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Guidance for applying absolute environmental sustainability assessment on activities at different scales (BETA version)

Bjørn, A., Paulillo, A., Sanye Mengual, E., De Laurentiis, V., Vea, E., Hauschild, M.Z., Sala, S.

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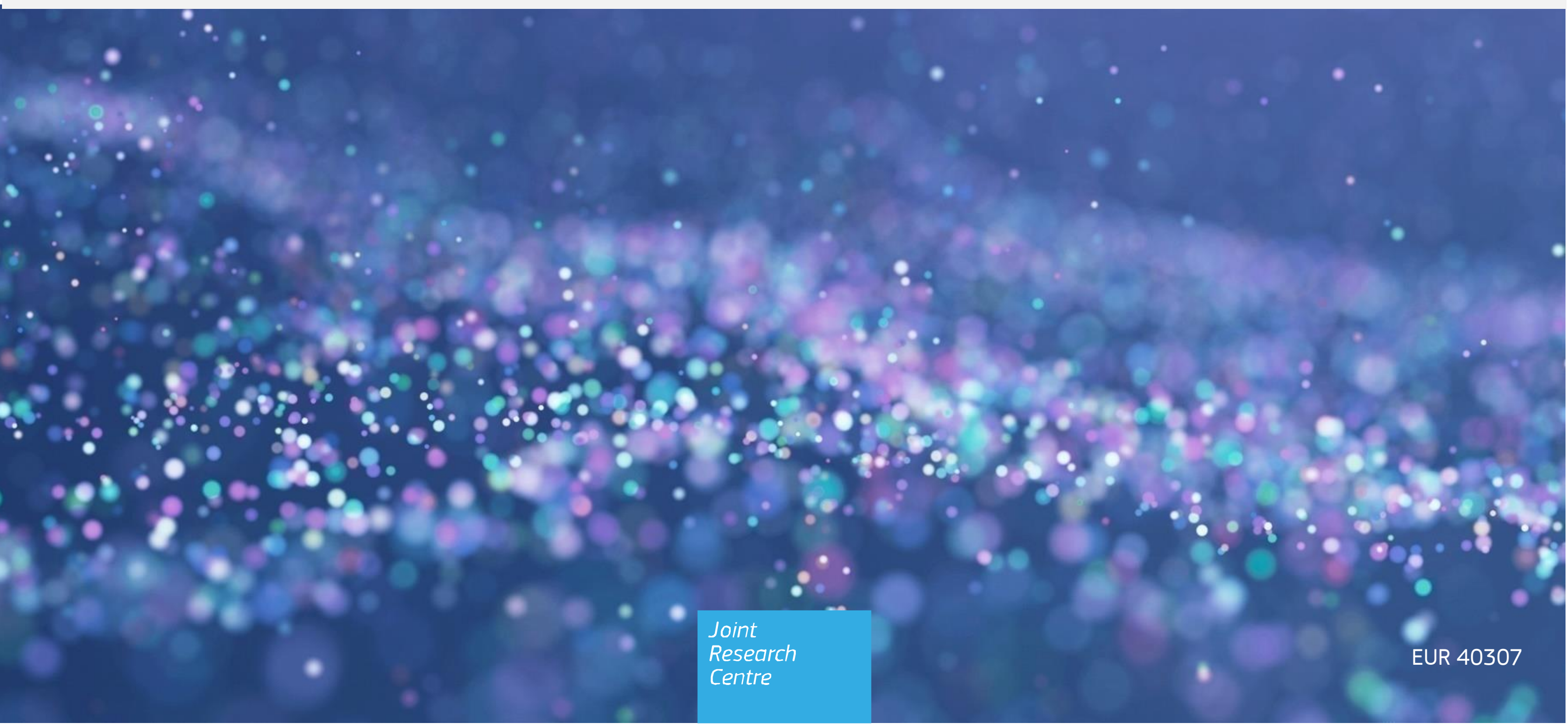

Joint Research Centre

EUR 40307

Contact information

Name: Serenella Sala
Address: Via E. Fermi, 2417, Ispra (VA), Italy
Email: serenella.sala@ec.europa.eu

EU Science Hub

https://joint-research-centre.ec.europa.eu

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Abstract

Absolute Environmental Sustainability Assessment (AESA) involves comparing the environmental burdens of individual activities to planetary boundaries and other environmental carrying capacities to understand what it takes for these activities to be environmentally sustainable. AESA has attracted great interest, but the lack of a harmonized and comprehensive guidance document has inhibited its practical application.

Here, we present the beta version of the first practical guidance for how to apply AESA to activities at different scales. Based on existing academic studies, our guidance structure AESA in three main phases (environmental impact estimation, carrying capacities allocation and results interpretation), comprising nine steps and eleven sub-steps. The presentation of each (sub-)step is supported by three cross-cutting case studies covering a sample of residential buildings in Denmark, a major Indian cement company and the total consumption of the European Union.

Our guidance builds on existing environmental accounting guidelines and standards, such as the International Life Cycle Data (ILCD) Handbook for product-level life cycle assessment and the company-level Greenhouse Gas Protocol and highlights where AESA requires a divergence from the existing practice. The guidance is not normative around the unique carrying capacity allocation step, and instead offers a broad overview of existing methods, choices and considerations.

A key aim of this beta guidance is to collect feedback from the user community, after which a consolidated guidance document will be published in early 2026. Please follow this link to submit your feedback: **https://www.survey-xact.dk/LinkCollector?key=Q8NNSDMMU695**.

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Authors

Anders Bjørn[1,2]

Andrea Paulillo[3]

Esther Sanyé-Mengual[4]

Valeria De Laurentiis[4]

Eldbjørg Vea[1,2]

Michael Zwicky Hauschild[1,2]

Serenella Sala[4]

[1] Centre for Absolute Sustainability, Technical University of Denmark, Kongens Lyngby, Denmark

[2] Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

[3] Department of Chemical Engineering, University College London, London, UK

[4] Joint Research Centre (JRC), European Commission, Ispra, Italy

1. Introduction

Product life cycle assessment is typically used to identify the options or scenarios with the lowest environmental burdens (Hauschild *et al* 2018). The same is true for other methods and tools within the underlying field of Industrial Ecology (Jelinski *et al* 1992) for the studies of activities at larger scales, such as companies and countries. However, in a context where total production and consumption increase, pursuing the greenest options identified by a life cycle assessment (LCA) or another comparative assessment does not necessarily prevent total environmental burdens from increasing to unsustainable levels. In other words, a relative approach to environmental sustainability assessment and subsequent decision-making ("what is the greenest option?") does not necessarily lead to societies that are environmentally sustainable in absolute terms, meaning that they meet the needs of people within the Earth's environmental carrying capacities. We therefore need assessments that relate environmental burdens of human activities at different scales to these carrying capacities, for example, as quantified in the planetary boundaries framework (Richardson *et al* 2023, Steffen *et al* 2015, Rockström *et al* 2009). Such absolute environmental sustainability assessments (AESA) allow decision-makers to understand how much the environmental burdens of individual activities must be reduced in order to stay within the planet's carrying capacities.

This document offers the first practical guidance for how to carry out AESA on activities at different scales. AESA is a relatively young technique and AESA methods, datasets and practices have, so far, mainly been presented and discussed in academic journals. This guidance document integrates, summarizes and harmonizes the existing body of academic knowledge with the aim of making it accessible to a broader audience. Further, the document draws on the experience of its authors in applying AESA and teaching it to students. The guidance is supported by practical examples of AESAs at different scales to exemplify and facilitate the use of the technique for decision-support at different scales. The guidance introduces the main steps involved in conducting AESA and presents considerations that are important for selecting specific AESA methods and datasets and for making methodological choices. The guidance does not prescribe the use of specific AESA methods and datasets and is, hence, of an informative (not normative) nature.

The guidance builds on other existing guidelines and standards for estimating environmental burdens of human activities, such as by the International Organization for Standardization (ISO 2006a, 2006b), the International Life Cycle Data (ILCD) Handbook for product-level LCA (EC 2010) and the Greenhouse Gas (GHG) Protocol for corporate carbon accounting (WBCSD/WRI 2004). It is therefore recommended for the reader to already be familiar with these guidelines. Throughout this document, references will be made to specific pre-existing guidance emphasizing aspects that are of special importance for AESA and highlighting where and why AESA diverges from existing guidance.

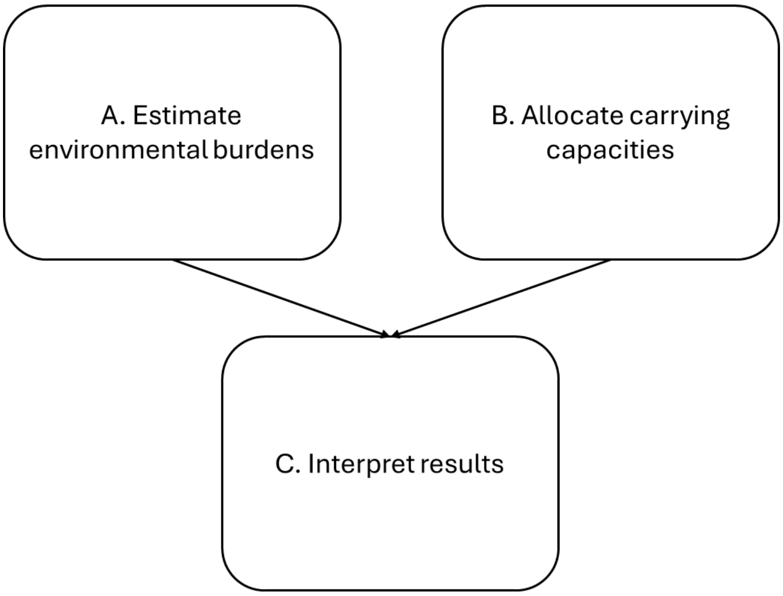
A key aim of this beta version of the AESA guidance is to collect feedback from the user community, after which a consolidated guidance document will be published in early 2026. Please follow this link to submit your feedback: **https://www.survey-xact.dk/LinkCollector?key=Q8NNSDMMU695**.

Below, Section 2 present the AESA framework, including a description of its three phases, and present the terminology used in this guide (the "what"). Section 3-5, the main bulk of this document, then details each assessment step (the "how") and offers three cross-cutting case studies at different scales (a sample of residential buildings in Denmark, a major Indian cement company and the total consumption of EU). Section 6 provides concluding remarks and an outlook

2. AESA framework and definitions

Figure 1 presents the three assessment phases of AESA, which are briefly described in the text below. Table 1 presents working definitions of key AESA terms that are used throughout this guidance and includes alternative terms that the reader may have encountered elsewhere in the AESA literature.

Figure 1. The three phases of AESA. See Section 3-5 for detailed guidance on individual assessment phases, steps and sub-steps.



Source: Own elaboration.

A. Estimate environmental burdens of the studied activity: this follows a life-cycle perspective, covering material acquisition, manufacturing, use and waste handling, and covers multiple environmental problems, such as climate change, terrestrial acidification, water scarcity and land use. This comprehensive systems perspective helps avoiding sub-optimization by identifying potential burden shifts from interventions across life-cycle stages and environmental problems.

B. Allocate carrying capacities to the studied activity**:** this translates global (or regional) environmental carrying capacities (for example, in the form of planetary boundaries) to maximum allowable burdens of the studied activity. The allocation of carrying capacities is inherently subjective, as it essentially involves sharing a scarce resource (the carrying capacity) between individual societal activities (products, etc.) and there is not one objectively correct way to do this.

C. Interpret results: this involves comparing the estimated environmental burdens to the allocated carrying capacities. If the estimated burdens are lower than the allocated carrying capacities, then the activity can be considered environmentally sustainable. If this is not the case, burden reduction targets can be calculated and potential interventions for meeting the targets can be planned. The interpretation phase also includes an assessment of the robustness of results in light of uncertainties and choices.

Table 1. Key AESA terms used in this document. Updated from Bjørn et al (2020).

Term	**Definition**	**Similar terms**
Absolute environmental sustainability assessment	An assessment that evaluates the absolute environmental sustainability of an anthropogenic activity by comparing its estimated environmental burden to its allocated carrying capacity, taking a life cycle perspective and, ideally, having complete coverage of impact categories.	Context-based sustainability assessment; Planetary boundaries-based life cycle assessment (PB-LCA); Planetary accounting.
Allocated carrying capacity	The carrying capacity assigned to an anthropogenic activity or process.	Assigned, apportioned, entitled, downscaled, (fair) share of carrying capacity.
Allocation principle	A principle used to allocate carrying capacity to an anthropogenic activity or process.	Assignment principle, sharing principle, effort-sharing principle, burden-sharing principle or approach.
Anthropogenic activity	A system of linked anthropogenic processes that delivers a function.	Object of study, (anthropogenic) system, human activity.
Anthropogenic process	A single process of an anthropogenic activity.	Unit process.
Carrying capacity	The maximum continuous burden that the environment can sustain without taking critical damage. Here, "critical damage" indicates that some environmental damage is compatible with sustainable development, but only up to a critical level.	Safe operating space (for a planetary boundary), sustainable level of burden, environmental space, burden space, emission/burden budget, critical load/value.
Characterization factor	A factor that by multiplication translates a matching environmental flow to an equivalent environmental burden for the impact category and environmental indicator in question. Note that multiple characterization factors exist for environmental flows that contribute to more than one impact category.	Conversion factor, translation factor.
Environmental burden	The resulting burden on the environment from the combined environmental flows of the activity, expressed as an equivalent mass of a reference environmental flow (e.g., CO_2eq), a change in state (e.g., increased concentration of pollutant) or impact (e.g., potentially affected species fraction).	Footprint, impact score, environmental impact, impact potential, (characterized) indicator score, environmental pressure, environmental interference.
Environmental flow	A flow of emission or resource consumption exchanged between an anthropogenic process and the environment, measured in a physical unit, e.g., kg/year. Environmental	Elementary flow, environmental stressor.

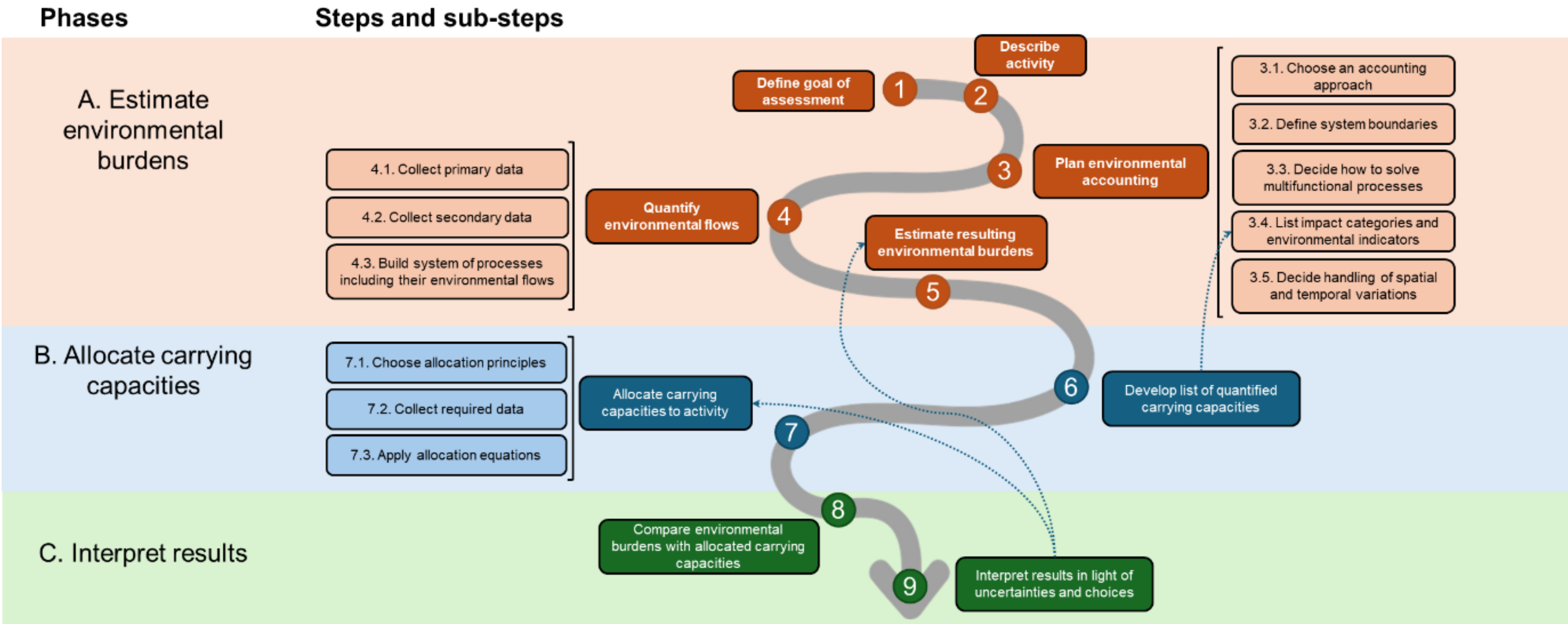
	accounting involves the compilation of all environmental flows from the life cycle of an anthropogenic activity and this is sometimes referred to as a life cycle inventory (LCI).	
Environmental indicator	An indicator expressing the environmental burden for a given impact category. The indicator value is calculated by multiplying the relevant environmental flows with corresponding characterization factors, followed by summation to a single value.	Impact indicator, control variable, category indicator.
Impact category	An environmental problem (such as climate change) that environmental flows (such as a list of individual greenhouse gases) can be classified to and for which one or more environmental indicators (such as Global Warming Potential-100 (GWP100)) are tied.	Earth-system process.

Source: Own elaboration.

2.1. Steps of an AESA

The following three sections (3-5) offer step-by-step guidance for the nine assessment steps and eleven sub-steps (Figure 2). For each (sub-)step in Section 3-5, the embedded text boxes show the application of the guidance to the three cross-cutting case studies (a sample of residential buildings in Denmark, a major Indian cement company and the total consumption of EU). A supplementary AESA case study on total consumption in the UK developed using Environmentally-Extended Input-Output Analysis is presented in Annex 1. The text below also flags important interrelations with subsequent assessment steps (see blue parts), such as how the outcome of a step shapes or constrains the opportunity space for a later step or how the handling of a step should potentially anticipate later steps (exemplified by the three dotted arrows in Figure 2).

Figure 2. Nine assessment steps and eleven sub-steps under the three AESA phases. The three dotted arrows indicate cases where the practitioner should potentially anticipate a later (sub-)step (e.g., 6) when carrying out a specific (sub-)step (e.g., 3.4).



Source: Own elaboration.

3. PHASE A: Estimate environmental burdens

3.1. STEP 1: Define goal of assessment

Similar to conventional product-level LCA (EC 2010, Hauschild *et al* 2018), this initial step clarifies the reason(s) for carrying out the study and its intended audience. For example, if the study is part of a research project, what role does it serve within the project (e.g., addressing a specific research question or hypothesis)? If the study has been directly commissioned, who commissioned it and why? What is the likely background knowledge and interests of the intended audience?

This context can be important for deciding on certain methodological choices (such as the list of carrying capacities to use, see Step 6), as well as for the focus of the interpretation of results and conclusion (Step 9).

40 buildings case:

This AESA study is part of a PhD project at the Technical University of Denmark and was motivated by the real-life issue of deciding what LCA impact categories to include (or focus on) when performing and communicating LCAs of buildings (Lund *et al* 2025). At the heart of the issue is a desire to balance the risk of burden-shifting (e.g., if only covering climate change) with the risk of “decision paralysis” amongst the intended audience of building LCAs (e.g., if including all 15+ midpoint impact categories). The case study performed AESA on a sample of 40 Danish residential buildings and identified the impact categories for which the allocated carrying capacity was exceeded for one or more buildings as relevant to include in building LCAs, broadly.

Stakeholders include LCA researchers as well as LCA practitioners in the building industry, such as consultants performing and communicating LCAs to decision-makers in the building industry.

UltraTech Cement case:

UltraTech Cement Limited is the largest cement company in India, with a production capacity of more than 100 million tonnes cement per year (SBTi 2025). The company also operates in the United Arab Emirates, Bahrain and Sri Lanka.

The company carried out a limited AESA study, in the form of science-based target for climate change. The AESA is here considered limited because it only includes climate change. The company cites a range of drivers and benefits of having a science-based target, including enhancing its brand reputation among customers, building resilience against imminent regulatory changes, bolstering confidence and credibility among investors and driving internal innovation (SBTi 2025).

EU consumption case:

This AESA study was carried out in a collaboration between University College of London (UCL) and the European Commission’s Joint Research Centre (EC-JRC). The goal of the study was to compare different AESA methods, including different allocation principles, on a single case study with the aim of understanding the underlying reasons for differences in results (Paulillo n.d.). The case study was the EU consumption footprint model (Mengual *et al* 2025), which has been developed by the EC-JRC to support EU policy-making, such as for monitoring the evolution of the environmental impacts of EU consumption in the context of circular economy (Eurostat 2025a), Sustainable Development Goal (SDG) 12 (Eurostat 2025b), or the 8th European Action Programme (EEA 2025). In these monitoring frameworks, the EU Consumption Footprint is assessed against absolute sustainability references.

Stakeholders include EU policymakers, LCA researchers and LCA practitioners.

3.2. STEP 2: Describe activity

This step describes the studied activity, in terms of what is produced or consumed over a defined period. The appropriate way to describe this depends on the scale of the activity:

— At the product scale, a functional unit should be described, following conventional LCA (Hauschild *et al* 2018, EC 2010). In short, this means describing what function is provided, how much (quantity), how well (quality) and for how long.

— For companies or industries, the quantities of individual products that have been produced over the period should be stated.

— For communities of people (ranging from individual households to countries), the number of people and their consumption of individual products during the period should be stated.

In all cases, the activity description serves as a reference when planning the environmental accounting (Step 3) and quantifying environmental flows (Step 4). A reference is particularly important in AESAs involving multiple solutions or scenarios (e.g., product configurations) for the same activity, to ensure unbiased comparisons. For example, if a comparison of multiple products is included, they should all fulfill the functional unit. The activity description is typically also important for the allocation of carrying capacity (Step 7).

40 buildings case:

This case is at the product-scale and the functional unit was defined as housing of one person during 50 years in Denmark.

UltraTech Cement case:

The company produced 59Mton cementitious product in 2017 (the base year) and the production steadily increased to 112Mton cementitious product in 2023 (the latest year with available data) (CDP 2023).

EU consumption case:

The Consumption Footprint is a model that represents the total consumption of EU citizens in a year and the associated environmental flows (i.e., emissions and resource consumption).

3.3. STEP 3: Plan environmental accounting

The planning of environmental accounting involves five sub steps that can typically be performed one after the other, meaning little or few iterations are needed.

3.3.1. STEP 3.1: Choose an accounting approach

An environmental accounting approach encompasses the data sources and modelling framework used to calculate the environmental flows (emissions and resource consumption) that the studied activity is deemed responsible for. The most suitable environmental accounting approach typically depends on the scale of the studied activity, as different types of data are available at different scales. For example, for studies of activities at the country scale (e.g., total consumption in a year), data related to trade between industries and the environmental flows of individual industries can be exploited through Environmentally-Extended Input-Output Analysis (see case study in Annex 1) (Stadler *et al* 2018), while life cycle assessments of activities at the product level may instead use primary data from the commissioner (e.g., a company) complemented by data from generic life cycle inventory (LCI) datasets (Hauschild *et al* 2018, EC 2010).

An important requirement, no matter the scale of the activity studied, is that the accounting approach follows the attributional accounting philosophy. In short, this means that the accounting approach should be able to calculate the environmental flows that the activity can be considered responsible for. This is different from the consequential accounting philosophy, which focuses on estimating the change in global environmental flows caused by an activity, under consideration of market interactions (such as modelling how the market reacts to a marginal increase or decrease in demand for a specific good) (Hauschild *et al* 2018, EC 2010). The reason that only attributional accounting is permitted is that the allocation step of AESA (Step 7) requires the quantified environmental flows to be additive (Brander *et al* 2019). This means that the sum of direct environmental flows calculated for all individual activities globally should, in principle, be equal to global environmental flows. By contrast, consequential accounting does not lead to additive estimations of environmental flows, since it builds on marginal changes in emissions. Note that this requirement of attributional accounting partially conflicts with some LCA guidelines that recommend or require consequential accounting, or a mix of attributional and consequential accounting, for certain "decision contexts" (Hauschild *et al* 2018, EC 2010).

Note that the mandatory attributional accounting philosophy restricts the opportunity space for solving multifunctional processes (Step 3.3).

40 buildings case:

The AESA was based on individual process-based LCAs for each of the 40 case buildings.

UltraTech Cement case:

The company used the GHG Protocol to calculate GHG emissions for scope 1, 2 and 3 in the period and its science-based targets for scope 2 emissions (further detailed below) refer to the location-based accounting approach (CDP 2023).

EU consumption case:

The AESA was based on a macro-scale model of EU consumption patterns combining individual process-based LCAs of 165 representative products within five consumption categories: food, housing, mobility, appliances and household goods.

3.3.2. STEP 3.2: Define system boundaries

In attributional accounting, the system boundary separates the anthropogenic processes for which the studied activity is responsible from other processes in the global economy. The setting of a system boundary both involves normative considerations (for example, is a product responsible for the environmental flows from the commuting and lunches consumed by workers involved in its value chain?) and practical considerations (which processes should the practitioners focus their limited time on, in terms of data collection?) (Hauschild *et al* 2018, EC 2010).

Wide system boundaries (e.g., "cradle to grave") are generally recommended, as they potentially allow decision-makers to avoid (or, at the least, identify and manage) "burden shifting", which happens if an intervention reduces environmental burdens from processes inside the system boundary at the expense of increased environmental burdens of processes outside the boundary. However, the goal definition and description of activity (Step 1 and 2) could justify narrower system boundaries. For example, it may be appropriate to omit life cycle stages prior to waste generation for studies of waste treatment activities. Likewise, some LCA standards for the building sector omit certain life cycle processes (see textbox belove with 40 buildings case).

At this point in the planning phase, it is advised to visualize system boundaries by drawing a process diagram containing a selection of processes expected beforehand to have high environmental flows. This will inform the data collection (Step 4).

Note that in the context of AESA, the system boundary should ideally be the same for the quantification of an activity´s environmental flows and for the allocation of a share of the carrying capacity to the activity (Step 7).

40 buildings case:

The LCI of each case building was modelled following the "cradle-to-grave" approach of the Danish BR18 standard (Social- og Boligstyrelsen 2018) (building on the EU-wide BS EN 15804:2012+A2:2019 standard (ES 2021)), which groups processes into A1-A3 (production of building products), B4 (replacement of products), B6 (operational energy), and C3-C4 (treatment of waste and disposal). Note that the BR18 standard omits certain processes from the "cradle-to-grave" system boundary, such as transportation of building materials to the building site (A4), operational water use (B7) and deconstruction or demolition (C1). It is important to be mindful of this omission when allocating carrying capacity to each case building (see Step 7).

UltraTech Cement case:

The company followed the GHG Protocol (WBCSD/WRI 2004) and included processes within, respectively, scope 1 (direct emissions), 2 (indirect emissions from purchased and consumed electricity, heating, cooling, and steam) and 3 (other indirect emissions), with scope 3 processes further subdivided into 15 categories (1. Purchased goods and services, 2. Capital goods, 3. Fuel- and energy-related activities (not included in scope 1 or scope 2), 4. Upstream transportation and distribution, 5. Waste generated in operations, 6. Business trave, 7. Employee commuting, 8. Upstream leased assets, 9. Downstream transportation and distribution, 10.

Processing of sold products, 11. Use of sold products, 12. End-of-life treatment of sold products, 13. Downstream leased assets, 14. Franchises, 15. Investments) (SBTi 2025).

EU consumption case:

The LCI of each representative product was modelled following the "cradle-to-grave" approach. The life cycle was divided into main stages: raw material extraction, primary production (food), manufacturing or processing (food), distribution, retail, use, and end of life.

3.3.3. STEP 3.3: Decide how to solve multifunctional processes

After determining the system boundary, the practitioner may realize that some processes are partly within and partly outside the boundary. This is the case for processes that fulfill multiple functions (e.g., producing more than one product), some of which are not related to the activity studied. For example, an activity may be supplied with electricity from a combined heat and power plant, but not using the heat output, or a waste treatment process may provide both the function of treating the waste of the product studied by an AESA (inside the system boundary) and produce recycled materials that can be used as inputs for producing other products (outside the system boundary).

An approach is therefore needed to "solve" the multifunctional processes, with the aim of attributing a portion of the total environmental flows of each process to the functions or products within the system boundary. Given the requirement of AESA to be based fully on attributional accountings (Step 3.1), there are three main options for handling multifunctional processes, in contrast to the wider range of options offered by existing LCA standards (Hauschild *et al* 2018, EC 2010).

The first option is to, whenever possible, subdivide a process into its elementary processes (aka "unit processes") by obtaining more information about how it operates. For example, a factory may produce multiple products, but detailed data about its operation may reveal that each product is manufactured from a dedicated production line. In this case, the factory is not a truly multifunctional process and can instead be modelled as separate processes for each production line. The AESA can then include the process(es) that fall within the system boundaries. However, subdivision will in many cases not be possible, such as for a combined heat and power plant or a cow from which both meat and milk are obtained.

The second option is to allocate the environmental flows of the multifunctional process between its functions. This allocation can be based on different properties that can be determined for all its functions, for example physical (such as mass or energy content) or economic (such as prices). Economic allocation of environmental flows may be preferable in AESAs where the allocation of carrying capacities to the studied activity also involves considerations of economic value (see Step 7).

The third and last option is to expand the initial description of the activity to encompass the entire multifunctional process. For example, a study initially focused on electricity production from combined heat- and power generation could be expanded to also include heat production. Such cases of "system expansion" requires revisiting the assessment goal (Step 1), activity description (Step 2), and system boundary definition (Step 3.2). System expansion also affects the carrying capacity allocation (Step 7).

Note that the handling of multifunction processes through "substitution" (i.e., subtracting the environmental impacts of an alternative way of producing the process outputs falling outside the system boundaries) is not permitted within AESA, since it would correspond to injecting an element of consequential accounting into an otherwise attributional modeling framework. The only scenario where substitution is consistent with attributional modelling and AESA is in the case of closed loop recycling. For example, recycled aluminum from waste treatment of the studied product activity (e.g., a beverage) that is used to produce a new identical product (the same beverage) reduces the need for virgin aluminum in the product manufacturing. In such a case, the multifunctional recycling process (managing waste and creating recycled aluminum) should be included within the AESA system boundaries and the inputs of virgin materials to the manufacturing should be calculated as the total aluminum required minus the quantity of recycled aluminum.

40 buildings case:

The multifunctional processes of each building case were solved by using the "Allocation - cut off by classification" system model of ecoinvent (ecoinvent 2024), which is consistent with attributional modelling (see also guidance to Step 4.2).

UltraTech Cement case:

The company solved multifunctional processes by following the GHG protocol, which is based on an attributional accounting philosophy (WBCSD/WRI 2004). For example, the scope 3 category End-of-Life Treatment of Sold Products accounts for the emissions taking place using one (or multiple) waste management technologies. Hence, recycled materials from the company´s waste streams are available for other companies to use as inputs in their production “burden free”.

EU consumption case:

The multifunctional processes of each representative product were solved by using the "Allocation - cut off by classification" system model of ecoinvent (ecoinvent 2024), which is consistent with attributional modelling (see also guidance to Step 4.2).

3.3.4. STEP 3.4: List impact categories and environmental indicators

At this point, the practitioner should develop a list of the impact categories and corresponding environmental indicators for which the environmental burdens resulting from the environmental flows of the activity will be quantified (Step 5). It is important to define this list prior to collecting data on environmental flows (Step 4), as it influences the type of data to be collected.

The list of impact categories should reflect the goal of the study. However, in general, it is advisable to include a complete list of impact categories (e.g., as defined within a coherent life cycle impact assessment method) to avoid that interventions made to reduce the environmental burdens of the covered impact categories lead to increased burdens for impact categories that are not covered.

In addition, it is recommended to anticipate the list of quantified carrying capacities to be included in the study (Step 6). This is because the environmental indicators used to quantify environmental burdens and carrying capacities must be identical. For example, the GWP100 indicator can both be used to translate individual GHG emissions of a studied activity to CO_2-equivalents, thereby indicating the activity´s burden on climate change (Step 5), and to express the carrying capacity for climate change (Step 6).

Note that different impact assessment methods have different lists of impact categories, that have typically been developed to be mutually exclusive and collectively exhaustive (Owsianiak *et al* 2014, Hauschild *et al* 2013). Therefore, it is not advisable to combine impact categories from different impact assessment methods (for example, Impact World+ (Bulle *et al* 2019) and LC-IMPACT (Verones *et al* 2020)), as that could lead to some environmental problems being "double counted" and other problems to be unintentionally omitted.

Note also that AESA commonly includes environmental indicators at the "midpoint" level, since carrying capacities, for example in the form of planetary boundaries, are normally quantified at that point in impact pathways, typically coinciding with the pressure- or state level in the Driver-Pressure-State-Impact-Response (DPSIR) framework (Ryberg *et al* 2016, Hellweg *et al* 2023). By contrast, environmental indicators at the "endpoint" level are rare in AESA, since carrying capacities are generally not defined as a maximum level of ecosystem or human damage. A notable exception is when an AESA explicitly includes biodiversity as a separate impact category, for example following the planetary boundaries framework (Richardson *et al* 2023), instead of including it implicitly through midpoint categories linked to ecosystem quality (Wolff *et al* 2017).

40 buildings case:

The following impact categories from the Environmental Footprint (EF) 3.1 framework, with minor adjustments, were included (environmental indicators in parentheses):

-Ecotoxicity freshwater (Comparative Toxic Unit for ecosystems).

-Acidification (Accumulated Exceedance).

-Eutrophication – freshwater (Fraction of nutrients reaching freshwater end compartment (P)).

-Eutrophication – marine (Fraction of nutrients reaching marine end compartment (N)).

-Eutrophication – terrestrial (Accumulated Exceedance).

-Land use (Soil erosion).

-Climate change (Radiative forcing as Global Warming Potential (GWP100)).

-Ozone depletion (Ozone Depletion Potential).

-Photochemical ozone formation (Tropospheric ozone concentration increase).

-Water use (User deprivation potential (deprivation-weighted water consumption)).

-Particulate matter (Impact on human health).

-Ionising radiation (Human exposure efficiency relative to U235).

-Human toxicity – cancer (Comparative Toxic Unit for humans).

-Human toxicity - non-cancer (Comparative Toxic Unit for humans).

-Mineral resource use (Abiotic resource depletion (ADP ultimate reserves)).

UltraTech Cement case: only climate change was included, following the GWP100 environmental indicator, as prescribed by the GHG Protocol (Greenhouse Gas Protocol 2016, WBCSD/WRI 2004).

EU consumption case:

The AESA included the following impact categories from the PB-LCIA method (Ryberg *et al* 2018b) (environmental indicators in parentheses):

-Atmospheric aerosol loading (Aerosol Optical Depth)

-Biogeochemical flows - N, global (Industrial and intentional

biological fixation of nitrogen)

-Biogeochemical flows - P, global (Phosphorus flow from

freshwater system into ocean)

-Biogeochemical flows - P, regional (Phosphorus flow from

fertilizers to erodible soils)

-Climate change (Atmospheric CO_2 concentration)

-Climate change (Energy imbalance at top-of-atmosphere)

-Freshwater use - basin dry/semidry/humid (Blue water withdrawal as % of

mean monthly flow)

-Freshwater use – global (Consumptive blue water use)

-Land-system change – global (Area of forested land as % of

original forest cover)

-Ocean acidification (Carbonate ion concentration, with

respect to aragonite saturation state)

-Stratospheric ozone depletion (Stratospheric O_3 concentration in

Dobson Units)

Note that Land-system change - regional was not included due to lack of inventory data (Paulillo n.d.).

3.3.5. STEP 3.5: Decide handling of temporal and spatial variations

For most impact categories other than climate change, the location of an environmental flow matters for the resulting environmental burden. Similarly, some locations have higher environmental carrying capacities than others. Regarding the time dimension, the environmental burdens of an environmental exchange can be sensitive to its timing (for example, the consumption of water in dry vs. wet season) and environmental carrying capacities may change over time.

The practitioner must decide how to address these temporal and spatial complexities in the remaining assessment steps. The simplest possible AESA disregards the space and time dimension and simply calculates global and annual average environmental burdens of each environmental flow across locations and timesteps, followed by aggregation to a single score that is then compared to a single allocated carrying capacity for each impact category (Step 8). This corresponds to assuming that all life cycle environmental flows occurred in the same year, which may not be a good assumption (Guinée *et al* 2022). At the other extreme, is an AESA that calculates environmental burdens separately for all environmental flows that fall into the same unit of space and time (e.g., watershed and year), followed by comparison to allocated local and temporal carrying capacities (Bjørn *et al* 2020b). While the latter approach is more difficult to carry out and can be more challenging to communicate to decision-makers, it is more accurate and could avoid falsely concluding that an activity is sustainable, even though it actually contributes to carrying capacity exceedances in certain locations at certain times.

The choice of approach for handling temporal and spatial variations matters for the data to be collected on the studied activity´s environmental flows (Step 4.1 and 4.2), the modeling of resulting environmental burdens (Step 5), the spatial and temporal resolution of carrying capacities (Step 6) and the carrying capacity allocation (Step 7).

40 buildings case:

The AESA used a combination of carrying capacities for the European continent from Bjørn and Hauschild (2015), since the majority of the environmental flows were assumed to occur in Europe, and global carrying capacities from Sala et al (2020) where European carrying capacities were not available.

The total life cycle burdens of each building were attributed to a single year by division with its expected lifetime, hence ignoring temporal variations in burdens and carrying capacities.

UltraTech Cement case:

Climate change is a global impact category (1kg of CO_2 has the same climate burden no matter where it is emitted) and the company therefore aggregated its emissions across different locations to a single number.

Following the GHG Protocol (WBCSD/WRI 2004) and Science-based Targets Initiative (SBTi 2023), the company accounted for its historic emissions at annual times steps.

EU consumption case:

The AESA combined regional and global carrying capacities depending on the impact category (Ryberg *et al* 2018b), as detailed in the previous step. For those representative products with a longer lifespan than one year, total life cycle burdens were attributed to a single year by division with the lifespan. As in the buildings case study, this approach ignores temporal variations in burdens and carrying capacities.

3.4. STEP 4: Quantify environmental flows

The quantification of the environmental flows of the studied activity is guided by the defined system boundaries (Step 3.2) and contains three sub steps that are highly interrelated. Hence, it is advised to perform the sub steps in parallel.

3.4.1. STEP 4.1: Collect primary data

Depending on the study´s assessment goal (see Step 1), primary data about the activity´s environmental flows are typically available. For example, a company commissioning an AESA on its product may be able to supply the practitioner with primary data from its production (e.g., resource consumption and different solid waste and pollutant streams of its factory), as well as a detailed "bill of materials" and the identity of large tier 1 suppliers. And for AESA studies at city- or national scale, statistical agencies may have relevant consumption data for the population in question.

The practitioner should collect such primary data for compiling an inventory of environmental flows (Step 4.3). This can generally be done following existing environmental accounting standards developed for different scales (e.g., product, company or national). However, the practitioner should be mindful about any additional requirements related to the spatial and temporal resolution of data when performing an AESA (Step 3.5), as well as the chosen approach for solving multifunctional processes (Step 3.3).

40 buildings case:

The researcher accessed existing LCI models (covering environmental flows) of each of the 40 building cases from a Danish green building certification program (DGNB) (Lund *et al* 2025).

UltraTech Cement case:

The company presumably collected physical activity data from its direct operations (mass of materials consumed, power consumed, solid waste generated, etc.) as well as procurement data (money spent on different products).

EU Consumption case:

Primary data of the Consumption Footprint model includes two levels: consumption data per representative product and foreground LCI data of the life cycle of each representative product. Primary data was obtained from the EC-JRC Consumption Footprint model, which combines consumption statistics with a collection of process-based LCI models of 165 representative products. These LCIs are aligned with the Product Environmental Footprint (PEF), when possible. Preparatory policy documents (e.g., EU Ecolabel) and Product Environmental Footprint Category Rules (PEFCRs) are used when available, as they represent the average EU product. The data collection and modelling assumptions are detailed in Sanyé Mengual et al (2023).

3.4.2. STEP 4.2: Collect secondary data

Depending on the system boundaries of the studied activity (see Step 3.2), there is typically a lack of primary data for determining the environmental flows of all anthropogenic processes. The practitioner must therefore complement the primary data with secondary data from generic data sources. Different generic data sources are appropriate to use for activities at different scales. At the product scale, for example, datasets containing product flows and environmental flows of individual anthropogenic processes (such as ecoinvent (Wernet *et al* 2016)) can be utilized, while at the national scale, environmental extended input output (EEIO) models already contain complete data on trade flows from national accountings, as well as a compilation of data from statistical agencies on the average environmental flows per unit of economic output from each industry (Stadler *et al* 2018) (see Annex I).

As for Step 4.1 (collecting primary data), the practitioner can follow existing environmental accounting guidance for the relevant scale. Again, special attention must be given to the spatial and temporal resolution of data. For example, if the aim is for the AESA to have a fine resolution (see Step 3.5), then data that is representative of the actual locations and times of the life cycle should be prioritized and datapoints should be tagged with location and time information.

Also here, special care must be taken around multi-functional processes (Step 3.3). For example, the ecoinvent database for generic background processes exists in different versions, termed "system models", corresponding to different solutions to multi-functional processes. The three system models "Allocation, cut-off by classification", "Allocation, cut-off, EN15804" and "Allocation at the point of substitution" are compatible with AESA, as they follow an attributional accounting approach. On the contrary, the remaining system model, "Substitution, consequential, long-term", is not compatible with AESA, since it contains consequential modelling elements (ecoinvent 2024). Note that "Allocation, cut-off, EN15804" is similar to "Allocation, cut-off by classification", but with the modelling of some unit processes adjusted to conform with the EN15804 standard, mainly related to the point in a life cycle at which a material is considered a waste.

40 buildings case:

The practitioner primarily relied on the generic LCI database ecoinvent (Wernet *et al* 2016) in the system model "Allocation - cut off by classification" (version 3.7) for adjusting the LCI models obtained from the DGNB. This adjustment was necessary since the original LCI models did not cover environmental flows for all the impact categories and burden indicators included in the AESA (Lund *et al* 2025).

UltraTech Cement case:

The company presumably combined the already collected activity and procurement data with matching emission factors. These emission factors may in some cases be location- and time-specific, such as the average annual emission factor of the local power grid at the company´s individual operation sites, and in some cases global averages, such as the combined emissions of mining, processing and transporting limestone.

EU consumption case:

The model relies on two LCI databases for secondary processes: ecoivent (version 3.6, "Allocation - cut off by classification") (Wernet *et al* 2016) and agrifootprint (5.0) (van Paassen *et al* 2019).

3.4.3. STEP 4.3: Build system of processes including their environmental flows

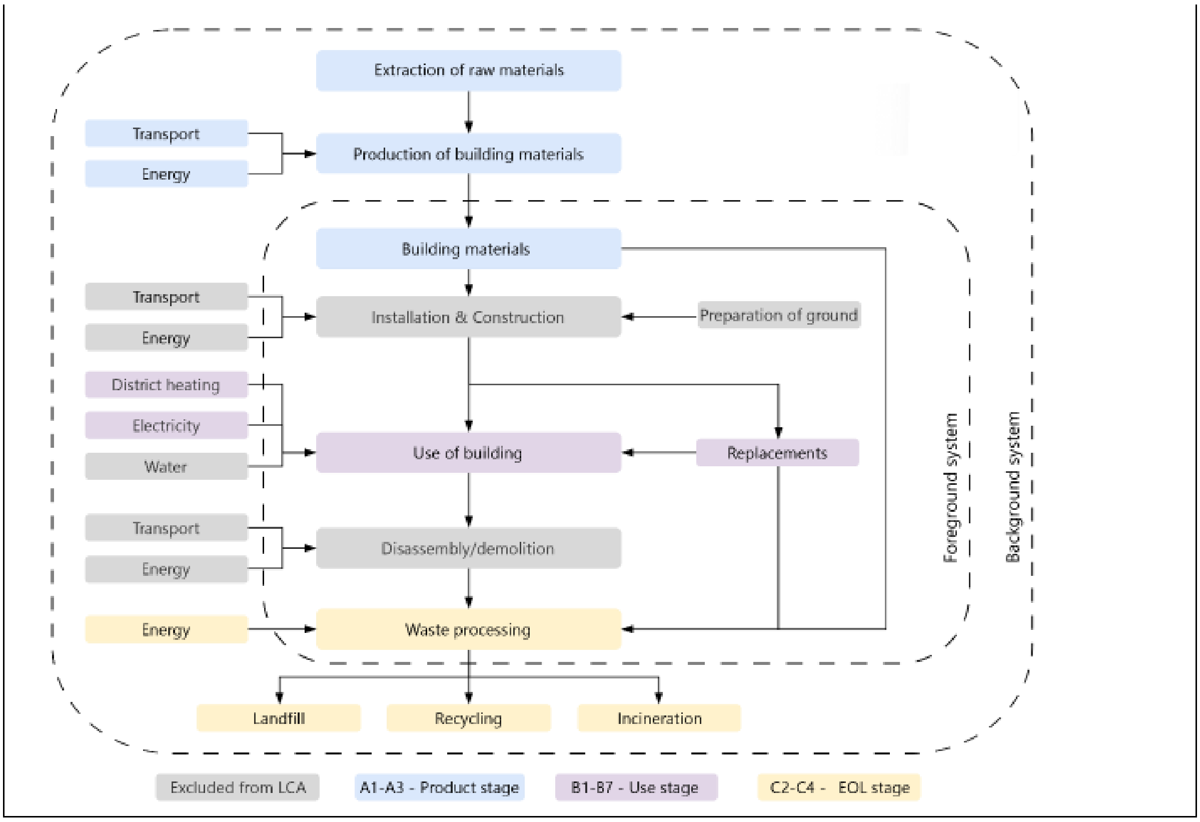
During the collection of primary (Step 4.1) and secondary (Step 4.2) data, the data should be organized into a network of anthropogenic processes. These processes are connected by the product flows that they exchange and these flows should be quantitatively scaled to the described activity (Step 2) (e.g., the functional unit, in the case of product-level AESAs). Each process then contains a list of quantified environmental flows that is also scaled to the described activity. This system of processes and their environmental flows is often constructed using dedicated software or tools. For example, an LCA software with links to a database with secondary data (Step 4.2) may be used for studies at the product scale. Likewise, a Python implementation of the Exiobase EEIO model may be used for studies at the national scale (Annex I).

For organizing the data collection (Step 4.1 and 4.2) and presenting and interpreting results (Step 5, 8 and 9), it can be useful to divide the system of processes into groups. For example, for studies of activities where a central actor can be identified, processes within the system boundary can be divided into a direct part, containing processes that this actor directly controls, and an indirect part, containing other processes that are required for the activity to take place. The distinction of scope 1 emissions (direct) from scope 2 and 3 emissions (indirect) within the GHG Protocol (WBCSD/WRI 2004) is a good example of such a grouping. The grouping of processes can inform data collection (Step 4.1 and 4.2), by separating processes for which primary data provided by the central actor are likely to exist (sometimes called the "foreground system") from processes, typically indirect, for which secondary data can serve as a proxy (sometimes called the "background system"). Processes can also be grouped into chronological phases, for example distinguishing "upstream" indirect processes from "downstream" indirect processes, relative to the central actor, or dividing a life cycle into a raw material stage, a manufacturing stage, a use stage, and an end-of-life stage.

Note that depending on the approach to managing spatial and temporal variations (Step 3.5) the mapping of the environmental flows may need to be divided into different locations and time steps, for this information to be carried over to the estimation of environmental burdens (Step 5) and their subsequent comparison to the allocated carrying capacities (Step 8).

40 buildings case:

The practitioner used the LCA software OpenLCA (GreenDelta 2024) to model the LCI of each case building, following this illustrative system diagram, where anthropogenic processes are grouped according to the BS EN 15804:2012+A2:2019 standard (ES 2021):



UltraTech Cement case: The company used the emission accounting tool(s) made available through the SBTi India Incubator (SBTi 2025) and the Cement CO_2 and Energy Protocol developed by the World Business Council for Sustainable Development (WBCSD) (CDP 2023).

EU consumption case: The LCIs of the consumption footprint model were generated in Python, with consumption statistics combined with the environmental pressures of each representative product, which, in turn, were modelled in Simapro software (PRé, 2024).

3.5. STEP 5: Estimate resulting environmental burdens

Having determined all environmental flows of the system (Step 4), it is time to apply characterization factors to estimate burdens for each impact category and environmental indicator. Here, the practitioner should use the characterization factors from the specific impact assessment method that has been chosen for the study (Step 3.4) and with which the list of carrying capacities is compatible (Step 6). Note that if the impact assessment method offers both an average and a marginal set of characterization factors (Boulay *et al* 2020), the average set should be used to be compatible with attributional accounting, which AESA builds on (Bjørn *et al* 2016).

In practice, the application of characterization factors is typically done in the same tool that is used for mapping and quantifying environmental flows (Step 4). For example, LCA software typically allows users to apply characterisation factors for a range of major impact assessment methods to the modelled life cycle inventories and, moreover, to import additional sets of characterization factors.

Again, the practitioner should be mindful of the handling of spatial and temporal variations (Step 3.5). For example, it may be necessary to apply characterization factors for specific locations and times to the matching groups of environmental flows (Step 4.3).

40 buildings case:

The practitioner used the pre-existing set of characterization factors for the EF3.1 method integrated in the LCA software OpenLCA (GreenDelta 2024).

UltraTech Cement case:

In accordance with the GHG Protocol (WBCSD/WRI 2004, Greenhouse Gas Protocol 2016), the company used the characterization factors for the GWP100 indicator, presumably from the latest Intergovernmental Panel on Climate Change (IPCC) assessment report.

EU consumption case:

The practitioner used a custom Python code to apply the PB-LCIA method of Ryberg et al (2018b) to the LCI, hence calculating the resulting environmental burdens for each impact category.

4. PHASE B: Allocate carrying capacities

4.1. STEP 6: Develop a list of quantified carrying capacities

Having estimated the environmental burdens of the studied activity, the practitioner should develop a list of quantified carrying capacities for each impact category included in the study. The scientific literature contains a range of estimates of these carrying capacity values (Bjørn *et al* 2020a, Paulillo and Sanyé-Mengual 2024, Vea *et al* 2020). When sourcing the list of carrying capacity values from the scientific literature, the practitioner should ensure that they were developed for the same impact assessment framework, with the same characterization models that were used for quantifying environmental burdens (see Step 3.4 and 5) to ensure consistency between the indicators and units, and not only between the names of impact categories.

For transparency, the practitioner should state both the original carrying capacity values and any potential translation (done in the scientific literature) of those values to the environmental indicators used in the impact assessment framework (Step 3.4). For example, original carrying capacities for climate change are commonly stated as a maximum increase in global surface air temperature (e.g., 2 degrees), while this must be translated to annual amounts of CO_2-equivalent emissions, following the GWP100 indicator, to be compatible with many impact assessment frameworks.

40 buildings case:

The academic study (Lund *et al* 2025) documents the carrying capacities in the following table:

Impact categories	Area of protection	Original threshold estimate	Carrying capacity
Ecotoxicity freshwater	Ecosystems	HC5 (NOEC)	1.12E+14 CTUe
Acidification		1100 mol H^+ eq/Ha/year	6.59E+10 mol H^+ eq.[a]
Eutrophication - freshwater		0.3 mg/L water	3.50E+08 kg P eq.[a]
Eutrophication - marine		1.75 mg/L water	2.29E+02 kg N eq.[a]
Eutrophication - terrestrial		1390 mol N eq /Ha/year	4.27E+11 molc N eq.[a]
Land use		0.85 tons eroded soil/ha/year	6.01E+12 kg C deficit[a]
Climate change	Both ecosystems & human health	2°C global temperature increase	6.81E+12 kg CO_2 eq.
Ozone depletion		7.5% decrease in avg. ozone conc.	5.39E+08 kg CFC-11 eq.
Photochemical ozone formation		3 ppm·h AOT40 (daylight hours)	4.35E+10 kg NMVOC eq.[a]
Water use		Conservation of 57% of river flows for aquatic ecosystems and 30% for terrestrial ecosystems	1.82E+14 m^3 world eq. depriv.
Particulate matter	Human health	10 µg PM 2.5/m^3	5.17E+05 Disease incidence
Ionising radiation		10 µg PM 2.5/m^3	5.27E+14 kBq U235
Human toxicity - cancer		10 µg PM 2.5/m^3	9.61E+05 CTUh
Human toxicity - non-cancer		10 µg PM 2.5/m^3	4.10E+06 CTUh
Mineral resource use	Resource use	Reduction with factor 4.08	1.07E+08 kg Sb eq.

UltraTech Cement case:

The company used a method developed by SBTi that was based on the "well-below 2°C" ceiling of the Paris Agreement as an original carrying capacity (SBTi 2025). The SBTi method (assumed here to be the sectoral decarbonization approach (Krabbe *et al* 2015)) relied on a climate scenario generated by the International Energy Agency from an integrated assessment model to translate this warming limit into a global CO_2e emission pathway starting from actual global emissions in the company base year (2017) and ending in 2050 with substantially lower emissions.

EU consumption case:

The carrying capacities are represented by the Safe Operating Space (SOS) delineated by the 2015 version of the Planetary Boundaries framework (Steffen *et al* 2015), as covered by the PB-LCIA method of (Ryberg et al (2018b, 2018a):

Impact category	Unit	Planetary Boundary (Steffen et al., 2015)	Natural background level (Steffen et al., 2015 and references therein)	Full safe operating space
Climate change - energy imbalance	Wm^{-2}	1	0	1
Climate change - CO_2 concentration	ppm CO_2	350	278	72
Stratospheric ozone depletion	DU	275	290	15
Ocean acidification	mol	2.75	3.44	0.69
Biogeochemical flows – P, regional	Tg P yr^{-1}	26.2	20	6.2
Biogeochemical flows – N, global	Tg N yr^{-1}	62	0	62
Land-system change – global	%	75	100	25
Land-system change – boreal	%	85	100	15
Land-system change – tropic	%	85	100	15
Land-system change – temperate	%	50	100	50
Freshwater use – global	$km^3\ yr^{-1}$	4000	0	4000
Freshwater use - basin dry	–	1	0	1
Freshwater use - basin semidry	–	1	0	1
Freshwater use - basin humid	–	1	0	1
Atmospheric aerosol loading	–	0.25	0.14	0.11

The case study covered all impact categories, except the regional boundaries for land-system change, due to lack of environmental flows at this spatial resolution (Paulillo n.d.).

4.2. STEP 7: Allocate carrying capacities to activity

The allocation of carrying capacities to the studied activity contains three sub steps. In practice, these sub steps can be performed in parallel, since the choice of principles, and their specific operationalizations, is often constrained by availability of data.

4.2.1. STEP 7.1: Choose allocation principles

The allocation of global (or regional) carrying capacities to the activity studied is one of the defining characteristics of AESA. It is inherently subjective, meaning that a consensus will probably never be established on a single "right way" to allocate in each assessment context. In addition, studies have shown that AESA results are often sensitive to the allocation principle (Bjørn *et al* 2020a, Ryberg *et al* 2020).

Table 2 briefly presents 8 broadly applicable allocation principles and Figure 3 shows the scales that each allocation principle can be applied to. Since some allocation principles are only applicable at certain scales (Figure 3), it is often necessary to combine multiple principles, particularly if the studied activity is a single product. Table 2 and Figure 3 are based on our observations from existing AESA studies (Bjørn *et al* 2020a, Ryberg *et al* 2020) and only shows what is logically possible. They should therefore not be interpreted as a recommendation or an ethical endorsement of the presented allocation principles.

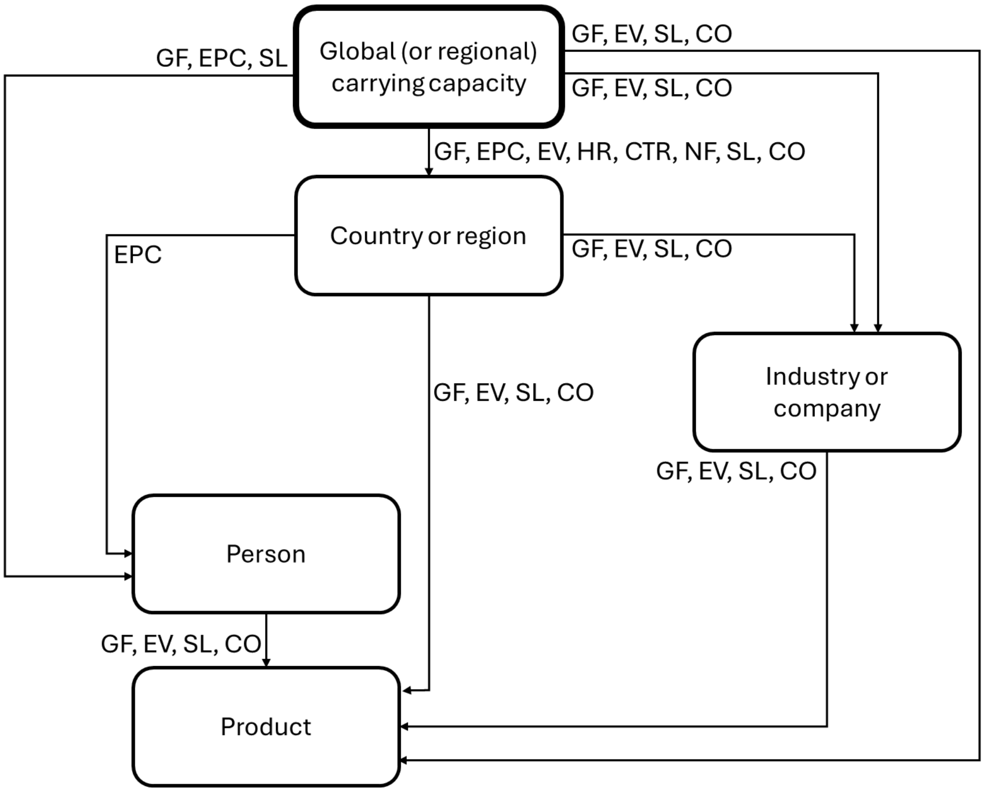
Table 2. Key Presentation of 8 broadly applicable allocation principles. The principles are sequenced roughly according to their frequency of use in the AESA literature (Bjørn *et al* 2020a, Ryberg *et al* 2020).

Allocation principle	**Description**

Grandfathering (GF)	The carrying capacity is allocated proportionally to the environmental impacts of the activity in a past reference year.
Equal per capita (EPC)	Every person receives the same carrying capacity share.
Economic value (EV)	The carrying capacity allocated to an activity is proportional to its economic value (generation), for example as measured by value added (≈contribution to GDP) or prices.
Historical responsibility (HR)	An actor whose historical environmental impacts are disproportionally high (low) receives a lower (higher) allocation.
Capability to reduce (CTR)	The higher (lower) an actor´s capability to reduce impacts, for example as measured by GDP per capita, the lower (higher) the allocated carrying capacity.
Needs fulfilment (NF)	The carrying capacity allocated to a region is higher (lower) if the inhabitants have not fulfilled (have fulfilled) their basic needs.
Sufficiency lifestyles (SL)	The carrying capacity allocated to a product or a basket of products is proportional to their degree of use in a sufficiency lifestyle scenario, such as the "decent living standard"(Millward-Hopkins *et al* 2020).
Cost optimization (CO)	The carrying capacity allocation follows a least-cost scenario of all (global) activities constrained by carrying capacities.

Source: Own elaboration.

Figure 3. Mapping of the applicability of the eight allocation principles (acronyms explained in Table 2) to actors and activities (boxes) at five different spatial scales. Note that this mapping only considers applicability and not fairness.



Source: Own elaboration.

It is crucial that the practitioner applies at least two allocation principles (or at least two sets of allocation principle combinations, see Figure 3) as part of a sensitivity analysis, informing the study´s interpretation (Step 9), and transparently documents why each approach was chosen. This justification should include arguments for why an allocation approach can be considered fair, but also note any potential counterarguments. For example, the use of the grandfathering principle to allocate country-level carrying capacities to individual industries can, on the one hand, be considered fair, as it takes into accounting that some industries (e.g., agriculture) have a larger need to cause environmental burdens than others (e.g., IT services). On the other hand, the use of grandfathering can also be considered unfair, since it effectively punishes industries that have already made efforts to reduce burdens (hence, have already "picked the low hanging fruits") and since it does not consider differences across industries in how easy or hard it will be to further reduce burdens (i.e., capabilities to reduce).

40 buildings case:

The study included three different allocations, of which the first two combined two allocation principles and the third involved a single allocation principle:

- Equal per capita, followed by Economic value.
- Equal per capita, followed by Sufficiency lifestyles.
- Grandfathering.

The study did not systematically argue for or against the fairness of each principle.

UltraTech Cement case:

The company appears to have used the sectoral decarbonization approach (SDA) for calculating a science-based target. SDA involves a single combination of the following four allocation principles (Krabbe *et al* 2015, Bjørn *et al* 2021):

- Grandfathering.
- Activity growth (a variant of the economic value principle).
- Emission intensity convergence (not covered by Table 2 or Figure 3).
- Cost-optimization.

Note that SDA generally leads to less ambitious reduction targets from cement companies than the alternative sector-generic absolute contraction approach (ACA), which is based purely on Grandfathering (Bjørn *et al* 2021). This is because the cement sector is amongst the sectors with the highest cost of reducing emissions. Hence, the Cost-optimization principle results in relatively low emission reduction requirements for cement companies.

UltraTech (like most other companies with approved SBTs) does not directly argue for or against the fairness of the allocation principle behind its target. However, SBTi has to some extent done this (Chang *et al* 2022).

EU Consumption case:

The study included four different allocation principles:

- Equal per capita
- Capability to reduce

- Grandfathering
- Historical responsibility

Capability to reduce was based on per capita Gross Domestic Product (GDP), whilst for grandfathering and historical responsibility, carbon emissions are taken as proxy to represent all the considered carrying capacities. Various reference years were considered for grandfathering and responsibility as a sensitivity analysis. For the former, it was considered the signing of Kyoto protocol (~1990), the Paris Agreement (~2015) as well as 2020 as an exemplar of a recent year, whilst for the latter, the beginning of the industrial revolution (~1870), the beginning of intense research on climate impacts (~1970), and the signing of the Kyoto protocol (~1990), which are key dates for climate change science and negotiations.

4.2.2. STEP 7.2: Collect data required for allocation

In parallel to deciding what allocation principles to include in the AESA (Step 7.1), the practitioner must collect the data that is required for applying these principles. Some allocation principles require more data than others. However, each principle always requires two types of data, the first relates to the activity studied and the second is the corresponding data at the global (or regional) level where carrying capacities are defined. For example, the equal per capita principle, which can be used to translate global carrying capacities into country-level carrying capacities (Table 2 and Figure 3), requires data on the population in the studied country, as well as global population data. The global data are often made available in documentation of allocation methods, while the activity-specific data must always be collected directly by the practitioner.

40 buildings case:

The practitioner used the following data sources to obtain the data required by the four allocation principles (Lund *et al* 2025):

- Population data from UNDESA.
- Expenditure data from Statistics Denmark.
- Final energy consumption from a decent living scenario (Millward-Hopkins *et al* 2020).
- Global burdens relative to carrying capacities from (Sala et al (2020).

UltraTech Cement case:

For applying the sectoral decarbonization approach, the company would have used internal data on production of cementitious product and emissions in the base year (2017), as well as projections of production in the target year (2032).

The remaining global and industry-level data needed for applying the SDA method (Krabbe *et al* 2015, Bjørn *et al* 2021) was already integrated in SBTi´s target-setting tool (SBTi 2020).

EU Consumption case:

The study relied on the following data sources:

- Population data from 2021 based on World Bank (World Bank 2024b).
- Per capita GDP at purchasing power parity (current international $) for 2021 from World Bank (World Bank 2024a).
- Country-level per capita CO_2 emissions from Our World in Data (Our World in Data 2024).

4.2.3. STEP 7.3: Apply allocation equations

Finally, the practitioner is ready to apply an operationalization of the chosen allocation principle(s) (Step 7.1). In practice, this means using one or more equations with the activity-level data and global data collected in Step 7.2 to calculate allocated carrying capacities. When documenting these calculations, it is important to be transparent about the choices embedded in the operationalization of each allocation principle and justify these choices. For example, many principles (such as Historical responsibility, see Table 2) require the choice of a reference year or a reference period, to which the global and activity-level data must correspond.

Note also that, depending on the handling of spatial and temporal variations (Step 3.5), it may be appropriate to calculate a single allocation to the studied activity, or to calculate multiple allocations for different locations and time steps in the activity life cycle.

40 buildings case:

The equations for the three (combinations of) allocation principles are:

$$Allocated\ share_{EPC \to EV} = \frac{Pop_{Denmark}}{Pop_{Macro}} \cdot \frac{FCE_{Dwelling}}{FCE_{Total}} \cdot \frac{1}{Number\ of\ residents}$$
$$Allocated\ share_{EPC \to SL} = \frac{Pop_{Denmark}}{Pop_{Macro}} \cdot \frac{DLE_{Dwelling}}{DLE_{Total}} \cdot \frac{1}{Number\ of\ residents}$$
$$Allocated\ share_{GF} = \frac{EB_{reference}}{CC}$$

Where:

-Pop = population.

-Macro = global for global carrying capacity and Europe for European carrying capacities.

-FCE = final consumption expenditure.

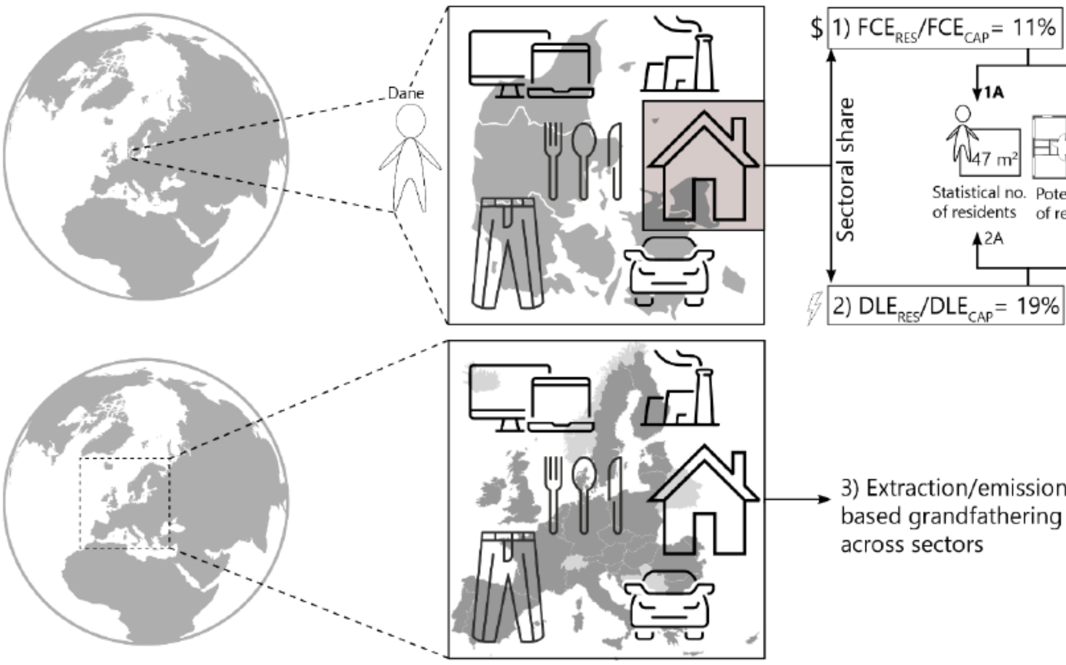
-Number of residents: estimated from national statistics or the building layouts.

-DLE = decent living energy: estimated from Millward-Hopkins et al (2020).

-EBreference = Current environmental burden of each case study house, for a given impact category.

-CC = carrying capacity at global or European level, for a given impact category.

The figure below illustrates the three allocation approaches, including the two different techniques for estimating the number of residents:



UltraTech Cement case:

The company presumably used the version of the SDA method that has been implemented in the SBTi Excel-based target-setting tool for "homogenous sectors" (Krabbe *et al* 2015, Bjørn *et al* 2021, SBTi 2020). This implementation is based on the following set of equations along with data from the "Well-below 2°C" IEA scenario that was embedded in the SBTi tool at the time UltraTech Cement calculated its target (Krabbe *et al* 2015):

"Company intensity pathways are derived from the company's base year intensity and the sectoral intensity pathway. To account for current performance, a factor d is formulated as the distance from the company intensity (CI,) in base year b to the sector intensity (SI) in year 2050:

$$d = CI_b - SI_{2050}$$

The company intensity in the base year is provided by the company, and the sector intensity provided by an external scenario. To converge the company's intensity towards the sectoral decarbonization pathway, we define p as a function of year y, which is essentially an index of the sector decarbonization, expressed from 0 to 1:

$$p_y = (SI_y - SI_{2050})/(SI_b - SI_{2050})$$

All sector intensities in this equation are derived from an existing scenario. Next we define my ; a term that accounts for changes in market share (the share of company activity CA in sector activity SA):

$$m_y = (CA_b/SA_b)/(CA_y/SA_y)$$

The company's activity in the base year and the projected activity of the company are provided by the company. The sector activity is retrieved from an external scenario. This means that the total sector activity is not the actual activity, but rather the projection from the scenario. Note *that the term my is not the change in market share, but rather the inverse, resulting in a decreasing my with increasing market share.*

A company's intensity in year y can then be expressed as

$$CI_y = dp_y m_y + SI_{2050}\text{”}$$

From the use of these equations, the company was able to define its science-based target, subsequently approved by SBTi, as:

"UltraTech Cement commits to reduce scope 1 GHG emissions by 27% per ton of cementitious material by FY2032 from a FY2017 base year. UltraTech Cement also commits to reduce scope 2 GHG emissions by 69% per ton of cementitious material within the same time frame." (SBTi 2025).

EU Consumption case:

The following table shows the operationalization of the four allocation principles:

Principle	Equation
Equal per capita (EPC)	$EPC = \frac{Pop_S}{Pop_W}$
Capability to reduce (CTR)	$CTR = \frac{GDP_{Cap,W}}{GDP_{Cap,S}} \times \frac{Pop_S}{Pop_W} \times \alpha_{AtP}$
Grandfathering (GF)	$\mathrm{GF}_{T,PB} = \frac{Pr_{Cap,S,PB,T}}{Pr_{Cap,W,PB,T}} \times \frac{Pop_S}{Pop_W} \times \alpha_{AR}$
Historical responsibility (HR)	$HR_{T,PB} = \frac{PrCum_{Cap,W,PB,T}}{PrCum_{Cap,S,PB,T}} \times \frac{Pop_S}{Pop_W} \times \alpha_{Re}$

Where:

- Pop_W and Pop_S represent the global and the system's population;
- $GDP_{Cap,W}$ and $GDP_{Cap,S}$ represent the global and the system per capita Gross Domestic Product (GDP);
- $Pr_{Cap,S,PB,T}$ and $Pr_{Cap,S,WB,T}$ represent the system and the global per capita environmental pressures relevant to a specific PB at year T;
- $PrCum_{Cap,S,PB,T}$ and $PrCum_{Cap,S,WB,T}$ represent the system and the global cumulative environmental pressures relative to a given PB from start year T.
- α_{AtP} , α_{AR}, α_{Re} are scaling factors ensuring that allocation factors for all countries sum to one. The scaling factors are calculated based on the Table below:

The equations for the different types of scaling factors (α) are:

$$\alpha_{AtP} = \frac{Pop_W}{GDP_{Cap,W} \times \sum_S \frac{Pop_S}{GDP_{Cap,S}}}$$

$$\alpha_{AR} = \frac{Pr_{Cap,W,PB,T} \times Pop_W}{\sum_S (Pr_{Cap,S.PB,T} \times Pop_S)}$$

$$\alpha_{Re} = \frac{Pop_W}{PrCum_{Cap,W,PB,T} \times \sum_S \frac{Pop_S}{PrCum_{Cap,S}, PB, T}}$$

This resulted in the following allocation shares of the global SOS:

Allocation approach	Reference year	Allocated share
EPC	2021	5.7%
CTR	2021	1.0%
GF	2015	10.8%
HR	1990	0.7%

5. PHASE C: Interpret results

5.1. STEP 8: Compare environmental burdens with allocated carrying capacities

Now that the environmental burdens of the studied activity have been calculated and the carrying capacities have been allocated, it is time for the practitioner to compare the two. This should be done for each impact category. In other words, the environmental burdens should not be aggregated across impact categories, although this is sometimes done in environmental accounting without the absolute sustainability perspective (Hauschild *et al* 2018, EC 2010).

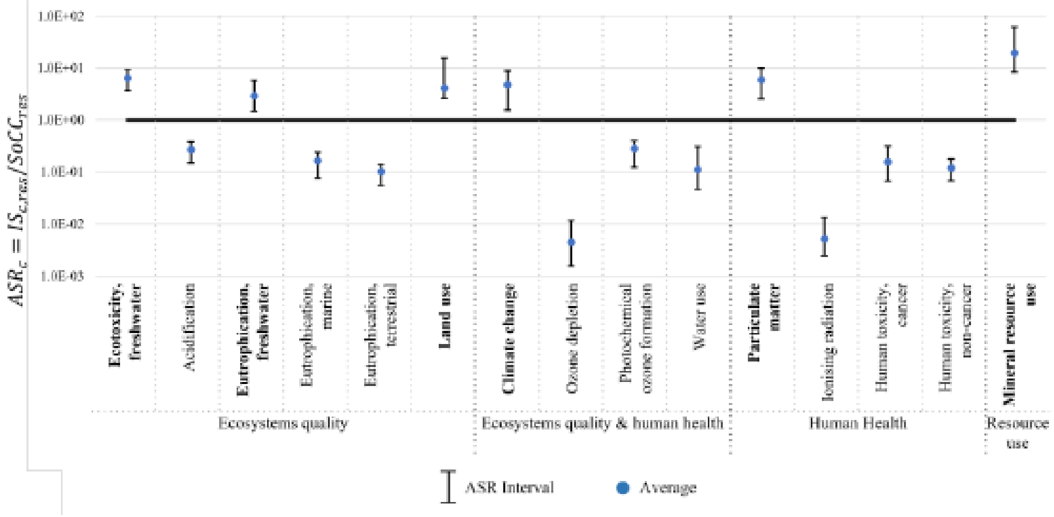
Note that if the study calculates burdens and allocate carrying capacities for individual locations and time steps (Step 3.5), then the comparison of environmental burdens and allocated carrying capacities for a given impact category should be done for each pair of location and time.

In a mathematical sense, the comparisons can be made in different ways. Arguably the most common way is to divide the environmental burden by the allocated carrying capacity (this is sometimes called a sustainability ratio), whereby values above 1 indicate that the activity´s environmental burdens are too high and must be reduced by the extend needed to stay below a value of 1. Another way is by subtracting the environmental burdens from the allocated carrying capacity, whereby a negative value indicates that a burden is too high. Note that the comparison of burdens to allocated carrying capacity must be done for each of the included allocation approaches (Step 7), and thereby inform the interpretation of results (Step 9).

Note also, that AESAs are sometimes performed not to understand if current burdens are too high or low enough, but to inform future burden reduction targets. Science-based targets are a good example of this. In that case, current burdens are already known to be too high, and the outcome of the AESA is instead a quantification of how much current burdens must be reduced in one or more future years (or cumulatively, across a future time period).

40 buildings case:

The practitioner calculated absolute sustainability ratios (ASRs) as the environmental burden divided by the corresponding allocated carrying capacity for each of the 40 case buildings, impact categories and sets of allocation principles. The following figure shows the resulting ranges of the sustainability ratios across the 40 buildings for the Equal per capita → Economic value allocation:



The other two allocation approaches (including the alternative way to quantify number of residents) resulted in similar conclusions, in terms of whether the sustainability ratio is above or below 1 for a given impact category, with the exception of Freshwater ecotoxicity, for which the Grandfathering allocation principle resulted in a ratio below 1 for all 40 buildings (Lund *et al* 2025).

UltraTech Cement case:

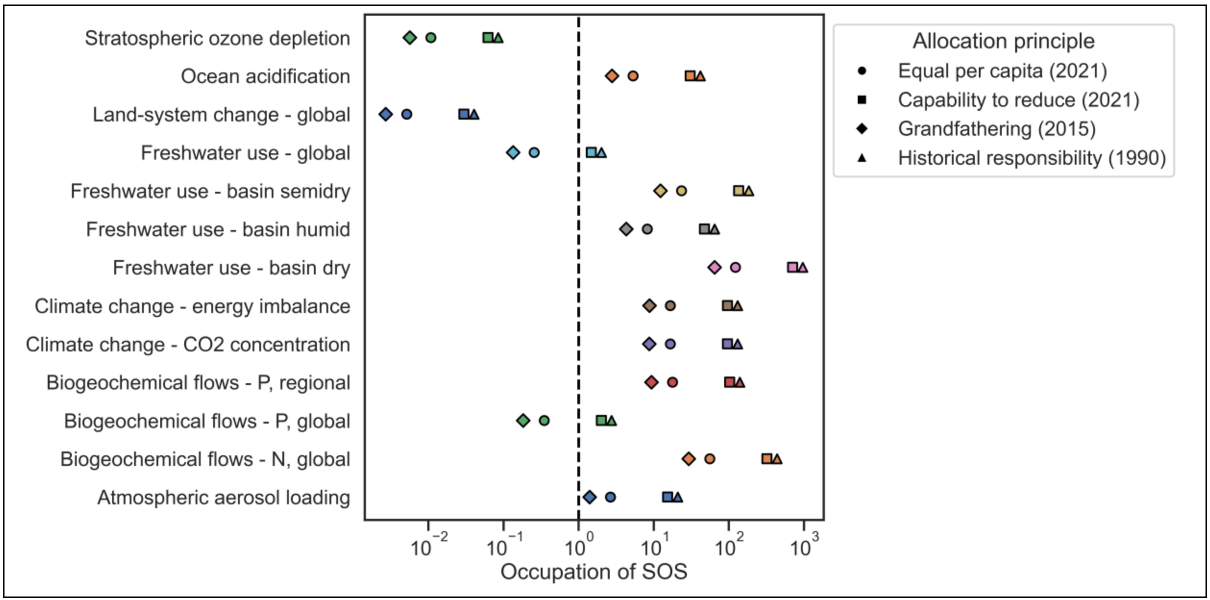
After using the SBTi target-setting tool (presumably the SDA component), the company announced a target, approved by SBTi, of reducing scope 1 GHG emissions 27% per ton of cementitious material by FY2032 from a FY2017 base year and of reducing scope 2 GHG emissions 69% per ton of cementitious material within the same time frame (SBTi 2025).

According to the company´s disclosures to CDP, it had achieved a 12% reduction in its scope 1 emission intensity from FY2017 to FY2023 (from 0.632 to 0.557 tons CO_2 per ton of cementitious product), which made the company on track to achieving its reduction target for FY2023, assuming a linear trajectory (CDP 2023).

However, the company reported a 14% increase in scope 2 emission intensity from FY2017 to FY2023 (from 0.014 to 0.016 tons CO_2 per ton of cementitious product), indicating that a change in practice is needed for realizing the 69% reduction pledged in FY2032 (CDP 2023).

EU Consumption case:

The results of AESA are reported in terms of “occupation” of the allocated Safe Operating Space (aSOS), which is another term for sustainability ratio, for the four allocation principles used (Paulillo n.d.):



5.2. STEP 9: Interpret results in light of uncertainties and choices

As a final step, the practitioner must interpret the AESA results in light of the study´s goal definition (Step 1). Typically, this step involves a conclusion about the impact categories (potentially for specific locations and time steps) for which the allocated carrying capacity are exceeded and by how much. The robustness of these conclusions should be assessed based on results of the different allocation principles (Step 7), as well as other major sources of uncertainty, such as in the quantification of environmental flows (Step 4) and burdens (Step 5).

In practice, it can be useful to carry out a sensitivity analysis, both involving different allocation approaches (Step 7) and other choices made during the quantification of environmental flows (Step 4), such as assumptions around the types and locations of technologies far upstream to the central actor. Uncertainty propagation can also be performed with the purpose of understanding to what extend combined uncertainties across different assessment steps affect the initial results and conclusions drawn from a deterministic analysis (Puig-Samper *et al* 2025). For example, some LCA software enable uncertainty propagation assessments in the form of Monte Carlo analysis. In the context of AESA, an important aim of sensitivity and uncertainty analysis is to gauge the robustness of the initial finding on the size of the environmental burdens relative to the allocated carrying capacities.

The interpretation step will typically also involve recommendations about interventions that can effectively help bring the environmental burdens of the studied activity down to a sustainable level. Such recommendations could consider i) which anthropogenic processes within the system boundary that are “hot spots” in terms of carrying capacity exceedance, ii) what are the technical or behavioral potential of reducing the burdens of these hot spot processes, and iii) what power does the central actor have to make such changes happen.

40 buildings case:

The 40 case buildings were found to exceed their assigned carrying capacity for 5-6 impact categories, depending on the allocation approach. Hence, the study concluded that, from an AESA perspective, these 5-6 impact categories should be prioritized for inclusion in LCAs within the building sector (Lund *et al* 2025).

UltraTech Cement case:

According to the company, its scope 1 emissions made up around 88% of its total scope 1, 2 and 3 emissions in FY2023 (UltraTech 2024). The company has been successful in reducing its scope 1 emission emissions intensity, mainly through energy efficiency measures and the use of alternative fuels such as municipal solid waste and agricultural waste. However, by not having reduced its scope 2 emission intensity, the company is off-track to meeting the scope 2 component of its science-based target. The company is therefore looking into increasing the share of renewable energy in its electricity consumption. Reducing the carbon intensity of the companies´ consumed electricity becomes even more urgent if the company will be using kiln electrification to further drive down scope 1 emissions in the future (UltraTech 2024).

EU Consumption case:

The study indicates that the environmental impacts of EU consumption transgress its allocated SOS (aSOS) in most categories and for all allocation principles investigated, which implies a condition of environmental unsustainability.

Under the EPC principle, EU consumption exceeds its aSOS in 9 out of 13 categories considered, with transgression ranging from 2.65 for Atmospheric Aerosol Loading up to 122 for Freshwater, dry basin. The same number of categories are transgressed under the GF principle, though the extent of transgression is lower; the allocation factor for GF is higher than that for EPC, and the lower exceedance is proportional to the ratio of the allocation factors. Both Historical responsibility and Capability to reduce yield a higher number of transgressed categories (11 out of 13), including also Biogeochemical Flow of P, and Freshwater use, global. The extent of transgression is higher for Historical responsibility than for Capability to reduce. Both allocation factors are lower than EPC, reflecting higher than average historical contribution to climate change (from 1990) of EU countries and per capita GDP (in 2021). The sensitivity of AESA results to different reference years for grandfathering and historical responsibility was also analyzed and found to be comparable to the sensitivity to the allocation principle.

These results not only indicate that EU consumption is environmentally unsustainable, they also provide a reference for defining quantitative targets of reductions for policy-makers and other decision-makers. However, it is important to note that the extent of reductions is significantly dependent on the allocation principle. The results suggest that whilst the EU may be able in the short to mid-term to achieve environmental sustainability of its consumption under the GF perspective (i.e. an average reduction of slightly over 90%), the scale of the efforts becomes daunting under egalitarian (EPC) and even more so under prioritarian (HR and CPT) perspectives which require average reductions in the order of 120 to 160 times.

6. Conclusion

This report offers the first harmonized, comprehensive and practical guidance for how to carry out AESA on activities at different scales. The main novelty of the guidance is that it brings together AESA knowledge from the academic literature to a single, consistent and accessible document and that it offers in-depth practical examples through the use of three cross-cutting case studies.

The guidance is organized according to three phases, nine steps and eleven sub-steps. This organization should be seen as an initial suggestion and may change in later editions of this guidance. Various other aspects of this guidance may also change or become further elaborated in future versions, depending on the feedback of the AESA community. Please follow this link to submit your feedback: https://www.survey-xact.dk/LinkCollector?key=Q8NNSDMMU695

AESA is still a young sustainability assessment approach. The coming years are likely to witness scientific development along several lines, such as:

— Updated carrying capacity references according to the most recent scientific findings, for example within planetary boundaries research (Richardson *et al* 2023).

— Additional operationalization of allocation principles, for example improving allocations according to sufficiency lifestyles (Kromand *et al* 2025).

— More attention to spatial and temporal variations in environmental flows, environmental burdens and carrying capacities (Bjørn *et al* 2020b, Guinée *et al* 2022), for example, by integrating prospective environmental assessments and AESA (Sacchi *et al* 2022, Cardellini *et al* 2018).

Guidance for how to carry out AESA will need to be updated following such methodological improvements.

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List of abbreviations

Abbreviations	Full name
AESA	Absolute Environmental Sustainability Assessment
aSOS	Allocated Safe Operating Space
CTR	Capacity to reduce
CO	Cost optimization
DGNB	Danish green building certification program
EC-JRC	European Commission - Joint Research Centre
EEIO	Environmentally Extended Input Output
EF	Environmental Footprint
EPC	Equal per capita
EU	European Union
EV	Economic Value
GDP	Gross Domestic Product
GF	Grandfathering
GHG	Greenhouse Gas
GWP	Global Warming Potential
HR	Historical Responsibility
ILCD	International Life Cycle Data
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NF	Needs fulfilment

Abbreviations	Full name
PB-LCIA	Planetary Boundaries – Life Cycle Impact Assessment
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rule
SBTi	Science-based Targets initiative
SDA	Sectoral Decarbonization Approach
SDG	Sustainable Development Goal
SL	Sufficiency Lifestyles
WBCSD	World Business Council for Sustainable Development

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Figure 1. The three phases of AESA. See Section 3-5 for detailed guidance on individual assessment phases, steps and sub-steps. 6

Figure 2. Nine assessment steps and eleven sub-steps under the three AESA phases. The three dotted arrows indicate cases where the practitioner should potentially anticipate a later (sub-)step (e.g., 6) when carrying out a specific (sub-)step (e.g., 3.4). 9

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Annexes

Annex 1. Case study: Absolute Environmental Sustainability Assessment of UK consumption via Environmentally-Extended Input-Output Analysis (EE-MRIOA)

STEP 1: Define goal of assessment

This study was conducted as part of a PhD project focused on advancing AESA applications at country level. The objective of the study is to assess the environmental sustainability of the UK economy using a consumption-based perspective and under various allocation principles. Notably, the study also intended to develop, where relevant, PBs-specific allocation factors. The aspiration is to support target-setting and policy-making in the UK. The intended audience includes both researchers, including but not limited in LCA, industrial ecology, and policy-makers in the UK.

STEP 2: Describe activity

The study considers the UK's final demand – i.e. the sum of all goods and services consumed for final use in 2020 - including both domestic production and imports, and excluding exports.

STEP 3: Plan environmental accounting

STEP 3.1: Choose an accounting approach

The AESA is based environmentally-extended, multi-regional input-output (EE-MRIO) modelling.

STEP 3.2: Define system boundaries

The system boundaries cover the entire life cycle (from cradle to grave) of all products (including goods and services), domestically produced or imported, that are required to satisfy the UK final demand.

STEP 3.3: Decide how to solve multifunctional processes

Multifunctionality is not explicitly addressed within the study, rather this is solved within the EE-MRIO model chosen (Exiobase) primarily via economic/physical partitioning factors (Stadler et al., 2018).

STEP 3.4: List impact categories and environmental indicators

The AESA study included the following impact categories from the PB-LCIA method (Ryberg et al., 2018b):

- Atmospheric aerosol loading
- Biogeochemical flows - N, global
- Biogeochemical flows - P, global
- Biogeochemical flows - P, regional
- Climate change - CO_2 concentration
- Climate change - energy imbalance
- Freshwater use - global
- Land-system change - global

— Ocean acidification

— Stratospheric ozone depletion

Regional impact categories for freshwater use and land-system change are not included.

STEP 3.5: Decide handling of spatial and temporal variations

Space and temporal variations in environmental burdens and carrying capacities are not considered, for simplicity.

STEP 4: Quantify environmental flows

STEP 4.1: Collect primary data

No primary data is explicitly collected, since the UK's final demand is already captured by Exiobase. Hence, the study relies only on secondary data.

STEP 4.2: Collect secondary data

Secondary data is obtained from Exiobase, version 3.9.5 (Stadler et al., 2018).

STEP 4.3: Build system of processes including their environmental flows

The practitioner used the Python package PYMRIO (Stadler, n.d.) to calculate the elementary flows associated with the UK final demand.

The total elementary flows € are calculated following standard environmentally-extended input-output calculations:

$$E = B(I - A)^{-1} Y \qquad (1)$$

Where A is the technical coefficients matrix, I is the identity matrix, Y is the final demand vector and B is the environmental extensions per unit of economic output.

STEP 5: Estimate resulting environmental burdens

Environmental burdens are calculated using a custom Python script. The calculation relies on an ad-hoc mapping between the environmental extensions included in Exiobase and the characterisation factors of PB-LCIA.

STEP 6: Develop of quantified carrying capacities

Similar to "EU Consumption" case study presented in the main text, the carrying capacities correspond to the Safe Operating Space (SOS) estimated by the Planetary Boundaries framework (Steffen et al., 2015). All Earth-system processes and control variables are considered with the exception of the regional boundaries for land-system change and freshwater use. The SOS is considered as that "originally available", calculated as the difference between boundary values and the natural background, based on (Paulillo and Sanyé-Mengual, 2024; Ryberg et al., 2018a)

Table A1 reports the carrying capacities used.

Table A1. PBs and CVs

Planetary boundaries	Acronyms	Unit	Planetary boundary	Natural background level	SOS for humanity
Climate change – energy imbalance	EI	W/m^2	1	0	1
Climate change – atmospheric CO2 concentration	aCO_2	ppm	350	280	70
Stratospheric ozone depletion	SOD	DU	275	290	15
Ocean Acidification	OA	Ωarag	2.75	3.44	0.69
Nitrogen cycle	N	Tg/year	62	0	62
Phosphorus cycle-Regional	P-REG	Tg/year	26.2	0	26.2
Phosphorus cycle-Global	P-GLO	Tg/year	11	0	11
Land system change	LSC	%	75	100	75
Freshwater use	FWC	km^3	4000	0	4000
Atmospheric aerosol loading	AAL	AOD	0.25	0.1	0.15

Source: Based on Ryberg et al. (2020a).

AOD: Aerosol optical depth; DU: Dobson units

STEP 7: Allocate carrying capacities

STEP 7.1: Choose allocation principles

Similar to the EU Consumption case study, four allocation approaches principles are considered:

- Equal per capita
- Capability to reduce
- Grandfathering
- Historical responsibility

Capability to reduce is based on per capita Gross Domestic Product (GDP) (current US dollars). PBs-specific allocation factors are calculated for the Grandfathering and Historical responsibility principles.

STEP 7.2: Collect data required for allocation

Population and GDP data are taken from IMF (IMF, 2024) (World Economic Outlook, 2024) for 2020. Exiobase explicitly considers only 43 countries, with the remaining countries aggregated in 5 rest of world (ROW) regions. To calculate total per capita indicators (e.g. GDP per capita) for the ROW regions, the practitioners aggregated data from the remaining countries provided in the IMF.

Environmental burdens data for the Grandfathering and Historical responsibility principles are taken directly from Exiobase. The reference year for Grandfathering is 2015, whilst for Historical responsibility the practitioner considered cumulative emissions from 1995 (i.e. the earliest year available in Exiobase) to 2020.

STEP 7.3: Apply allocation equations

The same allocation equation used in the "EU consumption" case study (Section 4.2.3 of main text) are also used here.

The calculated allocation factors, which are based on (Yang and Paulillo, 2025) are reported below in Table A2 and A3:

Table A2. Allocation factors for Equal per capita (EPC) and Capability to reduce (AtP)

Allocation approach	Reference year	Allocation factor for the UK
EPC	2020	0.755%
CTR	2020	0.079%

Source: Own elaboration.

Table A3. PBs-specific allocation factors for Historical responsibility (HR) and Grandfathering (GF)

PBs	HR (2015)	GF (1995-2020)
EI	1.437%	0.241%
aCO2	1.448%	0.239%
SOD	1.509%	0.385%
OA	1.448%	0.239%
N	1.246%	0.237%
P-REG	0.877%	0.456%
P-GLO	0.666%	0.440%
LSC	0.789%	0.326%
FWC	0.706%	0.599%
AAL	0.759%	0.573%

Source: Own elaboration.

STEP 8: Compare environmental burdens with allocated carrying capacities

The environmental burdens are compared with the aSOS to determine the transgression level for each PB (TL_{PBi}), calculated as follows:

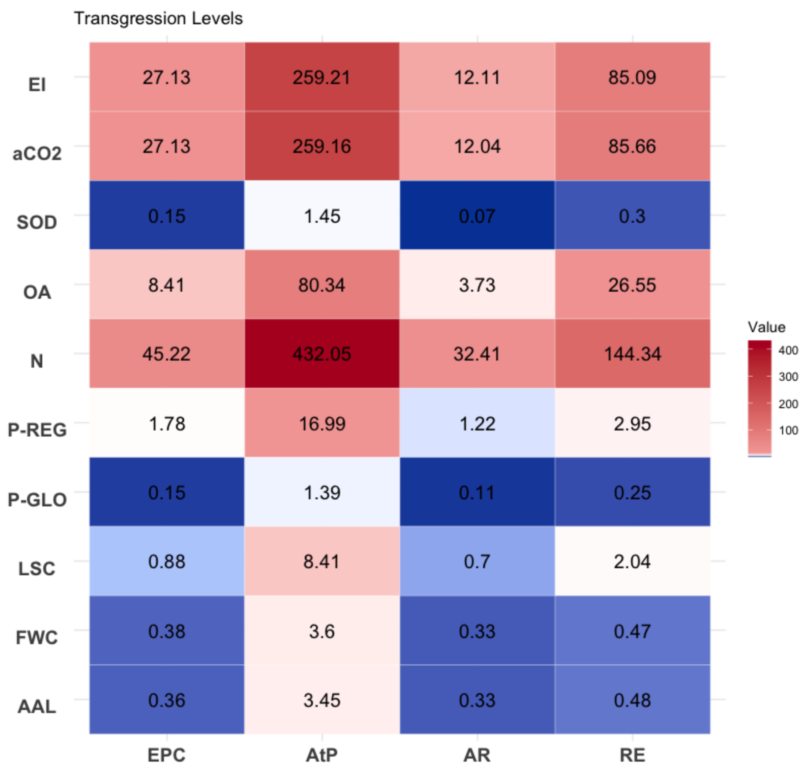
$$TL_{PBi} = \frac{E_{PBi}}{aSOS_{PBi}} \quad (2)$$

Where E_{PBi} is the environmental burdens for Planetary Boundary i (PBi), $aSOS_{PBi}$ is the allocated aSOS for PBi.

A TL higher the 1 indicates that the environmental impacts exceed the corresponding aSOS, implying that the system is environmentally unsustainability, and vice versa.

The results are reports in Figure A1.

Figure A1. PBs TLs across different sharing principles.



Source: Own elaboration.

EI: Energy imbalance; aCO_2: Atmospheric CO_2 concentration; SOD: Stratospheric ozone depletion; OA: Ocean acidification; N: Nitrogen cycle; P-REG: Phosphorus cycle – Regional; P-GLO: Phosphorus cycle – Global; FI: Functional integrity; FWB: Freshwater use – Blue water; FWG: Freshwater use – Green water; AAL: Atmospheric aerosol loading; LSC: Land system change.

STEP 9: Interpret results in light of uncertainties and choices

The AESA results suggest that UK consumption (as final demand) in 2020 was environmentally unsustainable. Five boundaries – namely, Energy imbalance, Atmospheric CO_2 concentration, Ocean Acidification, Nitrogen and Phosphorus (regional) flows – are exceeded regardless of the sharing principle used, although with varying transgression levels. For each allocation principle, the Nitrogen boundary shows the largest transgression level – although this is likely overestimated due to modelling issues in PB-LCIA (Algunaibet et al., 2019). Climate-related boundaries show the second highest transgression, suggesting that reductions between 12and 260 times are needed for UK carbon emissions being environmentally sustainable. The sensitivity analysis to the allocation principle suggest that the AESA outcomes are robust in that even under the most favourable allocation principle (i.e. Grandfathering) the UK consumption remains unsustainable.

Transgression of the remaining boundaries is allocation principle-dependent. Under the Capability to reduce principle all remaining boundaries are transgressed, whilst only the boundaries for phosphorus (regional) and land-system change are exceeded under Historical responsibility. No additional boundary is transgressed according to Equal per capita and Grandfathering principles.

The use of PBs-specific allocation factors appears to be relevant for both GH and Re principles; for cases, there is approximately a factor 2 difference between the smallest and largest one. For both principles, climate-related are allocated the smallest (under Re) and largest (under GF) share of the SOS. The variation between allocation factors across PBs affect the AESA results meaningfully. For example, under the Re principle the LSC boundary would have been transgressed had the allocation factor been based e.g. on the Energy imbalance (EI). Nevertheless, it must be noted that the Historical responsibility principle does not has the same relevance for all PBs, in that some Earth-system processes are less or not dependent on historical cumulative emissions (Yang and Paulillo, 2025).

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