HILCSA

Documentation and Manual for Holistic and Integrated Life Cycle Sustainability Assessment in openLCA

HILCSA Version 2.3

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HILCSA Holistic and Integrated Life Cycle Sustainability Assessment

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1 Background and Motivation

Established Life Cycle Assessment (LCA) methods evaluate ecological impacts across all stages of the life cycles of products, processes, and services. In contrast to traditional LCA, Life Cycle Sustainability Assessment (LCSA) incorporates social and economic dimensions. Holistic and Integrated Life Cycle Sustainability Assessment (HILCSA)[1] further advances this development as an innovative and unique approach, enabling a comprehensive, ISO 14040/14044-compliant, and integrated assessment of holistic social, ecological, and economic sustainability.

The motivation behind developing HILCSA, as introduced by Zeug et al. (2021, 2022, 2023) is to provide a method that integrates ecological, social, and economic sustainability in a single Life Cycle Impact Assessment (LCIA) method. This way, production systems can be assessed holistically, as numerous indicators across all three sustainability dimensions are evaluated and interpreted simultaneously. Additionally, HILCSA combines an LCSA with an SDG framework and integrates common LCIA methods technically to be applied in openLCA. It was specifically designed to compare prospective green technologies to a conventional reference system, but is not limited to that. HILCSA evaluates the environmental, social, and economic impacts of production and consumption systems to identify sustainability hotspots and synergies. Taking into account regional data and global development goals, the relative sustainability performance of value chains can be determined on multiple scales. The results can further be interpreted as risks and synergies of the corresponding product systems and their contribution to the Sustainable Development Goals (SDGs).

Several approaches in the scientific literature pursue integrated LCSA by applying environmental, social, and economic LCA methods separately. In contrast, HILCSA is unique in integrating a set of numerous impact categories and LCIAs into a sustainability framework and working environment. This unified framework facilitates and harmonizes the application of impact assessment methods.

[1] Official website: HILCSA - Helmholtz-Centre for Environmental Research

2 Conceptualization of HILCSA

HILCSA was originally developed by Dr.-Ing. Walther Zeug at the Helmholtz Centre for Environmental Research (UFZ), Leipzig. The method is based on the theory of Societal Relations to Nature (SRN), which views economic systems as provisioning systems[2] comprising both physical and social components. These systems of societal metabolisms mediate the transformation of natural resources into goods and services for fulfilling societal needs through infrastructure and economic processes.

While traditional LCA examines product systems and their impacts with a small set of disconnected indicators, LCSA considers multiple impacts in all sustainability dimensions. Nevertheless, LCSA is usually based on a linear summation of social LCA, environmental LCA, and life cycle costing, while each is assessed separately. For a more holistic perspective, HILCSA combines these three dimensions into a single assessment method to jointly evaluate parts of a system in an integrated and harmonized framework. In HILCSA, social sustainability is defined as the long-term, global fulfillment of societal needs and well-being, while ecological sustainability is perceived as the long-term environmental stability for social reproduction[3] within planetary and regional ecological boundaries (PB). Economic sustainability is understood as the means to support the fulfillment of societal needs within PB through efficient, effective, sufficient, and just economic systems (Figure 1).

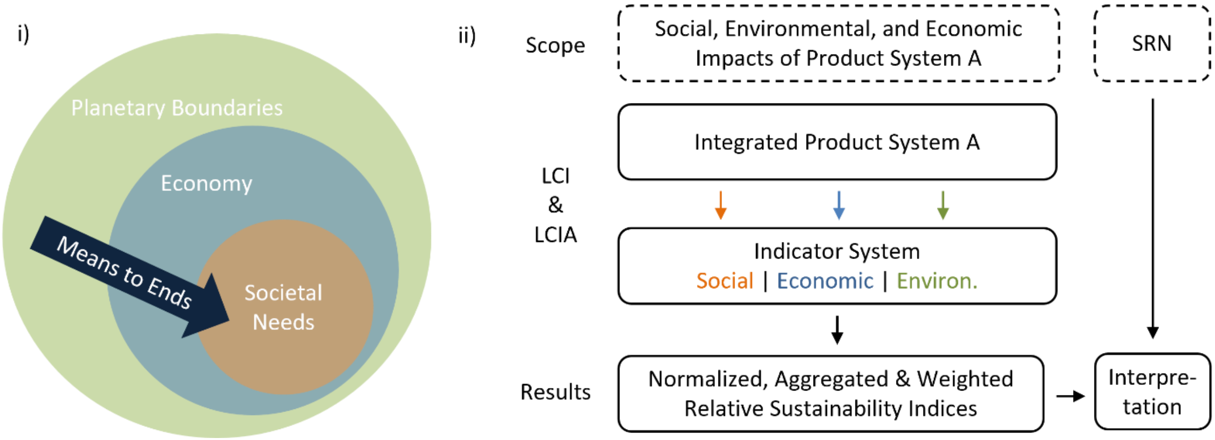


Figure 1: Sustainability concept and methodological framework of HILCSA, adapted from Zeug et al. (2023).

HILCSA integrates 80 social, ecological, and economic indicators. In this case, integration means the horizontal integration of impacts among all sustainability dimensions (see Figure 2) and the vertical integration of scales and scopes from the product to the regional level, considering Societal Relations to Nature (SRN) (Zeug et al., 2021). The method

[2] Social-ecological provisioning systems as described by the Institute for Spatial and Social-Ecological Transformations (ISSET) and Liehr et al. (2017)
[3] „Social Reproduction Theory" as in Herb and Uhlmann (2024)

provides a transdisciplinary and critical analysis of sustainability trade-offs, synergies, and hotspots in production and consumption systems, allowing an informed Multi-Criteria Decision Analysis (MCDA). By contrasting the modelled provision system with a reference, the relative sustainability performance can be assessed.

HILCSA v2.3 processes a broad range of social, ecological, and economic data to model processes, products, organizations, and regions, incorporating material and energy flows, as well as working time. Therefore, the method is fully implemented in the openLCA software to utilize the SoCa v3 database (based on Ecoinvent v3.10).

3 Impact Assessment Method

3.1 Integrated Life Cycle Impact Assessment Methods

HILCSA is based on the established LCIA methods ReCiPe 2016, EF 3.0, soca v3, and Cumulative Energy/Exergy Demand. Impact categories are retrieved from those and integrated into one impact assessment method in openLCA. The current HILCSA version 2.3 includes 80 indicators and can address 13 of 17 SDGs. While several indicators are connected to one SDG, no indicator is linked to more than one SDG to avoid double-counting. Substitution factors of impacts normalize the impact assessment results, which are then aggregated to the related SDG, sustainability dimension, and finally, to a total substitution factor of impacts (Figure 2). This final substitution factor represents the relative sustainability performance of product system A, compared to product system B.

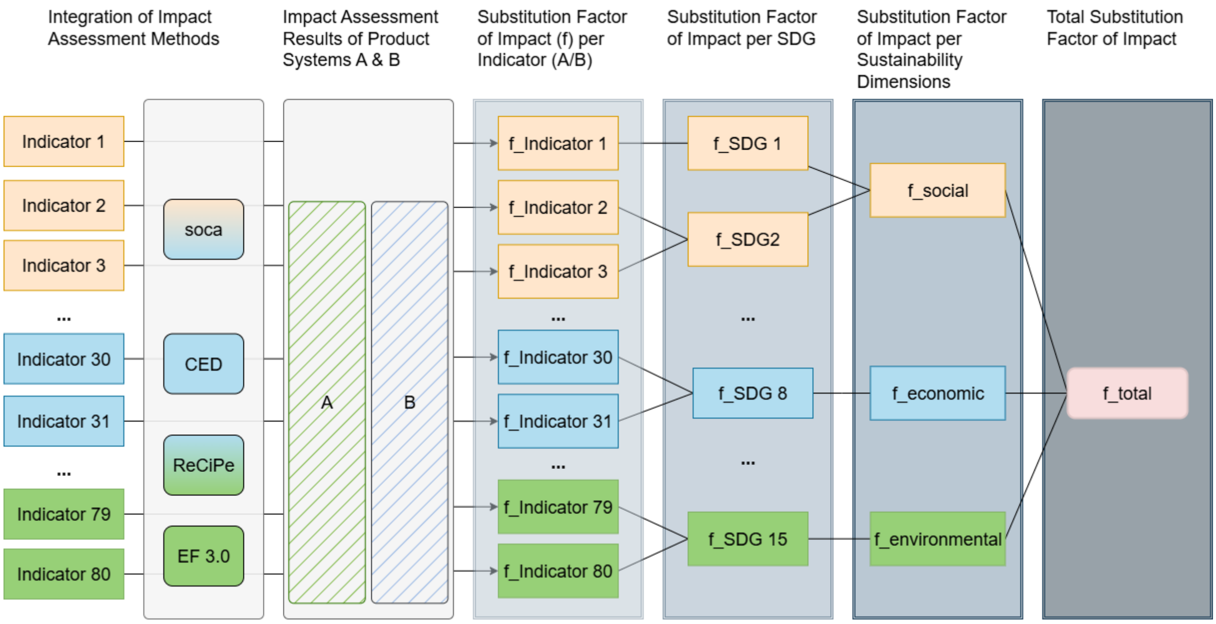


Figure 2: HILCSA LCA framework and aggregation levels.

3.2 Normalization, Weightings, and Aggregation

The Life Cycle Impact Assessment Results are normalized by setting two product systems with the same functional unit and full substitutability of products in relation to each other (Eq. 1). The impact assessment results of product system A are divided by the impact assessment results of product system B (reference system) for each indicator. This results in a substitution factor of impact (f) for each of the 80 indicators (f_sSDG). Each one is aggregated to its related SDG (f_SDG), which again is further aggregated to one of the three sustainability dimensions (f_SN-ECO-PB). The final substitution factor of impact (f_total, column AE) is calculated based on the substitution factors of impact per SDG.

In HILCSA v 2.3, no weightings are applied by default (R = 1.0). Former versions included values based on bioeconomy experts' perspectives on the importance of the SDG sub-goals, as elaborated in Zeug et al. (2019). However, for a more universal application, users can include their own weightings in column C (with R=1.0-10.0). The aggregation of substitution factors from the indicators to the total is based on the geometric mean, as shown in Eq. 2.1 to 2.3:

Eq. 1 $$f^{sSDG} = \frac{x^{A}_{sSDG}}{x^{B}_{sSDG}}$$

Eq. 2.1 $$f^{SDG} = \sqrt[R]{\prod_{sSDG=1}^{n} {f^{sSDG}}^{R^{sSDG}}} \qquad R := \sum_{sSDG=1}^{n} R^{sSDG}$$

Eq. 2.2 $$f^{Soci-Econ-Ecol} = \sqrt[R]{\prod_{SDG=1}^{n} {f^{SDG}}^{R^{SDG}}} \qquad R := \sum_{SDG=1}^{n} R^{SDG}$$

Eq. 2.3 $$f^{total} = \sqrt[R]{\prod_{SDG=1}^{15} {f^{SDG}}^{R^{SDG}}} \qquad R := \sum_{SDG=1}^{15} R^{SDG}$$

$x^{A}_{sSDG}, x^{B}_{sSDG}$ = Impact assessment results of product system A and B per indicator

f^{sSDG} = Substitution factor of impact per indicator (sub-SDG)

f^{SDG} = Substitution factor of impact per SDG

$f^{Soci-Econ-Ecol}$ = Substitution factor of impact per sustainability dimension

$\sqrt[R]{\prod_{i=1}^{n} {f_i}^{R_i}}$, $R := \sum_{i=1}^{n} R_i$ = Weighted geometric mean

R^{sSDG} = Weighting per indicator (sSDG)

R^{SDG} = Average of indicator weightings (R^{sSDG}) per SDG

The weightings and aggregation formulas are automatically applied, and the results are shown in the columns AB to AE of the Excel template. The underlying equations and side calculations are run in the columns AH to AQ for transparency reasons and must not be changed.

3.3 Indicator Selection

	Impact Category (SDG)	Indicator	Unit of Measurement	Source
Social Sustainability	1 - No Poverty	Social security expenditures	SS med risk hours/h	soca v3
	2 - Zero Hunger	Water consumption - HH	Daly/m^3 consumed	ReCiPe (End)
		Indigenous rights	IR med risk hours/h	soca v3
	3 - Good Health and Well-being	Health expenditure	HE med risk hours/h	soca v3
		Life expectancy at birth	LE med risk hours/h	soca v3
		DALYs due to indoor and outdoor air and water pollution	DALY med risk hours/h	soca v3
		Pollution	P med risk hours/h	soca v3
		Global Warming - HH	DALY/kg CO_2 eq.	ReCiPe (End)
		Stratospheric ozone depletion - HH	DALY/kg CFC11 eq.	ReCiPe (End)
		Photochemical ozone formation - HH	DALY/kg NO_x eq.	ReCiPe (End)
		Ionizing Radiation - HH	DALY/kBq Co-60 emitted to air eq.	ReCiPe (End)
		Fine particulate matter formation - HH	DALY/kg $PM_{2.5}$ eq.	ReCiPe (End)
		Toxicity - HH (cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	ReCiPe (End)
		Toxicity - HH (non-cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	ReCiPe (End)
	4 - Quality Education	Expenditures on education	EE med risk hours/h	soca v3
	5 - Gender Equality	Gender wage gap	GW med risk hours/h	soca v3
		Men in the sectoral labour force	M med risk hours/h	soca v3
		Women in the sectoral labour force	W med risk hours/h	soca v3
Economic Sustainability	6 - Clean Water and Sanitation	Drinking water coverage	DW med risk hours/h	soca v3
		Sanitation coverage	SC med risk hours/h	soca v3
	7 - Affordable and Clean Energy	Cumulative Energy Demand, Renewable energies	MJ	CED
		Cumulative Energy Demand	MJ	CED
		Cumulative Exergy Demand	MJ	CExD
	8 - Decent Work and Economic Growth	Contribution of the sector to economic development	CE med risk hours/h	soca v3
		Working time	h	extracted from soca v3
		Weekly hours of work per employee	WH med risk hours/h	soca v3
		Net migration	NM med risk hours/h	soca v3
		International Migrant Stock	IMS med risk hours/h	soca v3
		International migrant workers (in the sector/ site)	IMW med risk hours/h	soca v3
		Migration flows	MF med risk hours/h	soca v3
		Fair salary	FS med risk hours/h	soca v3
		Unemployment	U med risk hours/h	soca v3
		Child Labour, total	CL med risk hours/h	soca v3
		Trafficking in persons	Trafficking in persons/h	soca v3
		Frequency of forced labour	FL med risk hours/h	soca v3
		Goods produced by forced labour	GFL med risk hours/h	soca v3
		Association and bargaining rights	ACB med risk hours/h	soca v3
		Trade unionism	TU med risk hours/h	soca v3
		Non-fatal accidents	NFA med risk hours/h	soca v3

		Fatal accidents	FA med risk hours/h	soca v3
		Safety measures	SM med risk hours/h	soca v3
		Violations of employment laws and regulations	VL med risk hours/h	soca v3
		Workers affected by natural disasters	ND med risk hours/h	soca v3
	12 - Responsible Consumption and Production	Embodied agricultural area footprints	EAF med risk hours/h	soca v3
		Embodied biodiversity footprints	EBF med risk hours/h	soca v3
		Embodied forest area footprints	EFA med risk hours/h	soca v3
		Embodied water footprints	EWF med risk hours/h	soca v3
		Embodied GHG footprints	EWF med risk hours/h	soca v3
		Industrial water depletion	WU med risk hours/h	soca v3
		Fossil resource scarcity	USD2013/kg Cu	ReCiPe (End)
		Fossil fuels consumption	FF med risk hours/h	soca v3
		Biomass consumption	BM med risk hours/h	soca v3
		Minerals consumption	MC med risk hours/h	soca v3
		Resource use, minerals and metals	kg Sb eq.	EF 3.0
		Ionizing Radiation	Bq C-60 eq. to air	ReCiPe (Mid)
		Certified environmental management system	CMS med risk hours/h	soca v3
		Anti-competitive behaviour or violation of anti-trust and monopoly legislation	AC med risk hours/h	soca v3
	16 - Peace, Justice, and Strong Institutions	Risk of conflicts	ROC med risk hours/h	soca v3
		Public sector corruption	C med risk hours/h	soca v3
		Active involvement of enterprises in corruption and bribery	AI med risk hours/h	soca v3
Ecological Sustainability	13 -Climate Action	Climate Change	kg CO2 eq.	EF 3.0
		Climate Change (fossil)	kg CO2 eq.	EF 3.0
		Climate Change (biogenic)	kg CO2 eq.	EF 3.0
		Climate Change (land use change)	kg CO2 eq.	EF 3.0
	14 - Life Below Water	Global Warming - Freshwater ecosystems	Species.year/kg CO2 eq.	ReCiPe (End)
		Eutrophication freshwater	kg P eq.	EF 3.0
		Ecotoxicity freshwater	CTUe	EF 3.0
		Water use	m^3 world equiv.	EF 3.0
		Acidification terrestrial and freshwater	Mole of H+ eq.	EF 3.0
		Toxicity - Marine ecosystems	species·yr/kg 1,4-DBC emitted to sea water eq.	ReCiPe (End)
		Eutrophication marine	kg N eq.	EF 3.0
	15 - Life on Land	Land Use	Pt	EF 3.0
		Terrestrial Acidification	kg SO2 eq.	ReCiPe (Mid)
		Terrestrial ecotoxicity	kg 1,4-DB eq.	ReCiPe (Mid)
		Eutrophication terrestrial	Mole of N eq.	EF 3.0
		Global Warming - Terrestrial ecosystems	Species.year/kg CO2 eq.	ReCiPe (End)
		Photochemical ozone formation - Terrestrial ecosystems	Species.year/kg NOx eq.	ReCiPe (End)
		Acidification - Terrestrial ecosystems	Species.year/kg SO2 eq.	ReCiPe (End)
		Toxicity - Terrestrial ecosystems	species*yr/kg 1,4-DBC emitted to industrial soil eq.	ReCiPe (End)
		Water consumption - terrestrial ecosystems	species.yr/m3 consumed	ReCiPe (End)

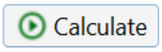
4 Step-by-Step Manual

Step-by-Step guide to apply HILCSA as an Impact Assessment Method in openLCA and how to prepare them for publications.

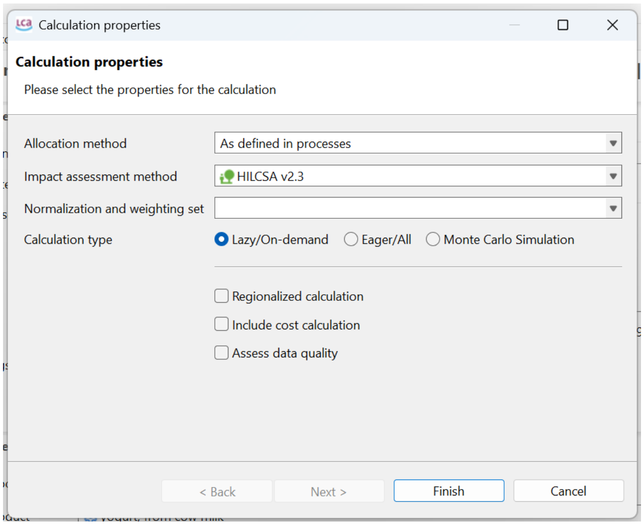
Prerequisites:

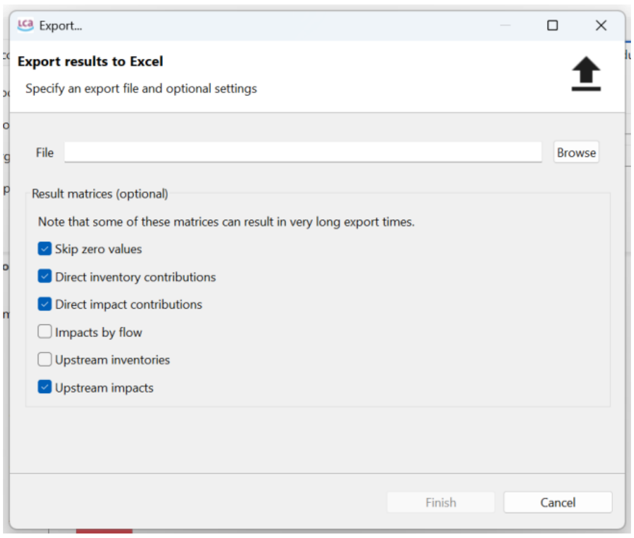
- Installed openLCA software
- Licensed soca v3 database (based on ecoinvent 3.10)
- Licensed HILCSA v2.3 method package

Calculation and Export of Results from openLCA

1. Download the soca v3 database and the HILCSA v2.3 method package from Nexus
2. Import the soca v3 database in openLCA (*File, Import, File*)
3. Now import the HILCSA v2.3 method into the database in openLCA (*File, Import, File*)
4. Create your Life Cycle Inventory (LCI) for both of your product systems (A & B) in openLCA using the soca v3 processes
5. Create a product system out of your LCI for product system A and click 

6. Choose HILCSA v2.3 from the list of impact assessment methods and run the calculation



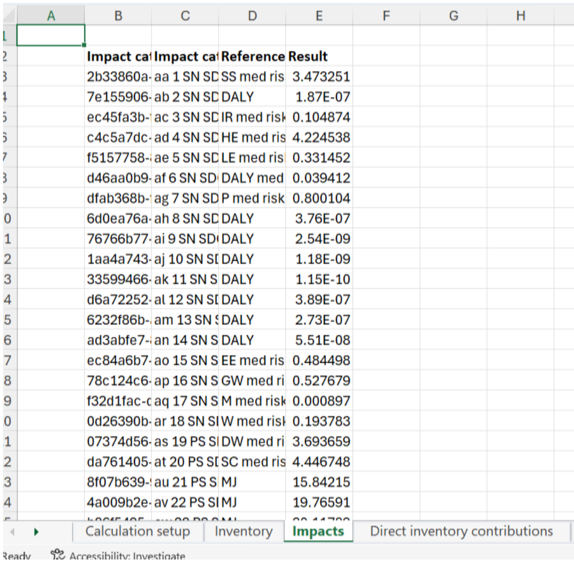


7. Export the results in Excel to a chosen folder on your device, check the box to include all upstream impacts, and click finish

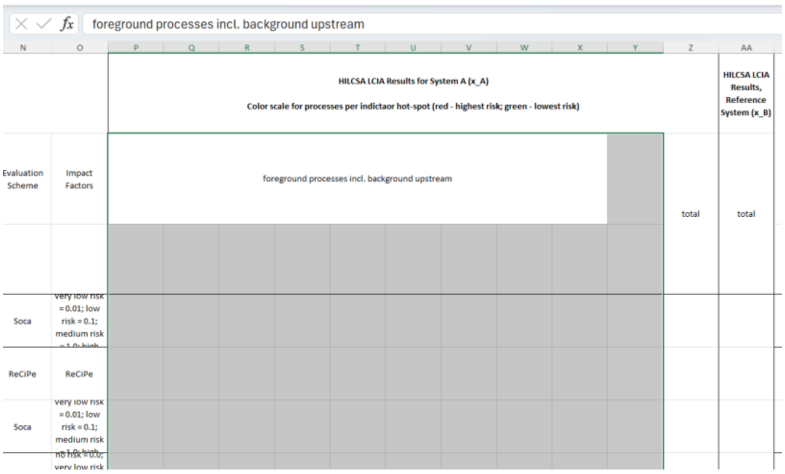
Info: The download of the result Excel can take a few minutes, no worries. If you run into an error, adjust the maximum memory usage under *File, Preferences, Configuration*, to a higher memory usage (approx. 80% of your hardware's RAM)

Import the results into the HILCSA v2.3 Excel Template

1. Go to the sheet “Impacts” in the result Excel file and copy the total impact values of the product system A (E3:E82) into the designated column (Z4:Z83) in the HILCSA template:



Impact ca	Impact ca	Reference	Result
2b33860a-	aa 1 SN SD	SS med ris	3.473251
7e155906-	ab 2 SN SD	DALY	1.87E-07
ec45fa3b-	ac 3 SN SD	IR med risk	0.104874
c4c5a7dc-	ad 4 SN SD	HE med ris	4.224538
f5157758-	ae 5 SN SD	LE med ris	0.331452
d46aa0b9-	af 6 SN SD	DALY med	0.039412
dfab368b-	ag 7 SN SD	P med risk	0.800104
6d0ea76a-	ah 8 SN SD	DALY	3.76E-07
76766b77-	ai 9 SN SD	DALY	2.54E-09
1aa4a743-	aj 10 SN S	DALY	1.18E-09
33599466-	ak 11 SN S	DALY	1.15E-10
d6a72252-	al 12 SN S	DALY	3.89E-07
6232f86b-	am 13 SN S	DALY	2.73E-07
ad3abfe7-	an 14 SN S	DALY	5.51E-08
ec84a6b7-	ao 15 SN S	EE med ris	0.484498
78c124c6-	ap 16 SN S	GW med ri	0.527679
f32d1fac-c	aq 17 SN S	M med risk	0.000897
0d26390b-	ar 18 SN S	W med risk	0.193783
07374d56-	as 19 PS S	DW med ri	3.693659
da761405-	at 20 PS S	SC med ris	4.446748
8f07b639-	au 21 PS S	MJ	15.84215
4a009b2e-	av 22 PS S	MJ	19.76591



2. Now, go to the "Total upstream impacts" sheet and copy the impacts for the foreground processes you want to compare to each other and paste them into the columns (P-Y) next to each other
3. You can adjust the number of rows individually to the number of foreground processes you want to analyze

Info: Now you have the impacts for each foreground process, including ALL upstream processes and their background systems. The last process producing the functional unit (Tier 1) encompasses all upstream processes and impacts of the value chain (Figure 3). To receive the direct impacts for a specific process, you have to subtract all input processes from the total upstream impacts (Figure 4).

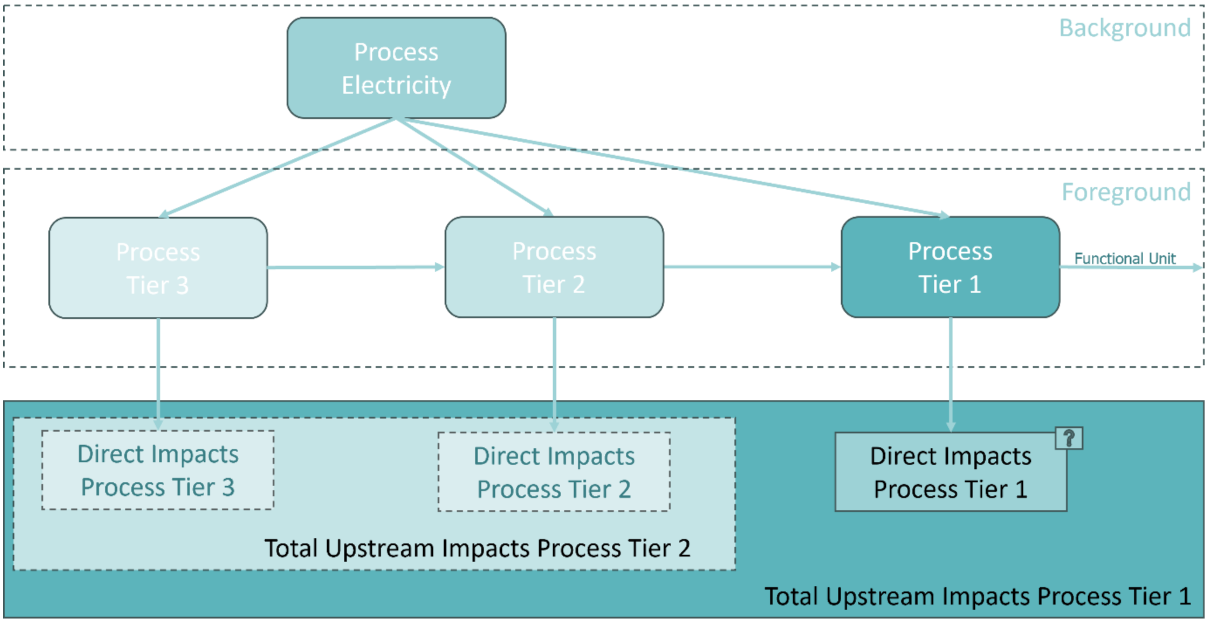


Figure 3: Composition of Total Upstream Impacts, including foreground and background processes; Process Tier 1 produces the functional unit.

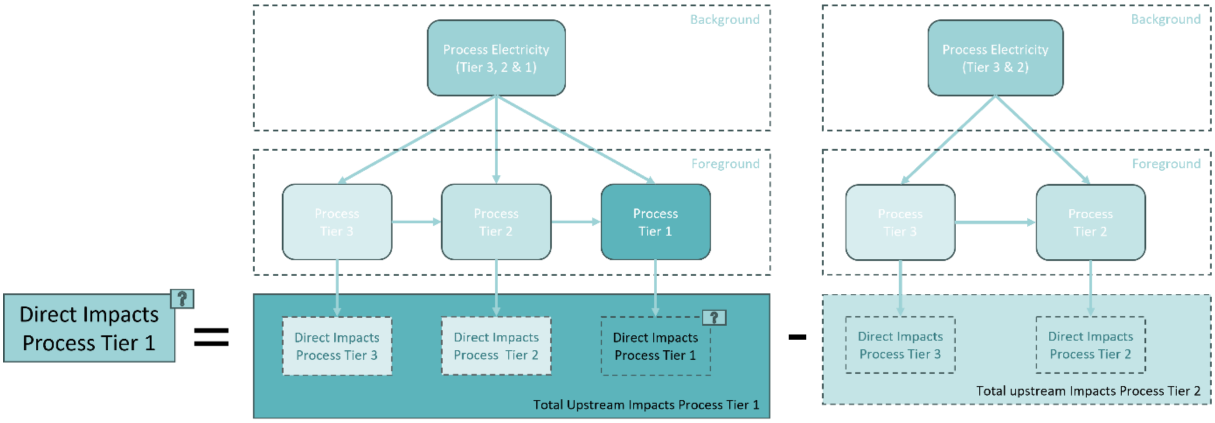


Figure 4: Calculation of Direct Impacts Process Tier 1;
Direct Impacts Process Tier 1 = (Total Upstream Impacts Process Tier 1) – (Total upstream Impacts Process Tier 2)

The Reference System B

1. Finally, repeat each step for the reference product system (B) you want to compare to your target product system (A) (Inventory, Product system & Excel export)
2. You can either copy the result values directly from the openLCA Tab "Impact analysis" or from the "Impacts" sheet of the exported Excel file. Paste the total impact values into the designated column (AA) in the HILCSA Excel template.
3. The Excel sheet will automatically set colors to highlight high and low risks of the product system, for example:

P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
HILCSA LCIA Results for System A (x_A) Color scale for processes per indictaor hot-spot (red - highest risk; green - lowest risk)											HILCSA LCIA Results, Reference System (x_B)	RESULTS substitution factors of impact (f)			
foreground processes incl. background upstream										total	total				
												f_sSDG	f_SDG	f_SN-ECO-PB	Total
4.39E+01	3.01E+00	3.22E+00	6.94E+00	1.09E+01	2.46E+00	1.20E+01	1.10E-01	2.25E+01	2.46E+00	1.38E+02	9.43E+02	0.15	0.15		0.31
2.81E-07	2.90E-09	1.09E-08	4.55E-06	2.58E-07	2.50E-09	8.13E-09	8.31E-10	4.54E-08	2.50E-09	4.30E-06	2.07E-06	2.08	0.71		
7.97E-01	4.56E-02	5.57E-02	1.59E-01	2.32E-01	8.07E-02	2.66E-01	1.99E-03	6.06E-01	8.07E-02	3.47E+00	1.42E+01	0.24			
1.88E+01	1.26E+00	1.38E+00	3.19E+00	4.88E+00	1.18E+00	5.25E+00	4.72E-02	1.05E+01	1.18E+00	6.10E+01	3.94E+02	0.15			

Figure 5: HILCSA color scheme indicating high and low risks of processes.

4. The substitution factors of impacts (f) are calculated automatically (columns AB-AE)
5. **Optional:** If you want to apply weightings to the indicators, set R (=1.0-10.0) to the preferred value in column C
6. Your HILCSA results are ready for interpretation!

HILCSA Figure (optional)

1. Open the PowerPoint file with the HILCSA Figure Template
2. You can now copy each cell of the aggregated SDG level (f_SDG) into the slide
3. Adjust the value of the substitution factor of impact
4. Copy the color of the original cell in Excel into the designated cell in the Figure by using the eyedropper function, for example:

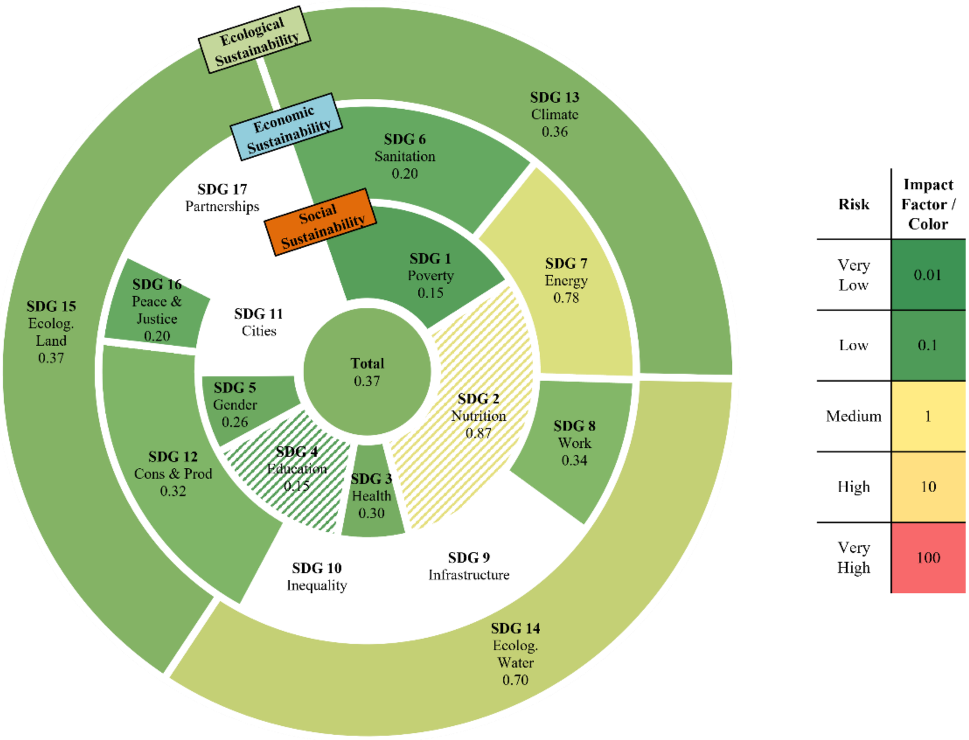


Figure 6: Relative sustainability of product system A compared to product system B; based on HILCSA results. Impact Factors <1 indicate a superior sustainability performance, while an impact factor >1 indicates higher risks compared to the reference product system B. The Figure was adopted from Zeug, Yupanqui, et al. (2023); hatched SDGs lack indicators, and white SDGs are not addressed.

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