknown environmental relevance in Switzerland and Europe (e.g. sulphate emissions in water bodies).

The Method of ecological scarcity allows the weighting of the resource withdrawals and pollutant emissions recorded and calculated in a Life Cycle Inventory. The basic principles of the method were first developed in 1978 (Müller-Wenk 1978). The first update took place in 1998 (Brand et al. 1998). Another update took place between 2005, 2008 and 2013 (Frischknecht et al. 2008; Frischknecht et al. 2013). The most recent version was published in 2021 (BAFU 2021).

The method of ecological scarcity is based on the "distance-to-target" principle. It uses the total current fluxes of an environmental impact (e.g. nitrogen oxides) of a country on the one hand and the fluxes of the same environmental impact that are considered maximum permissible (critical) within the framework of the environmental policy objectives of the respective country on the other. Both critical and current fluxes are defined in relation to Swiss conditions.

Fig. 5.1 shows a simplified procedure for this assessment method. This shows that the classification and characterisation steps are only carried out for part of the environmental problems. Otherwise, the environmental impacts (emissions and resource consumption) and waste quantities from the Life Cycle Inventory are weighted directly.

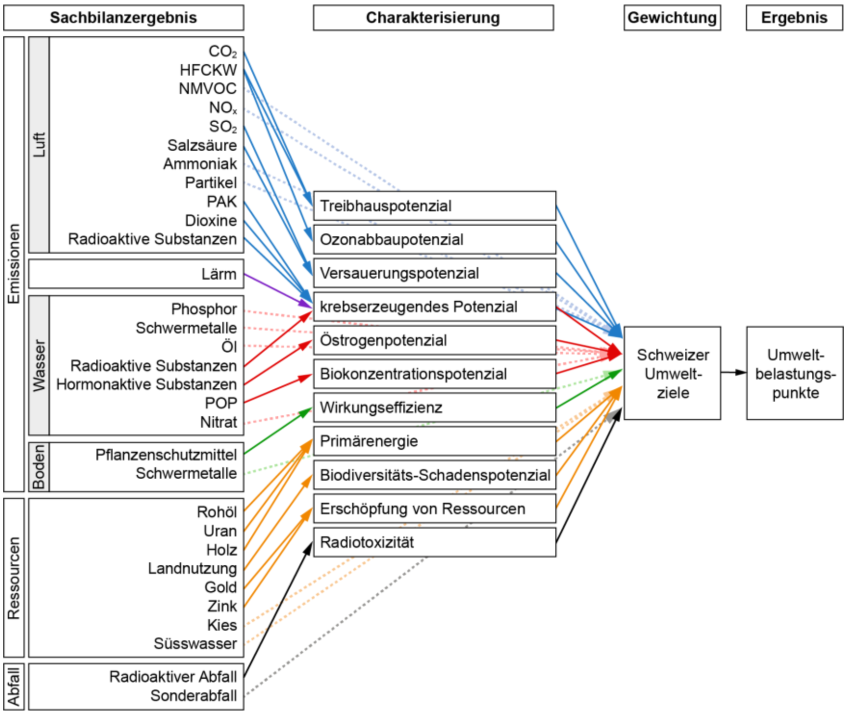

Fig. 5.1 Schematic illustration of the method of ecological scarcity 2013 (Frischknecht et al. 2013)

The evaluation is carried out using ecofactors which are defined as follows:

$$\text{Ecofactor} = \underbrace{K}_{\substack{\text{characterization}\\ \text{(optional)}}} \cdot \underbrace{\frac{1 \cdot \text{UBP}}{F_n}}_{\text{normalization}} \cdot \underbrace{\left(\frac{F}{F_k}\right)^2}_{\text{weighting}} \cdot \underbrace{c}_{\text{constant}} \qquad (8.1)$$

with: **K** = **Characterisation factor** of a pollutant or resource

Flow = Cargo of a pollutant, consumption quantity of a resource or quantity of a characterised environmental impact

Fn = **Normalisation flow**: Current annual flow, relative to Switzerland

F = **Current flow**: Current annual flow, related to the reference area.

Fk = **Critical flow**: Critical annual flow relative to the reference area.

c = **Constant (1012/a)**

UBP = **Environmental Impact Point**: Unit of the evaluated result.

Factor c is identical for all ecofactors and serves to improve the manageability of the numbers. The first factor is used for characterisation and is applied to pollutants (or resources) that have the same environmental impact (e.g. climate change). The characterisation factor is optional in this method, i.e. not all pollutants are characterised in this method. The second term is used for standardization/normalization and contains the denominator of today's Swiss flux. This is either given in characterised form (e.g. tonnes of CO2 equivalents per year) if a characterisation factor is applied to the relevant pollutant, or in its original form (e.g. tonnes of PM10 per year) if the pollutant has no characterisation factor. The third term contains the weighting step. Here the current emissions on the one hand and the targeted emission goal on the other hand are put into proportion and squared.

The ratio of current to critical flow is taken into account as a square. This has the effect that strong overruns of the target value (critical flow) are weighted disproportionately and strong underruns are weighted disproportionately, i.e. an additional emission is weighted more strongly the higher the pollution situation already is.

According to the authors of the method, waste is assessed according to the precautionary principle. This procedure does not comply with the requirements of ISO 14044 for the definition of environmental indicators (International Organization for Standardization (ISO) 2006). The derivation of eco-factors for individual pollutants also does not follow the specifications of the ISO standard, as these are only partially grouped according to environmental problems. These two indicators should therefore not be used for ISO-compliant life cycle assessments.

Thousands of eco-points (1000 UBP) correspond to the reference values shown in Tab. 5.1.

Tab. 5.1 Reference values for products and services causing 1000 eco-points

MoeK21	Thousand eco-points equal ...
1'489.5	litres of tapwater from Switzerland
4.0	centimeters road, used for one year
1.0	kilograms of fossil CO2, directly emitted
0.033	kilograms of fossil methane, directly emitted
1.30	grams copper input into agricultural soil
0.73	litres crude oil produced, with transport to the refinery
35.7	kilograms of gravel mining
0.5	grams pesticide application in agriculture
1.4%	of a person's private daily consumption in Switzerland, 2018
1.3%	the daily consumption of a person in Switzerland
2.7	km transport of one person by plane
2.9	km transport of one person by car (occupancy 1.6 persons)
65.4	km transport of one person by bicycle
4%	of a vegetarian menu with 4 courses
3%	of a meaty 3-course menu
5%	of the daily food consumption of a person in Switzerland, 2018
20.3	plastic carrier bags (production, distribution and disposal)
0.043	cotton T-Shirts
0.17%	of the production of a laptop
23%	of daily consumption for hobbies/leisure activities in Switzerland, 2018
42%	of daily consumption of furniture and household appliances in Switzerland, 2018

6 IMPACT World+ (2019)

6.1 What is ImpactWorld+?

ImpactWorld+ is a Life Cycle Impact Assessment (LCIA) methodology published in 2019[9] that extends beyond current regional modelling capabilities to a global level in order to consistently assess regional life cycle emission inventories in the context of a global economy. It should serve both industries and public administrations, through life cycle assessment (LCA) practitioners to support the development of production and consumption policies and to improve the products and services provided, while reducing environmental and health impacts.

6.2 How does ImpactWorld+ differ from other LCIA methods?

Current LCIA methods have some drawbacks (lack of regionalization for impacts, multiple sources of uncertainty including geographical and temporal variability). The ImpactWorld+ LCIA methodology aims for a better decision-making by increasing the discrimination power of LCA. It leads to more precise and environmentally relevant LCA results by applying more scientifically reliable and state of the art models. ImpactWorld+ integrates uncertainty related to characterization factors and/or impact categories, it uses leading edge characterization modelling. It is also the first global regionalized method, which allows assessing and discriminating a same emission occurring in different geographical locations across the globe.

6.3 Features

With IMPACT World+, a midpoint-damage framework with four distinct complementary viewpoints to present an LCIA profile: (1) midpoint impacts, (2) damage impacts, (3) damages on human health, ecosystem quality, and resources & ecosystem service areas of protection, and (4) damages on water and carbon areas of concerns, is proposed. Most of the regional impact categories have been spatially resolved and all the long-term impact categories have been subdivided between shorter- term damages (over the 100 years after the emission) and long-term damages.

The IMPACT World+ method integrates developments in the following categories, all structured according to fate (or competition/scarcity), exposure, exposure response, and severity: (a) Complementary to the global warming potential (GWP100), the IPCC Global Temperature Potentials (GTP100) are used as a proxy for climate change long-term impacts at midpoint. At damage level, shorter-term damages (over the first 100 years after emission) are also differentiated from long-term damages. (b) Marine acidification impact is based on the same fate model as climate change, combined with the H+ concentration affecting 50% of the exposed species. (c) For mineral resources depletion impact, the material competition scarcity index is applied as a midpoint indicator. (d) Terrestrial and freshwater acidification impact assessment combines, at a resolution of 2° × 2.5° (latitude × longitude), global atmospheric source-deposition relationships with soil and water ecosystems' sensitivity. (e) Freshwater eutrophication impact is spatially assessed at a resolution grid of 0.5° × 0.5°, based on a global hydrological dataset. (f) Ecotoxicity and human toxicity impact are based on the parameterized version of USEtox for continents. The authors consider indoor emissions and differentiate the impacts of metals and persistent organic pollutants for the first 100 years from longer-term impacts. (g) Impacts on human health related to particulate matter formation are modeled using the USEtox regional archetypes to calculate intake fractions and epidemiologically derived exposure response factors. (h) Water consumption impacts are modeled using the consensus-based scarcity indicator AWARE as a proxy midpoint, whereas damages account for competition and adaptation capacity. (i) Impacts on ecosystem quality from land transformation and occupation are empirically characterized at the biome level.

[9] https://link.springer.com/article/10.1007%2Fs11367-019-01583-0

The authors analyze the magnitude of global potential damages for each impact indicator, based on an estimation of the total annual anthropogenic emissions and extractions at the global scale (i.e., Bdoing the LCA of the world^). Similarly with ReCiPe and IMPACT 2002+, IMPACT World+ finds that (a) climate change and impacts of particulate matter formation have a dominant contribution to global human health impacts whereas ionizing radiation, ozone layer depletion, and photochemical oxidant formation have a low contribution and (b) climate change and land use have a dominant contribution to global ecosystem quality impact. (c) New impact indicators introduced in IMPACT World+ and not considered in ReCiPe or IMPACT 2002+, in particular water consumption impacts on human health and the long-term impacts of marine acidification on ecosystem quality, are significant contributors to the overall global potential damage.

According to the areas of concern version of IMPACT World+ applied to the total annual world emissions and extractions, damages on the water area of concern, carbon area of concern, and the remaining damages (not considered in those two areas of concern) are of the same order of magnitude, highlighting the need to consider all the impact categories. The spatial variability of human health impacts related to exposure to toxic substances and particulate matter is well reflected by using outdoor rural, outdoor urban, and indoor environment archetypes. For Bhuman toxicity cancer^ impact of substances emitted to continental air, the variability between continents is of two orders of magnitude, which is substantially lower than the 13 orders of magnitude total variability across substances. For impacts of water consumption on human health, the spatial variability across extraction locations is substantially higher than the variations between different water qualities. For regionalized impact categories affecting ecosystem quality (acidification, eutrophication, and land use), the characterization factors of half of the regions (25th to 75th percentiles) are within one to two orders of magnitude and the 95th percentile within three to four orders of magnitude, which is higher than the variability between substances, highlighting the relevance of regionalizing.

6.4 Conclusions

IMPACT World+ provides characterization factors within a consistent impact assessment framework for all regionalized impacts at four complementary resolutions: global default, continental, country, and native (i.e., original and non-aggregated) resolutions. IMPACT World+ enables the practitioner to parsimoniously account for spatial variability and to identify the elementary flows to be regionalized in priority to increase the discriminating power of LCA. IMPACT World+ does not provide recommended weighting factors.

7 Swiss environmental footprint indicators (2018)

Set of LCIA indicators applied by the FOEN (Frischknecht et al. 2018). Overview:

- Overall environmental footprint. Ecological scarcity method 2013 (Frischknecht et al. 2013)
- Greenhouse gas footprint (Solomon et al. 2007)
- Biodiversity footprint (Chaudhary et al. 2015; Chaudhary et al. 2016)
- Eutrophication footprint (Marine eutrophication, Goedkoop et al. 2009)
- Air pollution footprint (particulate matter, Goedkoop et al. 2009)
- Water footprint (Kounina et al. 2013)
- Material footprint (Ores, minerals, fossil energy, (woody) biomass) (Schoer et al. 2012).

Overall environmental footprint according to the Ecological scarcity method 2013 (Frischknecht et al. 2013).

Climate change (**greenhouse gas footprint**): The climate impact of greenhouse gases is expressed in terms of global warming potential (GWP) according to the 4th Assessment Report of the

Intergovernmental Panel on Climate Change (CO2 equivalents according to IPCC 2007). The additional heating effects of stratospheric emissions from aircraft are considered with a small factor. The calculation of the corresponding characterization factors is described in the technical report (Frischknecht et al. 2018). These emissions are also covered in the overall environmental footprint.

Loss of biodiversity through land occupation (**biodiversity footprint**): Land occupation has a major impact on biodiversity and species loss. The indicator for the species loss potential (Chaudhary et al. 2016) quantifies the potential damage of land use in relation to biodiversity. The indicator quantifies the loss of species in amphibians, reptiles, birds, mammals and plants by using an area as farmland, permanent crop, pasture, intensively used forest, extensively used forest or settlement area. The indicator weighted endemic species higher than species that are common. The loss of species is determined in relation to the biodiversity of the natural state of the area in the region concerned. This indicator was recommended by the UNEP SETAC Life Cycle Initiative as currently the best available indicator for a transitional period ("interim recommendation", Chaudhary et al. 2015; Chaudhary et al. 2016; Frischknecht & Jolliet 2017). Impacts on biodiversity are covered also in the overall environmental footprint with several different factors (land occupation, water use, eutrophication, pesticides, acidification, etc.).

Overfertilization (**eutrophication footprint**): The introduction of nitrogen into the environment causes a wide range of problems. The most obvious of these is marine eutrophication ("overfertilization"): This indicator quantifies the amount of nitrogen that potentially enters the oceans via the emission of nitrogen compounds into water, air and soil and contributes to overfertilization there (Goedkoop et al. 2009). The quantities of nitrogen are considered according to their marine eutrophication potential (kg N equivalents). These emissions are also covered in the overall environmental footprint.

Particulate matter (**air pollution footprint**): The extent of air pollution has a major influence on the health and thus the well-being of the population. Air pollution is described with primary and secondary particles and the associated effects on human health, such as respiratory diseases (Goedkoop et al. 2009). The emissions of the fine dust precursors NOX, SO2 and NH3 are added to the direct emissions of fine dust according to their potential to form fine dust (kg PM10 equivalents). These emissions are also covered in the overall environmental footprint.

Water use (**water footprint**): Describes how much Switzerland uses the global resource (fresh) water, considering the water shortage in the production regions. This is illustrated by the water scarcity indicator AWARE recommended by the UNEP SETAC Life Cycle Initiative (Boulay et al. 2018). Specifications: consuming water use, non-specific activity. Within some background databases water flows are only partly regionalized. These resource uses are also covered in the overall environmental footprint.

Raw materials (**material footprint**, RMC): The material footprint quantifies the consumption of raw materials at home and abroad caused by a country's domestic final demand. The Swiss material footprint is collected by the FSO according to the method of the Statistical Office of the European Union (Eurostat) and divided into the categories ores, minerals, fossil fuels and biomass (BFS 2015). In this study, the material footprint is modelled with the data used here to determine the influence of method and data basis on the results. For the quantification of the material footprint, the total amount of materials required for the manufacture of a product is considered, not just the product itself. Each raw material extraction is multiplied accordingly by one raw material equivalent (RÄ, quantity ore per kg metal, 95.8 kg ore per kg copper). The RÄ factors for ores are based on data from Schoer et al (2012). Only woody biomass is considered with the implementation of this method provided by FOEN and the KBOB database. No elementary flows concerning the production of agricultural biomass are recorded in the KBOB database that could be used with the factors provided for fish, fodder, etc. No extensions have been made to the background database for this indicator. These resource uses are also covered in the overall environmental footprint.

8 Environmental impacts according to ReCiPe (2016)

8.1 ReCiPe 2016

The authors of the updated ReCiPe 2016 (Huijbregts et al. 2017) implemented human health, ecosystem quality and resource scarcity as three areas of protection. Endpoint characterisation factors, directly related to the areas of protection, were derived from midpoint characterisation factors with a constant mid-to-endpoint factor per impact category. The authors included 18 midpoint impact categories.

The update of ReCiPe provides characterisation factors that are representative for the global scale instead of the European scale, while maintaining the possibility for a number of impact categories to implement characterisation factors at a country and continental scale. The authors also expanded the number of environmental interventions and added impacts of water use on human health, impacts of water use and climate change on freshwater ecosystems and impacts of water use and tropospheric ozone formation on terrestrial ecosystems as novel damage pathways. Although significant effort has been put into the update of ReCiPe, there is still major improvement potential in the way impact pathways are modelled. Further improvements relate to a regionalisation of more impact categories, moving from local to global species extinction and adding more impact pathways.

No single score weighting is proposed anymore for the updated version, but the weighting scheme proposed for the previous version still might be applied.

The method ReCiPe 2016 is outdated for some indicators e.g. the global warming potential for which the IPCC published newer characterisation factors in the meantime. Still it is used by some LCA practitioners because of its high scientific consistency.

8.2 ReCiPe 2008 (outdated)

The ReCiPe 2008 method (Goedkoop et al. 2009) was developed by the Dutch National Institute for Public Health and the Environment (RIVM), the Radboud University, the Dutch Institute of Environmental Sciences (CML) at Leiden University and PRé Consultants.

The method determines environmental indicators at midpoint and endpoint level. Analyses on both levels are possible. The following eighteen ReCiPe midpoint indicators are calculated (the reference substance is indicated in brackets)*:*

- Climate change (kg CO2 eq.)
- Ozone depletion (ODP) (kg CFC-11 eq.)
- Terrestrial acidification (kg SO2 eq.)
- Freshwater eutrophication (kg P eq.)
- Marine eutrophication (kg P eq.)
- Human toxicity (kg 1,4-DB eq.)
- Photochemical oxidation (kg NMVOC eq.)
- Particulate matter formation (kg PM10 eq.)
- Terrestrial ecotoxicity (kg 1,4-DB eq.)
- Freshwater ecotoxicity (kg 1,4-DB eq.)
- Marine ecotoxicity (kg 1,4-DB eq.)
- Ionising radiation (kg U235 eq.)
- Agricultural land occupation (m2*yr eq.)
- Urban land occupation (m2*yr eq.)
- Natural land transformation (m2 eq.)

- Water depletion (m3 eq.)
- Mineral resource depletion (kg Fe eq.)
- Fossil resource depletion (kg oil eq.)

The midpoint indicators are aggregated to three endpoint indicators:

- Damage to Human health (Disability-adjusted loss of life years)
- Damage to ecosystems (Loss of species during a year)
- Damage to resource availability (Increased cost)

The damages to these three safeguard subjects are weighted and aggregated to one single score. Three different perspectives were developed to represent different perceptions of the world with regard to time preference, uncertainty or local preference (hierarchist, individualist and egalitarian). The hierarchist perspective is the most balanced type (balance between future and present impacts, between risks and benefits and between his or her neighbourhood and the world).

9 Environmental product declaration (Environdec) (2018) - outdated

A former recommendations was made 2018-05-30 (Photo-oxidation Formation Potential, short: POFP) and 2018-06-08 (Water Scarcity Footprint). The characterisation models and factors to use for the default impact categories are available in the table below.

Tab. 9.1 Default environmental impact categories

Impact category (Unit)	Characterisation factors	Original reference(s)	Examples
Global warming potential (kg CO2 eq.) in SimaPro 'Global warming (GWP100a)'	GWP100, CML 2001 **baseline** Version: January 2016.	IPCC 2021	1 kg carbon dioxide = 1 kg CO2 eq. 1 kg methane = 28* kg CO2 eq. 1 kg dinitrogen oxide = 265 kg CO2 eq.
Acidification potential (kg SO2 eq.) in SimaPro 'Acidification (fate not incl.)'	AP, CML 2001 **non-baseline** (fate not included), Version: January 2016. *Please notice the use of non-baseline characterisation factors for acidification potential.*	Hauschild & Wenzel 1997	1 kg ammonia = 1.88 kg SO2 eq. 1 kg nitrogen dioxide = 0.7 kg SO2 eq. 1 kg sulphur dioxide = 1 kg SO2 eq.
Eutrophication potential (kg PO43- eq.) in SimaPro 'Eutrophication'	EP, CML 2001 **baseline** (fate not included), Version: January 2016.	Heijungs et al. 1992	1 kg phosphate = 1 kg PO43- eq. 1 kg ammonia = 0.35 kg kg PO43- eq. 1 kg COD (to freshwater) = 0.022 kg kg PO43- eq.
Photochemical oxidant formation potential (kg NMVOC eq.) in SimaPro 'Photochemical oxidation'	POFP, LOTOS-EUROS as applied in ReCiPe 2008	Goedkoop et al. 2009; Van Zelm et al. 2008	1 kg carbon monoxide = 0.046 kg NMVOC eq. 1 kg nitrogen oxides = 1 kg NMVOC eq.
Abiotic depletion potential – Elements (kg Sb eq.) in SimaPro 'Abiotic depletion, elements'	ADPelements, CML 2001, baseline	van Oers et al. 2002	1 kg antimony = 1 kg Sb eq. 1 kg aluminium = 1.09 * 10^-9 Sb eq.
Abiotic depletion potential – Fossil fuels (MJ, net calorific value) in SimaPro 'Abiotic depletion, fossil fuels'	ADPfossil fuels, CML 2001, baseline	van Oers et al. 2002	1 kg coal hard = 27.91 MJ 1 kg coal soft, lignite = 13.96 MJ
Water Scarcity Footprint (WSF) (m^3 H_2O eq) in SimaPro 'Water scarcity'	AWARE Method: WULCA Recommendations on characterization model for WSF 2015, 2017.	Boulay et al. 2018	Example: 582 m^3 H_2O consumed per ton of grapes produced in Mendoza, Argentina : WSF = 582 m^3H_2O x 54.15 (CF_{Agri}AWARE100) = 31,518 m^3eq/ton grape

10 Impact 2002+ (outdated)

10.1 Introduction

IMPACT 2002+ is a combination of four methods: IMPACT 2002 (Pennington et al. 2005), Eco-indicator 99 (Goedkoop and Spriensma. 2000, 2nd version, Egalitarian Factors), CML (Guinée et al. 2002) and IPCC.

Contact info: https://www.impactmodeling.org

The IMPACT 2002+ method was largely based on Eco-indicator 99. Compared to eco-indicator 99 the following changes were implemented:

- IMPACT 2002 factors replace Eco-indicator's Human Health carcinogenic and non-carcinogenic factors and for Aquatic and Terrestrial ecotoxicity factors.
- CML factors were used for Aquatic acidification and Aquatic eutrophication. The Aquatic eutrophication CF implemented in this method are those for a P-limited watershed.

- Climate change was redefined and separated from Human Health impacts and added as a separate damage category. The characterisation factors of IPPC 2001 500a were used for this impact category.
- For fossil fuel depletion the Energy content was used instead of the surplus energy needed for extraction. In the Resource depletion category however, results for mineral extraction and fossil fuel depletion were added together even though fossil energy content and surplus energy for minerals represent different concepts.
- The Eco-indicator 99 factors for Respiratory effects, Ionizing radiations, Land use and Mineral extraction remained unchanged.

10.2 Midpoint indicators

The respective midpoint units are the following:

- kg chloroethylene equivalents into air (written “kg C2H3Cl eq”) for Carcinogens and Non-carcinogens,
- kg PM2.5 equivalents into air (written “kg PM2.5 eq”) for Respiratory inorganics,
- Bq C-14 equivalents into air (written “Bq C-14 eq”) for Ionizing radiation,
- kg CFC-11 equivalents into air (written “kg CFC-11 eq”) for Ozone layer depletion,
- kg ethylene equivalents into air (written “kg C2H4 eq”) for Respiratory organics,
- kg triethylene glycol equivalents into water (written “kg TEG water”) for Aquatic ecotoxicity,
- kg triethylene glycol equivalents into soil (written “kg TEG soil”) for Terrestrial ecotoxicity,
- kg SO2 equivalents into air (written “kg SO2 eq”) for Terrestrial acidi/nutri,
- m2 organic arable land (written “m2org.arable”) for Land occupation,
- kg SO2 equivalents into air (written “kg SO2 eq”) for Aquatic acidification,
- kg PO4--- equivalents into a P-limited water (written “kg PO4 P-lim”) for Aquatic eutrophication,
- kgCO2 equivalents into air (written “kg CO2 eq”) for Global warming,
- MJ primary non-renewable (written “MJ primary”) for Non-renewable energy and
- MJ surplus (written “MJ surplus”) for Mineral extraction.

10.3 Endpoint indicators

The respective damage units are DALY for Human health, PDF*m2*yr for Ecosystem quality, kgeq CO2 into air (written “kg CO2 eq”) for Climate change and MJ primary non-renewable (written “MJ primary”) for Resources. These characterization factors are from the file "IMPACT2002+_v2.1_CF_1a.xls".

The supporting documents for IMPACT 2002+ (Jolliet et al. 2003, Humbert et al. 2009) and the factors can be downloaded at www.impactmodeling.org. This version has been formatted and released in October 2005. By Sébastien Humbert, info@impactmodeling.org, EPFL, October 2005. This file takes into account the updates regarding the flows Molybdenum (should be non-cancer), Chlordane (and its isomers), Cyhalothrin (and lambda- and gamma-) and Phthalate ("Phthalate, dioctyl-" has been changed by "Phthalate, di(2-ethylhexyl)-"). Characterization factors for "groundwater", "groundwater, long-term" and "ocean" emissions for carcinogens, non-carcinogens, aquatic ecotoxicity and terrestrial ecotoxicity have been set to 0. However, this does not indicate that no impacts will occur, but that currently we do not have available CF for groundwater emissions. See also: Humbert S, Margni M and Jolliet O (2009), IMPACT 2002+ : User Guide, Draft for version 2.1.

Impact categories Aquatic acidification and Aquatic eutrophication are midpoint indicators only, and therefore are not included in the endpoint.

10.4 Normalization

The damage factor reported in ecoinvent are normalized by dividing the impact per unit of emission by the total impact of all substances of the specific category for which characterization factors exist, per person per year (for Europe).

10.5 Weighting

About weighting: The authors of IMPACT 2002+ suggest considering the four damage oriented impact categories human health, ecosystem quality, climate change, and resources separately for the interpretation phase of LCA (see the IMPACT 2002+ user guidelines on https://www.impactmodeling.org).

The authors also suggest that if aggregation is needed, one could use self-determined weighting factors or a default weighting factor of one. As a default SimaPro also offers this weighting of 1:1:1:1

They also strongly recommend using the weighting triangle which helps analyzing the different weightings, rather than taking a decision instead of the decision maker. As the weighting triangle can only assess 3 damage categories at one time, Annex 5 of the IMPACT 2002+ user guidelines explains how to combine the climate change and resources consumption damage categories in order to have just 3 indicators.

Use default weighting factor of one, unless other social weighting values are available.

Ref: Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G and Rosenbaum R (2003). "IMPACT 2002+: A New Life Cycle Impact Assessment Methodology." Int J LCA 8 (6) 324-330.

11 CML 2001 (outdated)

The remaining category indicators considered in this study derive either from the CML 2001 (Guinée et al. 2001a, b) method.

12 Eco-indicator 99 (outdated)

The method Eco-indicator 99 (Goedkoop & Spriensma 2000a, b) is a damage oriented approach and one of the parent methods of the ReCiPe method. The LCA quantifies the impact on the safeguard subjects which in this method are:

- Human health,
- Ecosystem quality, and
- Mineral and fossil resources.

Environmental damage models were developed to link these three safeguard subjects with the release of pollutants and the extraction of resources. The damages to the three safeguard subjects are weighted and aggregated to one single score.

13 References

Ahbe et al. 2014 Ahbe S., Schebek L., Jansky N., Wellge S. and Weihofen S. (2014) Methode der ökologischen Knappheit für Deutschland – Eine Initiative der Volkswagen AG. Logos Verlag Berlin GmbH, Berlin, retrieved from: https://www.amazon.de/Methode-%C3%B6kologischen-Knappheit-Deutschland-Schriftenreihe/dp/3832538453.

Andreasi Bassi et al. 2023 Andreasi Bassi S., Biganzoli F., Ferrara N., Amadei A., Valente A., Sala S. and Ardente F. (2023) Updated characterisation and normalisation factors for the

Environmental Footprint 3.1 method. ISBN 978-92-76-99069-7, doi:10.2760/798894, JRC130796. EUR 31414 EN, Publications Office of the European Union, Luxembourg.

BAFU 2021 BAFU (2021) Ökofaktoren Schweiz 2021 gemäss der Methode der ökologischen Knappheit: Methodische Grundlagen und Anwendung auf die Schweiz. Bundesamt für Umwelt, Bern, retrieved from: https://www.bafu.admin.ch/uw-2121-d.

BFS 2015 BFS (2015) Der Material-Fussabdruck der Schweiz, retrieved from: https://www.bfs.admin.ch/bfs/de/home/statistiken/raum-umwelt/umweltgesamtrechnung/materialfluesse.assetdetail.350078.html.

Bösch et al. 2007 Bösch M. E., Hellweg S., Huijbregts M. A. J. and Frischknecht R. (2007) Applying Cumulative Exergy Demand (CExD) Indicators to the ecoinvent Database. *In: Int J Life Cycle Assess*, **12**(3), pp. 181-190, retrieved from: dx.doi.org/10.1065/lca2006.11.282.

Boulay et al. 2018 Boulay A.-M., Bare J., Benini L., Berger M., Lathuillière M. J., Manzardo A., Margni M., Motoshita M., Núñez M., Valerie-Pastor A., Ridoutt B., Oki T., Worbe S. and Pfister S. (2018) The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *In: Int J Life Cycle Assess*, **23**(2), pp. 368–378.

Boustead & Hancock 1979 Boustead I. and Hancock G. F. (1979) Handbook of Industrial Energy Analysis. Ellis Horwood Ltd., Chichester, England.

Brand et al. 1998 Brand G., Scheidegger A., Schwank O. and Braunschweig A. (1998) Bewertung in Ökobilanzen mit der Methode der ökologischen Knappheit - Ökofaktoren 1997. Schriftenreihe Umwelt 297. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern.

Chaudhary et al. 2015Chaudhary A., Verones F., de Baan L. and Hellweg S. (2015) Quantifying Land Use Impacts on Biodiversity: Combining Species–Area Models and Vulnerability Indicators. *In: Environmental Science & Technology*, **49**(16), pp. 9987-9995.

Chaudhary et al. 2016Chaudhary A., Pfister S. and Hellweg S. (2016) Spatially Explicit Analysis of Biodiversity Loss due to Global Agriculture, Pasture and Forest Land Use from a Producer and Consumer Perspective. *In: Environmental Science & Technology*, **50**, pp. 9987-9995.

Crenna et al. 2019 Crenna E., Secchi M., Benini L. and Sala S. (2019) Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA. *In: Int J Life Cycle Assess*, **24**, pp. 1851-1877.

De Laurentiis et al. 2019 De Laurentiis V., Secchi M., Bos U., Horn R., Laurent A. and Sala S. (2019) Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA. *In: Journal of cleaner production*, **215**, pp. 63-74.

ESU-services 2024a ESU-services (2024a) ESU World Food LCA Database - LCI for food production and consumption (ed. Jungbluth N., Meili C., Bussa M., Ulrich M., Solin S., Muir K., Malinverno N., Eberhart M., Annaheim J., Keller R., Eggenberger S., König A., Doublet G., Flury K., Büsser S., Stucki M., Schori S., Itten R., Leuenberger M. and Steiner R.). ESU-services Ltd., Schaffhausen, CH, retrieved from: https://www.esu-services.ch/data/fooddata/.

ESU-services 2024b ESU-services (2024b) The ESU background database based on UVEK-LCI DQRv2:2018. ESU-services Ltd., Schaffhausen, retrieved from: https://www.esu-services.ch/data/database/.

European Commission et al. 2010 European Commission, Joint Research Centre and Institute for Environment and Sustainability (2010) International Reference Life Cycle Data System (ILCD) Handbook - Specific guide for Life Cycle Inventory data sets. Publication office of the European Union, Luxembourg, retrieved from: lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-Specific-guide-for-LCI-online-12March2010.pdf.

European Commission et al. 2011 European Commission, Joint Research Centre and 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. EUR 24571

EN, Luxemburg, retrieved from: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Recommendation-of-methods-for-LCIA-def.pdf.

European Committee for Standardisation (CEN) 2022 European Committee for Standardisation (CEN) (2022) EN 15804+A2:2020/AC2021 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products (includes Corrigendum :2021). European Committee for Standardisation (CEN), Brussels, retrieved from: https://www.en-standard.eu/din-en-15804-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products-includes-corrigendum-2021/.

Fantke et al. 2016 Fantke P., Evans J., Hodas N., Apte J., Jantunen M., Jolliet O. and McKone T. E. (2016) Health impacts of fine particulate matter. In: *Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1*. (Ed. Frischknecht R. and Jolliet O.). pp. 76-99. UNEP/SETAC Life Cycle Initiative, Paris.

Fantke et al. 2017 Fantke P., Bijster M., Guignard C., Hauschild M., Huijbregts M., Jolliet O., Kounina A., Magaud V., Margni M., McKone T. E., Posthuma L., Rosenbaum R. K., van de Meent D. and van Zelm R. (2017) USEtox® 2.0 Documentation (Version 1), retrieved from: https://usetox.org.

FitzGerald et al. 2023 FitzGerald D., Bourgault G., Vadenbo C., Sonderegger T., Symeonidis A., Fazio S., Mutel C., Müller J., Dellenbach D., Valsasina L., Minas N., Baumann D. and Moreno Ruiz E. (2023) Documentation of changes implemented in the ecoinvent database v3.10. ecoinvent Association, Zürich, Switzerland, retrieved from: https://ecoinvent.org.

Frischknecht et al. 2000 Frischknecht R., Braunschweig A., Hofstetter P. and Suter P. (2000) Human Health Damages due to Ionising Radiation in Life Cycle Impact Assessment. *In: Review Environmental Impact Assessment*, **20**(2), pp. 159-189.

Frischknecht et al. 2007a Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2007a) Overview and Methodology. ecoinvent report No. 1, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: https://www.ecoinvent.org.

Frischknecht et al. 2007b Frischknecht R., Jungbluth N., Althaus H.-J., Bauer C., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M. and Nemecek T. (2007b) Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: https://www.esu-services.ch/data/ecoinvent/.

Frischknecht et al. 2008 Frischknecht R., Steiner R. and Jungbluth N. (2008) Methode der ökologischen Knappheit - Ökofaktoren 2006. Umwelt-Wissen Nr. 0906. ESU-services GmbH im Auftrag des Bundesamt für Umwelt (BAFU), Bern, retrieved from: https://www.bafu.admin.ch/publikationen/publikation/01031/index.html?lang=de.

Frischknecht et al. 2009 Frischknecht R., Steiner R. and Jungbluth N. (2009) The Ecological Scarcity Method - Eco-Factors 2006: A method for impact assessment in LCA. Federal Office for the Environment FOEN, Zürich und Bern, retrieved from: https://www.bafu.admin.ch/publikationen/publikation/01031/index.html?lang=en.

Frischknecht et al. 2013 Frischknecht R., Büsser Knöpfel S., Flury K. and Stucki M. (2013) Ökofaktoren Schweiz 2013 gemäss der Methode der ökologischen Knappheit: Methodische Grundlagen und Anwendung auf die Schweiz. Umwelt-Wissen Nr. 1330. treeze und ESU-services GmbH im Auftrag des Bundesamt für Umwelt (BAFU), Bern, retrieved from: https://www.bafu.admin.ch/uw-1330-d.

Frischknecht & Jolliet 2017 Frischknecht R. and Jolliet O. (2017) Global Guidance on Environmental Life Cycle Impact Assessment Indicators. Volume 1. United Nations Environment Programme, UNEP, Paris.

Frischknecht et al. 2018 Frischknecht R., Nathani C., Alig M., Stolz P., Tschümperlin L. and Hellmüller P. (2018) Umweltfussabdrücke des Schweizer Konsums: Zeitlicher Verlauf 1996

– 2015. Technischer Bericht. treeze Ltd / Rütter Soceco AG, Uster / Rüschlikon, commissioned by the Swiss Federal Office for the Environment (FOEN). Berne, retrieved from: https://www.bafu.admin.ch/uz-1811-d.

Goedkoop & Spriensma 2000a Goedkoop M. and Spriensma R. (2000a) The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands, retrieved from: https://www.pre.nl/eco-indicator99/.

Goedkoop & Spriensma 2000b Goedkoop M. and Spriensma R. (2000b) Methodology Annex: The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands, retrieved from: https://www.pre.nl/eco-indicator99/.

Goedkoop et al. 2009 Goedkoop M., Heijungs R., Huijbregts M. A. J., De Schryver A., Struijs J. and van Zelm R. (2009) ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edition. Report I: Characterisation, NL, retrieved from: lcia-recipe.net/.

Guinée et al. 2001a Guinée J. B., (final editor), Gorrée M., Heijungs R., Huppes G., Kleijn R., de Koning A., van Oers L., Wegener Sleeswijk A., Suh S., Udo de Haes H. A., de Bruijn H., van Duin R., Huijbregts M. A. J., Lindeijer E., Roorda A. A. H. and Weidema B. P. (2001a) Life cycle assessment; An operational guide to the ISO standards; Part 3: Scientific Background. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), Den Haag and Leiden, The Netherlands, retrieved from: https://www.leidenuniv.nl/cml/ssp/projects/lca2/lca2.html.

Guinée et al. 2001b Guinée J. B., (final editor), Gorrée M., Heijungs R., Huppes G., Kleijn R., de Koning A., van Oers L., Wegener Sleeswijk A., Suh S., Udo de Haes H. A., de Bruijn H., van Duin R., Huijbregts M. A. J., Lindeijer E., Roorda A. A. H. and Weidema B. P. (2001b) Life cycle assessment; An operational guide to the ISO standards; Parts 1 and 2. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), Den Haag and Leiden, The Netherlands, retrieved from: https://www.leidenuniv.nl/cml/ssp/projects/lca2/lca2.html.

Hauschild & Wenzel 1997 Hauschild M. and Wenzel H. (1997) Environmental Assessment of Products. Vol. 2: Scientific background. Chapman & Hall, London, Weinheim, New York.

Heijungs et al. 1992 Heijungs R., Guinèe J., Lankreijer R. M., Udo de Haes H. A. and Wegener Sleeswijk A. (1992) Environmental life cycle assessment of products - Backgrounds. Novem, rivm, Centre of Environmental Science (CML), Leiden.

Hoekstra et al. 2011 Hoekstra A. Y., Chapagain A. K., Aldaya M. M. and Mekonnen M. M. (2011) The water footprint assessment manual: Setting the global standard. Earthscan, ISBN 978-1-84971-279-8, London, Washington.

Horn et al. 2018 Horn R., Maier S., Bos U., Beck T., Lindner J. P. and Fischer M. (2018) LANCA® -Characterisation Factors for Life Cycle Impact Assessment, Version 2.5. Fraunhofer Verlag, ISBN 978-3-8396-0953-8, Stuttgart, retrieved from: https://www.bookshop.fraunhofer.de/buch/LANCA/244600.

Huijbregts et al. 2017 Huijbregts M. A. J., Steinmann Z. J. N., Elshout P. M. F., Stam G., Verones F., Vieira M., Zijp M., Hollander A. and van Zelm R. (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *In: Int J Life Cycle Assess*, **22**(2), pp. 138-147, 10.1007/s11367-016-1246-y, retrieved from: https://dx.doi.org/10.1007/s11367-016-1246-y.

International Organization for Standardization (ISO) 2006 International Organization for Standardization (ISO) (2006) ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines. ISO 14044:2006; Amd: 2017; Amd 2: 2020, Geneva, retrieved from: https://www.iso.org.

International Organization for Standardization (ISO) 2011 International Organization for Standardization (ISO) (2011) ISO 14046: Life cycle assessment - Water Footprint -

Requirements and guidelines. ISO14046.3:2011; Working Draft, Geneva, retrieved from: https://www.iso.org.

IPCC 2007 IPCC (2007) The IPCC fourth Assessment Report. Cambridge University Press., Cambridge.

IPCC 2021 IPCC (2021) Climate Change 2021: The Physical Science Basis, Cambridge University Press, United Kingdom and New York, NY, USA, retrieved from: https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.

Jungbluth & Meili 2018 Jungbluth N. and Meili C. (2018) Pilot-study for the analysis of the environmental impacts of commodities traded in Switzerland. ESU-services Ltd. financed by Swiss Federal Office for the Environment - FOEN, Schaffhausen, Switzerland, retrieved from: https://esu-services.ch/projects/trade/.

Jungbluth & Meili 2019 Jungbluth N. and Meili C. (2019) Recommendations for calculation of the global warming potential of aviation including the radiative forcing index. *In: Int J Life Cycle Assess*, **24**(3), pp. 404-411, DOI: 10.1007/s11367-018-1556-3, retrieved from: https://link.springer.com/article/10.1007/s11367-018-1556-3, https://rdcu.be/bbKZk.

Kounina et al. 2013 Kounina A., Margni M., Bayart J.-B., Boulay A.-M., Berger M., Bulle C., Frischknecht R., Koehler A., Milà i Canals L., Motoshita M., Núñez M., Peters G., Pfister S., Ridoutt B., van Zelm R., Verones F. and Humbert S. (2013) Review of methods addressing freshwater use in life cycle inventory and impact assessment. *In: Int J Life Cycle Assess*, **18**(3), pp. 707-721.

Lee et al. 2021 Lee D. S., Fahey D. W., Skowron A., Allen M. R., Burkhardt U., Chen Q., Doherty S. J., Freeman S., Forster P. M., Fuglestvedt J., Gettelman A., De León R. R., Lim L. L., Lund M. T., Millar R. J., Owen B., Penner J. E., Pitari G., Prather M. J., Sausen R. and Wilcox L. J. (2021) The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *In: Atmospheric Environment*, **244**, pp. 117834, https://doi.org/10.1016/j.atmosenv.2020.117834, retrieved from: https://www.sciencedirect.com/science/article/pii/S1352231020305689.

Milà i Canals et al. 2009 Milà i Canals L., Chenoweth J., Chapagain A., Orr S., Antón A. and Clift R. (2009) Assessing freshwater use impacts in LCA: Part I - inventory modelling and characterisation factors for the main impact pathways. *In: Int J Life Cycle Assess*, **14**, pp. 28-42, 10.1007/s11367-008-0030-z.

Miyazaki et al. 2004 Miyazaki N., Siegenthaler C., Schoenbaum T. and Azuma K. (2004) Japan Environmental Policy Priorities Index (JEPIX) - Calculation of Ecofactors for Japan: Method for Environmental Accounting based on the EcoScarcity Principle. 7. International Christian University Social Science Research Institute, Tokyo.

Müller-Wenk 1978 Müller-Wenk R. (1978) Die ökologische Buchhaltung: Ein Informations- und Steuerungsinstrument für umweltkonforme Unternehmenspolitik. Campus Verlag Frankfurt.

Nordic Council of Ministers 1995 Nordic Council of Ministers (1995) LCA-NORDIC technical report no. 10 and special reports no. 1-2., Kopenhagen.

Núñez et al. 2016 Núñez M., Bouchard C. R., Bulle C., Boulay A.-M. and Margni M. (2016) Critical analysis of life cycle impact assessment methods addressing consequences of freshwater use on ecosystems and recommendations for future method development. *In: Int J Life Cycle Assess*, **21**(12), pp. 1799-1815, 10.1007/s11367-016-1127-4, retrieved from: https://dx.doi.org/10.1007/s11367-016-1127-4.

OECD 2004 OECD (2004) Key environmental indicators. OECD Environment Directorate, Paris, retrieved from: https://www.oecd.org/dataoecd/32/20/31558547.pdf.

Pawelzik et al. 2013 Pawelzik P., Carus M., Hotchkiss J., Narayan R., Selke S., Wellisch M., Weiss M., Wicke B. and Patel M. K. (2013) Critical aspects in the life cycle assessment (LCA) of bio-based materials – Reviewing methodologies and deriving recommendations. *In: Resources, Conservation and Recycling*, **73**, pp. 211-228.

PCR 2024 PCR (2024) PCR 2019:14 Construction products (EN 15804:A2) - Version 1.3.4. The International EPD Consortium (IEC), retrieved from: https://api.environdec.com/api/v1/EPDLibrary/Files/fe17e14b-3ff4-4ab3-07a6-08dc685f3598/Data.

Pfister et al. 2009 Pfister S., Koehler A. and Hellweg S. (2009) Assessing the environmental impacts of freshwater consumption in LCA. *In: Environ. Sci. Technol.*, **43**(11), pp. 4098–4104, retrieved from: pubs.acs.org/doi/abs/10.1021/es802423e.

Pfister et al. 2011 Pfister S., Saner D. and Koehler A. (2011) The environmental relevance of freshwater consumption in global power production. *In: Int J Life Cycle Assess*, pp. 1-12.

Pimentel 1973 Pimentel D. (1973) Food Production and the Energy Crisis. *In: Science*, **182**(4111), pp. 443-449.

Posch et al. 2008 Posch M., Seppälä J., Hettelingh J. P., Johansson M., Margni M. and Jolliet O. (2008) The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifiying and eutrophying emissions in LCIA. *In: Int J Life Cycle Assess*(13), pp. 477-486.

Rosenbaum et al. 2008 Rosenbaum R. K., Bachmann T. M., Gold L. S., Huijbregts A. J., Jolliet O., Juraske R., Koehler A., Larsen H. F., MacLeod M., Margni M., McKone T. E., Payet J., Schuhmacher M., van de Meent D. and Hauschild M. Z. (2008) USEtox - the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle assessment. *In: International Journal of Life Cycle Assessment*, **13**(7), pp. 532-546.

Sala et al. 2018 Sala S., Cerutti A. K. and Pant R. (2018) Development of a weighting approach for the Environmental Footprint. (ed. JRC). Publications Office of the European Union,, ISBN ISBN 978-92-79-68042-7, EUR 28562, doi:10.2760/945290, Luxembourg, retrieved from: https://ec.europa.eu/jrc/en/publication/development-weighting-approach-environmental-footprint.

Saouter et al. 2018 Saouter E., Biganzoli F., Ceriani L., Versteeg D., Crenna E., Zampori L., Sala S. and R. P. (2018) Environmental Footprint : Update of Life Cycle Impact Assessment Methods – Ecotoxicity, freshwater, human toxicity cancer, and noncancer. JRC technical report. EUR 29495 EN, Publications Office of the European Union, Luxembourg ISBN 978-92-79-98182-1, DOI: 10.2760/178544.

Schoer et al. 2012 Schoer K., Giegrich J., Kovanda J., Lauwigi C., Liebich A., Buyny S. and Matthias J. (2012) Conversion of European product flows into raw material equivalents. ifeu - Institut für Energie- und Umweltforschung Heidelberg gGmbH, Heidelberg, DE.

Seppälä et al. 2006 Seppälä J., Posch M., Johansson M. and Hettelingh J. P. (2006) Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. *In: Int J Life Cycle Assess*, **11**(6), pp. 403-416.

SGP 1994 SGP (1994) Etude relative à la normalisation écologique des emballages en Belgique, raport final au ministre belge de la santé publique, de l'intégration sociale et de l'environnement, Liège.

Smakhtin et al. 2004 Smakhtin V., Revenga C. and Döll P. (2004) Taking into Account Environmental Water Requirements in Global-scale Water Resources Assessments. Comprehensive Assessment Secretariat, Colombo, Sri Lanka.

Solomon et al. 2007 Solomon S., Qin D., Manning M., Alley R. B., Berntsen T., Bindoff N. L., Chen Z., Chidthaisong A., Gregory J. M., Hegerl G. C., Heimann M., Hewitson B., Hoskins B. J., Joos F., Jouzel J., Kattsov V., Lohmann U., Matsuno T., Molina M., Nicholls N., Overpeck J., Raga G., Ramaswamy V., Ren J., Rusticucci M., Somerville R., Stocker T. F., Whetton P., Wood R. A. and Wratt D. (2007) Technical Summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment*

Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sonderegger & Stoikou 2023 Sonderegger T. and Stoikou N. (2023) Implementation of life cycle impact assessment methods in the ecoinvent database v3.10.

Struijs et al. 2009 Struijs J., Beusen A., van Jaarsveld H. and Huijbregts M. A. J. (2009) Aquatic Eutrophication. In: *ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors* (Ed. Goedkoop M., Heijungs R., Heijbregts M. A. J., De Schryver A., Struijs J. and Van Zelm R.).

van Oers et al. 2002 van Oers L., De Koning A., Guinée J. B. and Huppes G. (2002) Abiotic resource depletion in LCA - improving characterization factors for abiotic resource depletion as recommended in the new Dutch LCA Handbook. *In*, pp.

Van Zelm et al. 2008 Van Zelm R., Huijbregts M. A. J., Den Hollander H. A., Van Jaarsveld H. A., Sauter F. J., Struijs J., Van Wijnen H. J. and Van de Meent D. (2008) European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. *In: Atmos Environ*, **42**, pp. 441-453.

WMO 2014 WMO (2014) Scientific Assessment of Ozone Depletion: 2014. World Meteorological Organisation, Geneva.

Zampori & Pant 2019 Zampori L. and Pant R. (2019) Suggestions for updating the Product Environmental Footprint (PEF) method, Luxembourg, retrieved from: https://eplca.jrc.ec.europa.eu/permalink/PEF_method.pdf.