Scottish Waste Environmental Footprint Tool (SWEFT):

A review of widely used LCA indicators

EUROPE & SCOTLAND
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Zero Waste Scotland exists to lead Scotland to use products and resources responsibly, focusing on where we can have the greatest impact on climate change.

Using evidence and insight, our goal is to inform policy, and motivate individuals and businesses to embrace the environmental, economic, and social benefits of a circular economy.

We are a not-for-profit environmental organisation, funded by the Scottish Government and European Regional Development Fund.

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1 Executive Summary

The Scottish Carbon Metric (SCM), developed by Zero Waste Scotland, is a revolutionary tool that quantifies the carbon footprint of Scotland's waste, from resource extraction and manufacturing emissions, right through to waste management emissions. However, carbon footprinting is not the only measure of environmental sustainability and with it being the focus of many sustainability policies other areas of concern are not being communicated. Therefore, as leaps are being made in carbon emissions reduction, expanding the SCM to include key non-carbon environmental indicators becomes increasingly more important. Therefore, Zero Waste Scotland has embarked on a journey to develop the Scottish Waste Environmental Footprint Tool (SWEFT), a state-of-the-art tool that will enable policymakers to take into consideration the wider environmental impacts of waste when developing future waste strategies and measures.

This report highlights existing environmental impact categories that address these other environmental problems and offers recommendations on those deemed most suitable to be integrated into the upgraded SWEFT tool. The aim of this report is to determine other environmental indicators that can be used to give a more comprehensive evaluation and can support better decision-making across the broader spectrum of environmental sustainability. Suitability is based on relevance to current policies and targets for Scotland, accessibility and ease of communication to stakeholders and the general public, and significance in terms of environmental impact. An additional consideration is the quality/availability of data used to assess these impact categories. This report is structured around the impact categories reported in the International Reference Life Cycle Data System (ILCD) Handbook, recommended by the European Commission – Joint Research Centre (EU-JRC), and supported by evidence from academic studies. The ILCD handbook has been chosen as it provides a common basis for consistent, robust and quality-assured life cycle data and studies; delivered by EU-JRC, it is the most comprehensive research project in this area. However, methods to assess the quality of the data used to model waste categories will be evaluated alongside this work when incorporating non-carbon environmental impact categories into the SCM.

This review presents 16 environmental indictors, all of which will be modelled by the SWEFT tool and presented in future technical reports. However, for summary reports, analysis of five indicators will be focused on to enable clearer communication to the public and policymakers. These indicators, considered the most relevant and important to stakeholders, are climate change, resource (abiotic and water) depletion, land use and particulate matter. It is important to note that this tool is not designed to assess the sensitivity of every indicator presented here nor to quantify their impacts, but to provide policymakers with a wider understanding of the issue and total environmental cost of waste and materials.

2 Existing environmental indicators

Life cycle assessment (LCA), and life cycle thinking (LCT), are rapidly growing paradigms in the context of Sustainable Consumption and Production. Within an LCA, the emissions and resources associated with a specific product are documented in a life cycle inventory (LCI). Using this, a life cycle impact assessment (LCIA) can be undertaken to analyse the impact of emissions into water, air and soil as well as the consumption of natural resources. The contribution of these impacts on the three main areas of protection (human health, the natural environment and availability of resources) can also be assessed. The emissions and resources documented in the LCI are assigned to certain impact categories for the LCIA. These impact categories include climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. These are then converted into indicators, using factors calculated by impact assessment methods which represent the contribution to an impact per unit emission or resource consumed.

The most common framework to follow when conducting an LCA is the ISO 14040 [1] and this is supported by various guidance documents. One such document is the International Reference Life Cycle Data System (ILCD) Handbook which is a series of detailed technical documents to help LCA practitioners in business and government maintain consistent and high-quality results. ILCD recommend methods for each impact category based on the quality of characterisation models and related factors. Every product or system has an associated impact pathway and category indicators are measurable points along this pathway. One set of measurable points are impact categories at midpoint level, which are links in the cause-effect chain before an endpoint is reached, i.e. the impact on areas of protection.

When aiming to comply with the ILCD Handbook, if a study uses midpoint indicators for the assessment, the models and factors that have a level I, level II or level III recommendation must be used. These levels relate to the quality of recommended characterisation models and associated characterisation factors and are classified accordingly. **Level I** is classed as 'recommended and satisfactory', **level II** is 'recommended but in need of some improvements', and **level III** is 'recommended but to be applied with caution'. Level I is the highest quality and therefore preferred.

Of the 16 recommended midpoint methods, only three are classified as level I: climate change, ozone depletion and particulate matter/respiratory inorganics. Six are classed at level II: ionising radiation (human health), photochemical ozone formation, acidification, eutrophication (terrestrial), eutrophication (aquatic), and resource depletion (mineral, fossil fuel and renewable). The remainder are either level **II/III**, level **III** or 'interim'. When a classification states two levels, e.g. I/II, the first level refers to the level of recommendation of the method while the second level relates to recommendations for certain characterisation factors calculated within that method. 'Interim' describes a method that is considered the most promising among others for the same impact category but is still too immature to be recommended.

The following section provides a brief, non-technical overview of each of the impact categories included in the ILCD handbook. This is to allow the layman to understand and evaluate the potential categories under consideration. Please note that the ILCD supports both midpoint and endpoint impact categories but only midpoint is discussed in detail. A brief description of endpoint categories and why they are not considered is given at the end of this section.

2.1 Midpoint Impact categories

The 16 midpoint impact categories reported in the ILCD documentation are described below. These descriptions provide the meaning of each impact category, why they are considered impacts and the areas of protection that are affected. Based on the ILCD documentation, how each impact is measured and reported in terms of a category indicator is presented as well as the recommended LCIA method and its level of classification. Finally, climate change is a useful, common metric that is used to reflect the greatest areas of concern linked to current society, in relation to consumption and production.

Therefore, each impact category discussed in this section is reviewed based on its correlation with global warming potential, the de-facto LCIA method for modelling climate change.

At the end of this section, Table 1 outlines the impact categories and the ILCD recommended LCIA method, associated indicator, and classification level at midpoint.

2.1.1 Climate change

Commonly named 'global warming', this category refers to the impact of greenhouse gas (GHG) emissions and includes impacts such as rising temperatures, changes in precipitation, sea level rise, change of ocean currents, and storms. GHG emissions have the same effect regardless of where they occur and thus the impact category is considered to be global [2]. Climate equilibrium can be considered a life support function: the capacity of the environment to provide conditions for a long-term stable climate on earth [3]. Therefore, it is an important indicator of environmental sustainability and particularly relevant to Scottish policies and targets; limit global warming to well below 2°C [4] and be net zero emissions by 2045 [5].

Climate change is modelled in terms of radiative forcing, expressed as W/m^2, and is reported as kg carbon dioxide (CO_2) equivalent. This impact category is related to all three areas of protection: human health, the natural environment and availability of resources [6]. The LCIA method recommended by the ILCD [7] is global warming potential (GWP100) developed by the IPCC (2007, updated 2014) and is classified as level I, recommended and satisfactory.

Climate change and GWP are the most commonly used metric to evaluate environmental sustainability and is the current focus of the existing Scottish Carbon Metric. Therefore, the focus will be on the remaining impact categories.

2.1.2 Resource depletion

This impact category is split into the impact of depletion on water and minerals/fossil fuels/renewables. The term 'resource depletion' can refer to many different impacts arising from the use of resources. Therefore, it is difficult to define as an impact category and varies depending on the LCIA method that is used. The ILCD recommend that only methods incorporating the concept of resource scarcity are used as they are compatible with the 'availability of resources' area of protection. Therefore, the scarcity of resources and the limitations in their availability for current and future generations are key concerns for this impact category [9]. It considers the depletion of abiotic (non-renewable) resources, such as minerals and fossil fuels, and water as well as biotic (renewable) resources, such as wood and animals, to an extent.

2.1.2.1 Abiotic resources

Abiotic resources include fossil fuels, ranging from volatile materials like methane, to liquid petrol, to non-volatile materials like coal. Also included are minerals which are naturally occurring substances formed through geological processes, with characteristic chemical, structural and physical properties. Abiotic resource depletion is mainly an anthropogenic issue because these resources, and our reliance on them, are a consequence of society and culture. However, human health not directly affected but the natural environment and availability of resources are the areas of protection that are. The characterisation factor for this impact category is 'abiotic depletion potential' (ADP) and is expressed in kg of antimony equivalent (kg Sb-eq), the reference element [7]. The recommended LCIA method is CML 2002 [10] which has a classification level II, recommended but in need of some improvements.

2.1.2.2 Water scarcity

Water scarcity is an important impact category as it has a direct effect on human health; access to fresh drinking water is a life support function. Therefore, it impacts all three areas of protection – human health, the natural environment (water scarcity limits the environmental processes of regions and ecosystems) and availability of resources (to sustain agricultural, urban, industrial and recreational activities in a region). To measure resource depletion in terms of water scarcity it is important to consider which types of water result in water shortages. The LCIA database, ecoinvent, has four default sources – 'water, lake', 'water, river', 'water, well, in ground', and 'water, unspecified natural origin'. The characterisation factor for this impact category is 'water depletion potential' (WDP) and is expressed as water use related to local scarcity of water (m^3/m^3) [7]. The recommended LCIA method is the Swiss Ecoscarcity (water) model [11] which has the relatively low classification level III, recommended but to be applied with caution. The ILCD also endorse the recently developed AWARE (Available Water Remaining) method which is a regionalised LCIA method (more specifically, regionalised water scarcity footprint) that quantifies the relative available water remaining per (specified) area after satisfying the demand of aquatic ecosystems and human activities [12]. This new midpoint impact method is adopted in the SWEFT tool as it provides a more targeted assessment of water footprint that is based on consensus from LCA and hydrology experts and is recommended by Water Use in Life Cycle Assessment (WULCA), a working group of the UNEP-SETAC Life Cycle Initiative.

Regarding the relationship between the climate change and resource depletion midpoint categories, their impacts have one area of protection in common; the natural environment. Resource depletion has no direct impact on human health, unlike climate change, but a strong impact on the availability of resources. Therefore, this category can offer insight into a different area of damage that climate change cannot cover. There is contention in the literature as to the level of correlation between these impact categories and whether resource depletion can be represented by a carbon proxy [13], [14]. It is highly dependent on the product/system being modelled and the definition of the goal and scope.

2.1.3 Land use

Land use describes an area in terms of its socio-economic purposes, i.e. how the area is used, and it can be divided into two separate categories, land occupation and land transformation. Land occupation is the continuous use of an area of land for anthropogenic purposes such as agriculture, forestry, urban activities, etc. Land transformation refers to the changing use of an area of land, for example deforestation to make way for agriculture. Land use impacts include degradation of processes in the natural environment, soil fertility, potability of water, and biodiversity degradation [15]. This impact category significantly effects the natural environment area of protection and in addition, degradation of life support functions is linked to human health and the availability of resources.

The characterisation factor for land use is Soil Organic Matter (SOM) as a soil quality indicator and is expressed as changes in soil organic carbon (SOC) and SOM (kg C a/m^2a). The recommended LCIA method is based on the model developed by Mila i Canals, Romanya and Cowell [16], which has the relatively low classification level III, recommended but to be applied with caution.

As with resource depletion, land use has only one area of protection in common with climate change (the natural environment) and land use has no direct impact on human health but a strong impact on the availability of resources. Therefore, this category can also offer insight into a different area of damage that climate change cannot cover. So, climate change and land use have a low level of correlation and land use is poorly represented by a carbon proxy.

2.1.4 Particulate matter/respiratory inorganics

Particulate matter (PM) are complex mixtures of organic and inorganic substances, such as dust, pollen, soot and smoke. PM has both man-made and natural sources and can be classified into coarse, with particles ranging from 2.5 to 10 µm in diameter (PM_{10}), and fine, particles with a diameter less than 2.5 µm ($PM_{2.5}$). Particles less than 0.1 µm are classed as ultrafine but they make up only a small percentage of the total mass. Ambient concentrations of PM are exacerbated by emissions of primary and secondary particles, where primary particles are those directly released (through combustion process for example) and secondary particles are those formed by intermediate reactions of gases in the atmosphere (such as sulphate and nitrate). No matter where these emissions occur, they have the same effect and can thus be classed as global. Inhalation of different sizes of PM cause different health problems and chronic exposure to $PM_{2.5}$ can be attributed to reduced life expectancy [17]. When inhaled, PM_{10} reaches the upper part of the airways and lungs causing health problems. Therefore, the major area of protection affected by PM/respiratory inorganics is human health.

The characterisation factor for this impact category is the intake fraction for fine particles and is expressed in kg $PM_{2.5}$-eq. The recommended LCIA method is the RiskPoll model [18], which has the high classification of level I, recommended and satisfactory.

There is certain overlap between the substances modelled along the impact pathways of PM/respiratory organics and climate change. Additionally, they both have impacts on a global level and damage the human health area of protection. Therefore, there is potential for GWP to be an indicator for this impact category. However, the level of correlation is unclear and would depend on the product/system being modelled and the definition of the goal and scope.

2.1.5 Ozone depletion

Ozone depletion refers to the thinning of the ozone layer in the stratosphere and is caused by a reaction between ozone molecules (O_3) and chemical compounds such as gaseous chlorine and bromine, generated from human activity. This reduction in ozone concentration is unevenly distributed across the world, occurring more severely in polar regions and mid-latitudes. Ozone depletion has a long time-lag (about 20 to 100 years) so even if harmful compounds, such as chlorofluorocarbons (CFC's), have been heavily regulated, these persistent organic pollutants (POPs) are still causing damage. This breakdown of ozone results in increased UV-B (ultraviolet B-rays) intensity, causing various radiation impacts. Increased, long-term exposure has a strong detrimental impact on human health (e.g. skin cancer, cataracts) and the natural environment (e.g. decreased production of plankton affecting the food chain), as well as the availability of resources (crops such as rice are highly sensitive to UV-B).

Several dozen atmospheric compounds exist that are known to contribute to ozone depletion [3], known as ozone depleting substances (ODS). As with climate change, the effect of these substances is the same regardless of where they were emitted and are therefore classed as global. The impact pathway of these compounds is similar and thus they can be grouped into a single midpoint impact category. The corresponding midpoint indictor is Ozone Depletion Potential (ODP) and it is defined as a relative measure of the ozone depletion capacity of an ODS, expressed as 1 kg of an ODS relative to the ODP of 1 kg of CFC-11. CFC-11 is trichlorofluoromethane and is used as the reference [19]. The recommended assessment method is Steady State ODPs, published by World Meteorological Organisation in 1999 [20]. The ILCD classification level for this impact category is level I – recommended and satisfactory for all types of lifecycle-based decision support. Therefore, at midpoint ozone depletion as an indicator provides sufficient scientific robustness and certainty and is widely accepted by stakeholders [21].

The level of correlation between GWP and ODP is unclear, however both indicators directly impact the human health and natural environment areas of protection and both have global impacts.

2.1.6 Human toxicity

Human toxicity reflects the potential harm a unit of chemical causes when released into the environment [22]. This impact category is split into cancer effects and non-cancer effects, but they are discussed together here. Human toxicity considers chemical fate, human exposure and toxicological effect meaning the transportation of chemicals in the environment, the exposure to the chemical leading to a given intake, and the potential risks linked to the toxic intakes. It includes all impacts on human health caused by the direct emission of toxic substances, both indoor and outdoor, and impacts caused by fine particles and radiation [6]. The area of protection impacted by human toxicity is human health.

The characterisation factor for human toxicity is Comparative Toxic Unit for humans and is expressed as CTU_h. The ILCD recommended LCIA method is the USEtox model [23], which has the classification level II/III. The first level means the method is recommended but in need of some improvements and the second level means that certain characterisation factors calculated within that method are recommended but to be applied with caution.

Climate change is a poor indicator of human toxicity and GWP is unable to represent this impact category [13], [24]. They both damage the human health area of protection, but they model different areas of damage in their impact pathways. Human toxicity impacts occur on a regional or local level and cannot be reflected in the global impacts of the climate change category.

2.1.7 Ecotoxicity

Ecotoxicity is treated similarly to human toxicity in that it is based on the chemical fate, exposure and toxicological effect. It describes the potential for biological, chemical and physical stressors to affect ecosystems, i.e. all substances that are toxic to the environment. This impact category is split into freshwater and terrestrial/marine impacts, but they are discussed together here. Reporting ecotoxicity is complex due to the nearly unlimited number of species involved; the impact on a single species is incredibly difficult to model but toxicological effects are based on species level. Ecotoxicity is divided into acute and long-term effects and, depending on the environment, the impacts can be regional as well as local [2]. It includes all impacts on natural species and ecosystems caused by direct emission of toxic substances, including associated degradation products [6]. The main areas of protection associated with this category are the natural environment and availability of resources.

The characterisation factor for ecotoxicity of freshwater is Comparative Toxic Unit for ecosystems and is expressed as CTU_e. The ILCD recommended LCIA method is the USEtox model [23], which has the classification level II/III. The first level means the method is recommended but in need of some improvements and the second level means that certain characterisation factors calculated within that method are recommended but to be applied with caution. As yet there are no recommended midpoint methods for marine and terrestrial ecotoxicity.

As with human toxicity, climate change and the carbon footprint is a poor indicator for ecotoxicity [13], [14], [24]. The ecotoxicity impact category is related to process- or product-specific emissions/inputs that are not related to GHG emission processes in a product's life cycle [13]. Also, ecotoxicity impacts occur on a regional or local level, only potentially damaging to the natural environment area of protection, whereas climate change is global and affects both human health and the natural environment [2].

2.1.8 Ionising radiation

Ionising radiation is radiation, such as X-rays and gamma rays, that has sufficient energy to detach electrons from atoms or molecules, i.e. ionising them. This impact category is split into human health and ecosystem impacts but they are discussed together here. It is caused by the release of radioactive material to the environment and can come from naturally occurring radioactive materials (found in soil, water or the air) as well as man-made sources (such as nuclear power generation or medical radiation). This impact category follows the same framework as human and eco-toxicity with models which consider radiative fate and exposure, and the potential risk. The areas of protection that are impacted are human health (causing damage to living tissues and cancer) and the natural environment (plants, fish and mammals after chronic exposure).

The characterisation factor for ionising radiation in terms of human health is human exposure efficiency relative to uranium-235 and is expressed in kg uranium-235 equivalent (kgU^{235}-eq). The ILCD recommended LCIA method is the human health effect model [25] which has the classification level II, recommended but in need of some improvements. As yet there are no recommended midpoint methods for ionising radiation impacts on ecosystems. However, as an interim approach, i.e. promising but still too immature to be recommended, the method developed by Garnier-Laplace *et al.* [26] could be used [7].

Ionising radiation damages the same areas of protection as climate change but the level of correlation, and the extent to which GWP can represent this impact category, is unclear.

2.1.9 Photochemical ozone formation

Photochemical ozone formation, often called photochemical smog, is caused by the release of both natural and man-made substances into the atmosphere. This category includes all the impacts related to tropospheric (ground-level) ozone formation, caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxide emissions (NOx) and sunlight. It can be categorised into short-term, local impacts (contributing to photo smog, affecting human respiratory health) and medium-term, regional impacts ('tropospheric ozone' which damages crops, natural vegetation and man-made materials). Photochemical ozone formation is highly non-linear and dynamic due to the hundreds of chemical species involved and their global distribution [21]. This impact category affects all three areas of protection (human health, the natural environment and availability of resources) and is related to human toxicity, ecotoxicity, and particulate matter but models different substances and impact pathways [27]. Therefore, it again considers atmospheric fate and transport, exposure, and potency or effect.

The characterisation factor for photochemical ozone formation is tropospheric ozone concentration increase and is expressed in kg ethylene equivalent (kg C_2H_4-eq). The ILCD recommended LCIA method is the LOTUS-EUROS model [27], which is classified as level II, recommended but in need of some improvements.

Various studies have determined a strong correlation between the photochemical ozone formation and climate change impact categories [13], [14], [28]. Due to the overlap of compounds considered along their impact pathways, GWP can be used as an indicator of photochemical ozone formation. Additionally, the areas of protection that are impacted are the same for both impact categories.

2.1.10 Acidification

Acidification is caused by the release of photons into terrestrial or aquatic ecosystems. It refers to the diverse range of impacts that acidifying substances have on soil, plants, animals, and materials. For example, in terrestrial ecosystems acidification causes inefficient growth, and eventually death, of softwood forests. In aquatic systems it results in acid lakes which kills any wildlife. Additionally, acid rain damages buildings and monuments. This impact category is considered to be regional, contributing emissions have limited spatial impact, and effects are mostly seen in Scandinavia and middle/eastern Europe [2]. As with ecotoxicity (see below), this is a complex impact to model due to the varying substances and interactions involved and it impacts all three areas of protection.

Substances contributing to acidification include sulphur oxides, NOx, inorganic acids, and ammonia. The characterisation factor is Accumulated Exceedance (AE) and is expressed in mole H+-eq. The ILCD recommended LCIA method is Accumulated Exceedance [29], [30], which is classified as level II, recommended but in need of some improvements.

Acidification is related to climate change and the carbon footprint can act as an indicator, for example due to the GWP of nitrous oxide; more efficient use of nitrogen leads to fewer acidifying substances being released to the environment and lower GHG emissions [24]. Additionally, climate change and acidification both damage the natural environment area of protection so there is some overlap between these impact categories. However, unlike GWP, acidification has local and regional effects as opposed to global.

2.1.11 Eutrophication

This impact category is split into terrestrial and aquatic impacts, but they are discussed together here. Eutrophication includes all impacts that occur due to increased concentrations of macro-nutrients in ecosystems, both terrestrial and aquatic. Aquatic eutrophication refers to an over enrichment of minerals and nutrients in a body of water which causes excess algae and plankton growth, resulting in deterioration of the water body. It becomes oxygen-deprived and starved of light, killing animal and plant life. Terrestrial eutrophication refers to an over enrichment of nutrients in terrestrial ecosystems, causing changes in the function and diversity of species in nutrient poor ecosystems (e.g. raised bogs, dune heaths). In both cases, eutrophication is caused by the deposition of surplus nitrogen compounds (such as NOx from combustion processes and ammonia from agriculture) and phosphorus either from airborne emissions or water run-off. For this impact category, natural vegetation is the only direct endpoint, so it is not as complex to model as acidification, for example, and its impacts are based on whether phosphorus or nitrogen is the limiting nutrient. It includes all direct and indirect impacts of macro-nutrients on vegetation (natural and crops), in both terrestrial and aquatic ecosystems. The main areas of protection that are affected in this instance are the natural environment and availability of resources (for example, fishing or wood/crop productivity).

The characterisation factor for terrestrial eutrophication is Accumulated Exceedance (AE) and is expressed in mole N^+ equivalent. The ILCD recommended LCIA method is Accumulated Exceedance [29], [30], which is classified as level II, recommended but in need of some improvements. The characterisation factor for aquatic eutrophication is the fraction of nutrients reaching freshwater (kgP-eq) or marine end compartment (kgN-eq). The ILCD recommended LCIA method is the EUTREND model [31], which is classified as level II, recommended but in need of some improvements.

As with acidification, climate change can also be an indicator of eutrophication potential due to GHG emissions in nitrous oxide form [24]. Also, both impact categories cause damage to the natural environment area of protection. Again, however, eutrophication is not a global phenomenon, but impacts are on regional and local scales.

Table 1: Impact categories at midpoint and the recommended LCIA method, indicator and classification level (taken from [7]), as used in the SWEFT tool

Impact category	LCIA method	Indicator	Classification level
Climate change	Baseline model of 100 years [8]	Radiative forcing as Global Warming Potential (GWP100, kgCO_2-eq)	I
Ozone depletion	Steady-state ODPs 1999 [20]	Ozone Depletion Potential (ODP, kgCFC-11-eq)	I
Human toxicity (cancer effects)	USEtox model [23]	Comparative Toxic Unit for humans (CTU_h)	II/III
Human toxicity (non-cancer effects)	USEtox model [23]	Comparative Toxic Unit for humans (CTU_h)	II/III
Particulate matter/ respiratory inorganics	RiskPoll model [18]	Intake fraction for fine particles (kg $PM_{2.5}$-eq)	I
Ionising radiation (human health)	Human health effect model [25]	Human exposure efficiency relative to U^{235} (kgU^{235}-eq)	II
Ionising radiation (ecosystems)	No methods recommended		Interim
Photochemical ozone formation	LOTOS-EUROS [27]	Tropospheric ozone concentration increase (kgC_2H_4-eq)	II
Acidification	Accumulated Exceedance [29], [30]	Accumulated Exceedance (AE, mole H^+-eq)	II
Eutrophication (terrestrial)	Accumulated Exceedance [29], [30]	Accumulated Exceedance (AE, mole N^+-eq)	II
Eutrophication (aquatic)	EUTREND model [31]	Fraction of nutrients reaching freshwater (kgP-eq) or marine end compartment (kgN-eq)	II
Ecotoxicity (freshwater)	USEtox model [23]	Comparative Toxic Unit for ecosystems (CTU_e)	II/III
Ecotoxicity (terrestrial and marine)	No methods recommended		
Land use	Model based on Soil Organic Matter (SOM) [16]	Soil Organic Matter (kg, deficit)	III
Resource depletion (water) [1]	AWARE [12]	Available water remaining per area (m^3)	
Resource depletion (mineral, fossil and renewable)	CML 2002 [10]	Scarcity (kg antimony [Sb] -eq)	II

[1] In the original ILCD impact assessment method, the model for water consumption (as in Swiss Ecoscarcity) [11] is used to determine water resource depletion. However, the AWARE method, also endorsed by ILCD, has been chosen to replace this as it is more specialised to water footprinting (available at www.wulca-waterlca.org).

2.2 Endpoint impact categories

Endpoint impact categories are those at the end of the impact pathway and are directly related to the areas of protection. Figure 1 gives a visual representation of the midpoint and endpoint impact categories and their relation to the three areas of protection.

Of the 15 recommended endpoint methods, none are classified as level I. This is due to the fact that the farther the impact pathway is covered (i.e. from emissions or consumption of a substance to the eventual damages on the areas of protection), the higher the modelling uncertainties [13]. Particulate matter/respiratory inorganics has a classification level of I/II, photochemical ozone formation is level II and human toxicity (cancer effects) is level II/interim. The remainder are interim or unclassified as sufficiently mature models are often unavailable for most endpoint categories. Therefore, endpoint categories have not been discussed in this report due to the uncertainty associated with modelling and that lack of recommendation by ILCD.

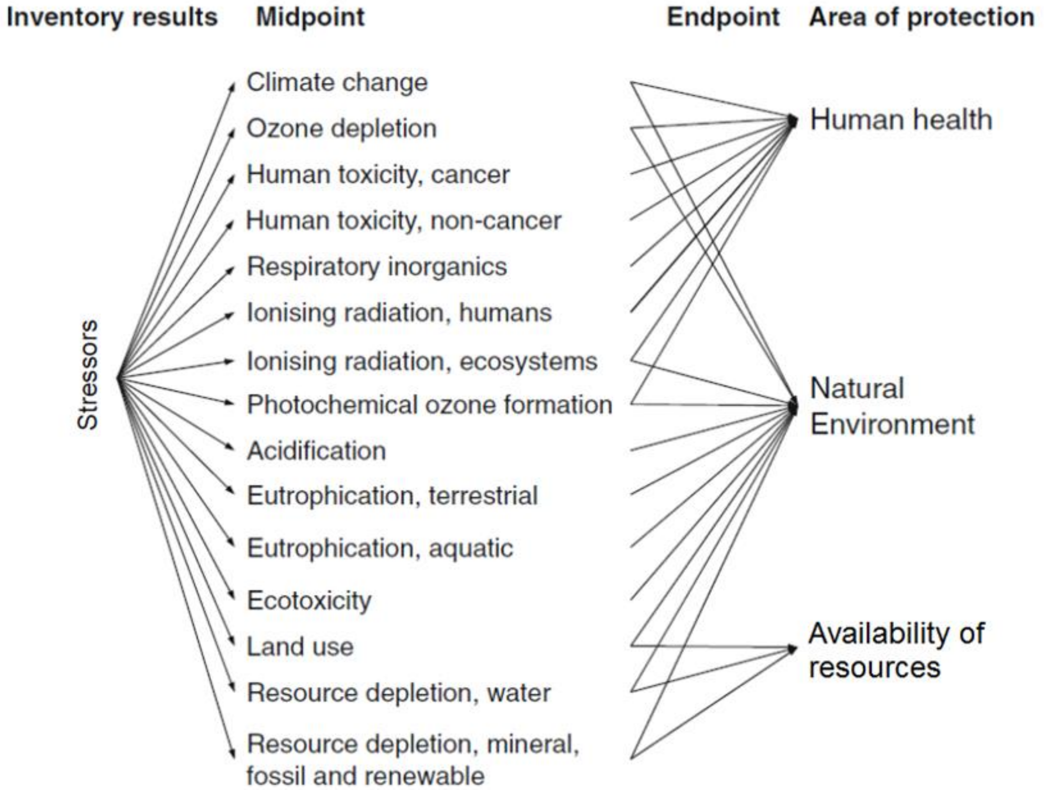

Figure 1: Framework of LCIA linking stressors from the LCI to impact categories at midpoint and endpoint level and finally to the three areas of protection. Here, ecotoxicity is merged into a single category. Adapted from [21]

3 Normalisation

A useful tool to compare the relative importance and contribution to sustainability of each of these midpoint impact categories is normalisation. The assignment of inventory results to impact categories, characterisation, and classification are all mandatory steps in an LCIA, whereas normalisation is an optional element [2]. Normalisation offers the ability to interpret indicator results alongside each other; it sets a common reference, enabling comparison of different environmental impacts. The most common method for normalisation is to determine the impact category indicators for a region, over a year, and divide the result but the number of inhabitants in that area [32]. This gives a result of ‘impact potential per person per year' for each impact category, expressed in person equivalents (PE) [2]. Appendix A provides a table of the normalisation factors for the 16 midpoint impact categories, as presented for the 'Development and application of a standardized methodology for the Prospective Sustainability Assessment of Technologies' (Prosuite) project [33].

To obtain accurate results from normalisation impact categories should only be compared if they represent the same geographic area (i.e. global, regional or local) and the normalisation factors used are representative of the area where the emissions occur. Regional and local data are generally not available in many of the LCIA databases and using global impacts as the normalisation reference will result in an imbalance; global impacts will appear much less as they are compared against the global population. Therefore, normalisation should be applied and interpreted with caution.

4 Relevance to policies and targets

This section summarises the connection of the presented impact categories with the Sustainable Development Goals (SDGs) stipulated by the UN [34], and based on the work done by Maier *et al.* [35] and Wulf *et al.* [36]. SDGs are the result of the 2030 Agenda for Sustainable Development, which has been adopted by all United Nations Member States since 2015, and they are the current dominant political framework [36]. Therefore, how each impact category is related to current environmental targets and SDGs is discussed. Table 2 shows the spatial variability of the reviewed impact categories, illustrating the geographic scale of their effects. However, in a global economy, even local impacts will have global coverage, for example waste originates from numerous places and is often exported far across the globe, where the environmental burden is taken on by those receiving the waste. SDGs are designed for countries or regions and focus on changing conditions on a country-level. Therefore, they are applicable to most of the impact categories. There are 17 SDGs in total but not all are relevant to this report, only those relating to environmental sustainability are considered. The following are those that are relevant, along with their relation to Scottish-specific targets:

- **No. 3**: Ensure healthy lives and promote well-being for all at all ages
    - ***Scotland-specific*** – includes goals to reduce maternal and infant mortality, mortality from non-communicable diseases, substance and alcohol abuse and smoking, sexual and reproductive health and rights, and road traffic accidents. Policies tackling these goals include the *Heart Disease Improvement Plan 2014*, the *Diabetes Improvement Plan Nov 2014*, *Suicide Prevention Action Plan 2018*, and the *2017 Mental Health Strategy*.
- **No. 6**: Ensure availability and sustainable management of water and sanitation for all
    - ***Scotland-specific*** – includes targets on availability of clean water, access to sanitation, and the efficient and sustainable management of water resources. Water governance is extensively covered by relevant law and policy, including The Water Services etc. (Scotland) Act 2005, the Water Resources (Scotland) Act 2013 and plans including Scotland's River Basin Management Plans.
- **No. 12**: Ensure sustainable consumption and production patterns
    - ***Scotland-specific*** – includes sustainable consumption and production planning, environmental footprint, reducing waste and pollution, sustainability education, sustainable tourism, and ending fossil fuel subsidies. Scotland have implemented the *Circular Economy Strategy 2016* to bring together all sectors and individuals to work towards a more circular economy, Additionally Scotland has a food waste reduction target of 33% by 2025.
- **No. 13**: Take urgent action to combat climate change and its impacts
    - ***Scotland-specific* –** this goal supports the Paris Agreement through resilience and adaptation, climate change policy and planning, and education and raising awareness. The Scottish Government implemented the *Climate Change (Scotland) Act 2009* with legislation such as the

Climate Change Plan. The Scottish Government has set a target to generate 50% of all Scotland's energy needs from renewable sources by 2030.

- **No. 14**: Conserve and sustainably use the oceans, seas and marine resources for sustainable development
  - ***Scotland-specific*** – focuses on minimising marine pollution and protection and conservation of marine ecosystems, including sustainable fisheries and the livelihoods of small-scale fishers. 20% of Scotland's sea areas are protected and it has exceeded the SDG target of 10% for conservation areas. There are a range of laws, plans and policies in place – including the Marine (Scotland) Act 2010 and Scotland's *National Marine Plan*.
- **No. 15**: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
  - ***Scotland-specific*** – includes sustainable management of ecosystems (e.g. inland freshwater ecosystems, forests, mountains), conservation and protection of biodiversity, and integration of biodiversity into national planning. Scotland has the largest proportion of sustainably managed forest in the UK; 57.7% against a UK average of 43.4%. The Scottish Government has laws concerning the management and protection of terrestrial ecosystems, e.g. the *Protection of Wild Mammals (Scotland) Act 2002*, the *Nature Conservation (Scotland) Act 2004*, and the *Forestry and Land Management (Scotland) Act 2018*. In terms of biodiversity integration into planning, the *Conservation of Habitats and Species Regulations 2017* targets this and the *Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017* outline Environmental Impact Assessments for planning.

Table 2: Geographic scale of the reviewed impact categories (taken from [2])

Impact category	Geographic scale		
	Global	Regional	Local
Climate change	X		
Ozone depletion	X		
Human toxicity		X	X
Particulate matter/ respiratory inorganics	X	X	
Photochemical ozone formation		X	X
Acidification		X	X
Eutrophication		X	X
Ecotoxicity		X	X
Land use			X
Resource depletion	X	X	X

Figure 2 illustrates the correlation between the relevant SDGs presented above and the impact categories of interest in this report [36]. Only the land use impact category has no direct relation. However, there is a strong link to **SDG 11** – 'Make cities and human settlements inclusive, safe, resilient and sustainable'; particularly, SDG indicator (i.e. subcategories for each goal) 11.3.1 – 'Ratio of land consumption rate to population growth rate' [34]. Scotland-specific targets for SDG 11 are concerned with many aspects of the urban agenda; housing, public transport, green space, waste, planning, and cultural/natural heritage protection. The *Community Empowerment (Scotland) Act 2015* provides a framework for planning, and community participation in the planning process; it relates directly to the implementation of SDG 11.3.1.

These connections with a major political framework for global sustainability demonstrate the importance of expanding the carbon metric tool to incorporate other areas of damage. Scotland is currently working towards these SDGs, for example through the Scottish Environment Protection Agency's (SEPAs) 'One Planet Prosperity' regulatory strategy. SEPA is also working beyond the SDGs with the voluntary formal Sustainable Growth Agreements [37]. Alongside the SDGs, there are existing climate change commitments at both global and national level for the reduction of GHG emissions, directly targeting the climate change impact category (see Climate change). Additionally, the renewable energy targets, both heat and power, combatting resource depletion (fossil fuels). The Scottish Government's 2015 Heat Policy Statement states that Scotland aims to largely decarbonise its heat system by 2050 [38]. The increasing energy and power generation from renewables will have an associated effect on the areas of protection [13], particularly the natural environment through damage to ecosystems (such as wind turbines affecting migrating birds [39]) and availability of resources through competing land use. However, despite this being an important consideration, exploring these issues is beyond the scope of this report. Also, this report does not consider the social or economic implications of the impact categories. Had it been, there would be a greater and more varied correlation with the SDGs.

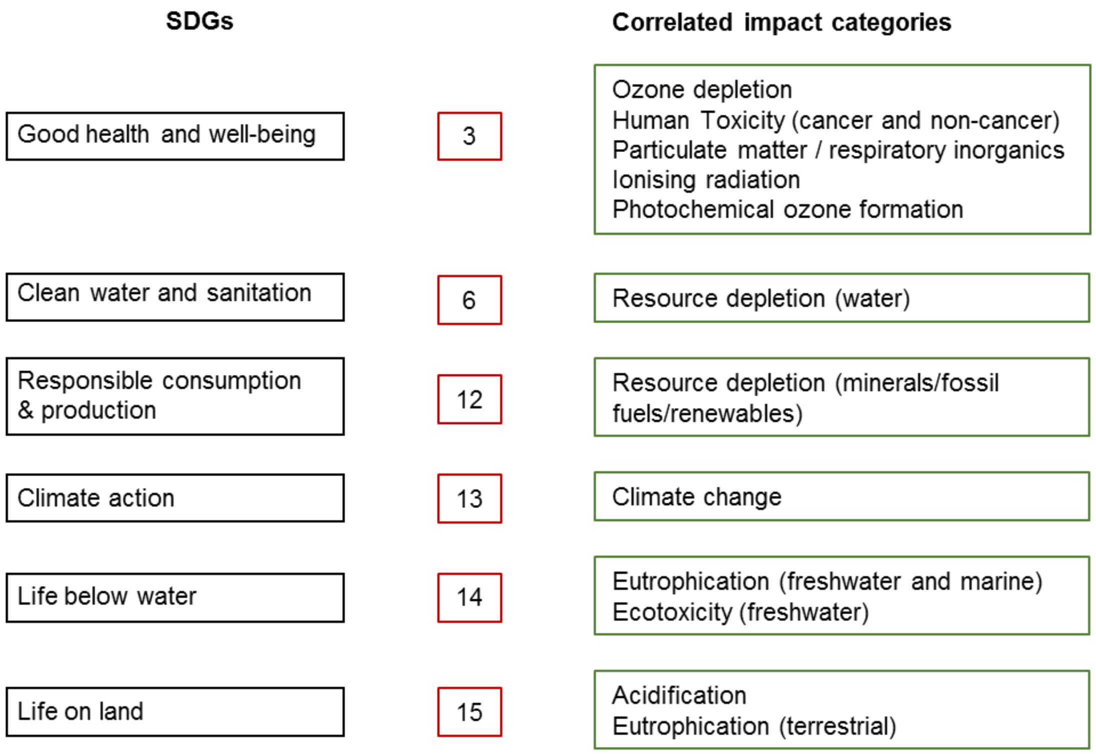

Figure 2: Relevant Sustainable Development Goals (summarised from those presented above) and the impact categories that correlate with each (taken from [36]**)**

5 Conclusion

The new SWEFT tool aims to review non-carbon impact categories as well as the carbon impact assessed by the original SCM. This report has described the midpoint impact categories and indicators included in the ILCD method and the LCIA methods that will be used in the SWEFT model. All 16 impact categories will be conveyed in technical reports, but they are complex and difficult to communicate to the public and policymakers. Therefore, in accompanying summary reports, key indicators will be provided to give a relevant overview of the total environmental cost of waste and materials. These should be chosen due to their relative ease of communication and the common importance to stakeholders.

Additionally, they should provide metrics that are not well represented by a carbon proxy, i.e. the climate change indicator. One way to determine the level of correlation between the climate change impact category and the other 15 midpoint categories is to look at the areas of protection that are affected by each. Figure 1 shows the LCIA relationship between the midpoint categories and areas of protection; land use and resource depletion (water and abiotic) are the only midpoint categories that directly impact the availability of resources, thus offering information on an entirely different damage area than climate change. In reality, climate change has a very real impact on the availability of resources (damage to crops, drought, famine, etc.) but LCIA methodologies focus on other areas of damage [7].

Therefore, as we live in a world with finite resources, the impact of resource depletion and land use are recommended for inclusion in the SWEFT tool. Finally, there is a growing interest globally in improving the quality of air, especially in mega cities, so it would be useful to also consider an indicator on air quality. Thus, the five indicators that will be represented in summary reports are climate change, resource (abiotic and water) depletion, land use and particulate matter.

6 References

[1] ISO14040, “Environmental management — Life cycle assessment — Principles and framework,” 2006.

[2] H. K. Stranddorf, L. Hoffmann, and A. Schmidt, “LCA technical report: Impact categories, normalisation and weighting in LCA. Update on selected EDIP97-data,” 2003.

[3] B. P. Weidema, *Life Cycle Impact Assessment definition study : Background document III. Analysis of midpoint categories.* Life Cycle Impact Assessment programme of The UNEP/SETAC Life Cycle Initiative., 2003.

[4] United Nations, “Paris Agreement,” *21st Conf. Parties*, p. 3, 2015, doi: FCCC/CP/2015/L.9.

[5] Scottish Government, “Reaching net zero,” *gov.scot*, 2019. [Online]. Available: https://www.gov.scot/news/reaching-net-zero/. [Accessed: 17-Sep-2019].

[6] SETAC-Europe, “Best Available Practice Regarding Impact Categories and Category Indicators in Life Cycle Impact Assessment,” *Int. J. Life Cycle Assess.*, vol. 4, no. 3, pp. 167–174, 1999.

[7] ILCD, “Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors,” 2011.

[8] IPCC, “Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,” Geneva, Switzerland, 2014.

[9] M. Z. Hauschild *et al.*, “Identifying best existing practice for characterization modeling in life cycle impact assessment,” *Int. J. Life Cycle Assess.*, vol. 18, pp. 683–697, 2013, doi: 10.1007/s11367-012-0489-5.

[10] J. B. Guinée *et al.*, *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards Series: Eco-efficiency in industry and science.* Dordrecht: Kluwer Academic Publishers, 2002.

[11] R. Frischknecht, R. Steiner, and N. Jungbluth, *The Ecological Scarcity Method - Eco-factors 2006: A method for impact assessment in LCA*. Umwelt-Wissen Nr.0906: Swiss Federal Office for the Environment (FOEN), Bern, 2009.

[12] A. M. Boulay *et al.*, “The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE),” *Int. J. Life Cycle Assess.*, vol. 23, no. 2, pp. 368–378, 2018, doi: 10.1007/s11367-017-1333-8.

[13] A. Laurent, S. I. Olsen, and M. Z. Hauschild, “Limitations of Carbon Footprint as Indicator of Environmental Sustainability,” *Environ. Sci. Technol.*, vol. 46, pp. 4100–4108, 2012, doi: 10.1021/es204163f.

[14] E. Gutierrez, S. Lozano, M. T. Moreira, and G. Feijoo, “Assessing relationships among life-cycle environmental impacts with dimension reduction techniques,” *J. Environ. Manage.*, vol. 91, pp. 1002–1011, 2010, doi: 10.1016/j.jenvman.2009.12.009.

[15] T. Mattila, T. Helin, R. Antikainen, S. Soimakallio, K. Pingoud, and H. Wessman, *Land use in life cycle assessment*. Helsinki: Finnish Environment Institute, 2011.

[16] L. Mila i Canals, J. Romanya, and S. J. Cowell, “Method for assessing impacts on life support functions (LSF) related to the use of ‘fertile land’ in Life Cycle Assessment (LCA),” *J. Clean. Prod.*, vol. 15, pp. 1426–1440, 2007, doi: 10.1016/j.jclepro.2006.05.005.

[17] World Health Organisation, “Health risks of particulate matter from long-range transboundary air pollution,” Copenhagen, WHO Regional Office for Europe, 2006.

[18] A. Rabl and J. V. Sparado, “The RiskPoll software, version 1.051,” 2004. .

[19] J. Struijs, H. J. van Wijnen, A. van Dijk, and M. A. J. Huijbregts, “Chapter 4: Ozone depletion,” in *ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors*, M. Goedkoop, R. Heijungs, M. A. J. Huijbregts, A. De Schryver, J. Struijs, and R. van Zelm, Eds.

2013.

[20] WMO, "Scientific Assessment of Ozone Depletion: 1998. Global Ozone Research and Monitoring Project - Report No. 44," ISBN 92-807-1722-7, Geneva, 1999.

[21] ILCD, "Framework and requirements for Life Cycle Impact Assessment models and indicators," 2010.

[22] E. G. Hertwich, S. F. Mateles, W. S. Pease, and T. E. McKone, "Human toxicity potentials for life-cycle assessment and toxics release inventory risk screening," *Environ. Toxicol. Chem.*, vol. 20, no. 4, pp. 928–939, 2001.

[23] R. K. Rosenbaum, T. M. Bachmann, O. Jolliet, R. Juraske, A. Koehler, and M. Z. Hauschild, "USEtox — the UNEP-SETAC toxicity model : recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment," *Int. J. Life Cycle Assess.*, vol. 13, pp. 532–546, 2008, doi: 10.1007/s11367-008-0038-4.

[24] E. Röös, C. Sundberg, P. Tidåker, I. Strid, and P. Hansson, "Can carbon footprint serve as an indicator of the environmental impact of meat production ?," *Ecol. Indic.*, vol. 24, pp. 573–581, 2013, doi: 10.1016/j.ecolind.2012.08.004.

[25] R. Frischknecht, A. Braunschweig, P. Hofstetter, and P. Suter, "Human health damages due to ionising radiation in life cycle impact assessment," *Environ. Impact Assess. Rev.*, vol. 20, pp. 159–189, 2000.

[26] J. Garnier-Laplace, K. Beaugelin-Seiller, R. Gilbin, C. Della-Vedova, O. Jolliet, and J. Payet, "A Screening Level Ecological Risk Assessment and ranking method for liquid radioactive and chemical mixtures released by nuclear facilities under normal operating conditions," *Radioprotection*, vol. 44, no. 5, pp. 903–908, 2009, doi: 10.1051/radiopro/20095161.

[27] R. van Zelm *et al.*, "European characterization factors for human health damage of PM 10 and ozone in life cycle impact assessment," *Atmos. Environ.*, vol. 42, pp. 441–453, 2008, doi: 10.1016/j.atmosenv.2007.09.072.

[28] S. Lasvaux, F. Achim, P. Garat, B. Peuportier, J. Chevalier, and G. Habert, "Correlations in Life Cycle Impact Assessment methods (LCIA) and indicators for construction materials: What matters?," *Ecol. Indic.*, vol. 67, pp. 174–182, 2016, doi: 10.1016/j.ecolind.2016.01.056.

[29] J. Seppälä, M. Posch, M. Johansson, and J. P. Hettelingh, "Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator," *Int. J. Life Cycle Assess.*, vol. 11, no. 6, pp. 403–416, 2006, doi: 10.1065/lca2005.06.215.

[30] M. Posch, J. Seppälä, J. Hettelingh, M. Johansson, M. Margni, and O. Jolliet, "The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA," *Int. J. Life Cycle Assess.*, vol. 13, pp. 477–486, 2008, doi: 10.1007/s11367-008-0025-9.

[31] J. Struijs, A. Beusen, H. van Jaarsveld, and M. A. J. Huijbregts, "Chapter 6: Aquatic Eutrophication," in *ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors*, M. Goedkoop, R. Heijungs, M. A. J. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, Eds. 2013.

[32] "HANDBOOK ON A NOVEL METHODOLOGY FOR THE SUSTAINABILITY IMPACT ASSESSMENT OF NEW TECHNOLOGIES."

[33] A. Laurent, M. Z. Hauschild, L. Golsteijn, M. Simas, J. Fontes, and R. Wood, "Deliverable 5.2: Normalisation factors for environmental, economic and socio-economic indicators," Prosuite, Copenhagen, 2013.

[34] United Nations, "Revised list of global Sustainable Development Goal indicators. Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators (E/CN.3/2017/2), Annex III," New York, 2017.

[35] S. D. Maier, T. Beck, J. F. Vallejo, R. Horn, J.-H. Sohlemann, and T. T. Nguyen, "Methodological Approach for the Sustainability Assessment of Development Cooperation Projects for Built Innovations Based on the SDGs and Life Cycle Thinking," *Sustainability*, vol.

8, pp. 1–26, 2016, doi: 10.3390/su8101006.

[36] C. Wulf, J. Werker, P. Zapp, A. Schreiber, H. Schlör, and W. Kuckshinrichs, *Sustainable development goals as a guideline for indicator selection in Life Cycle Sustainability Assessment*, vol. 69, no. May. Copenhagen, Denmark: The Author(s), 2018, pp. 59–65.

[37] SEPA, “One Planet Prosperity - Our Regulatory Strategy,” p. 12, 2016.

[38] T. S. Government, *Heat Policy Statement Towards Decarbonising Heat: Maximising the Opportunities for Scotland*. .

[39] A. T. Marques *et al.*, “Wind turbines cause functional habitat loss for migratory soaring birds,” *J. Amin. Ecol.*, pp. 1–11, 2019, doi: 10.1111/1365-2656.12961.

[40] M. A. J. Huijbregts, L. J. A. Rombouts, A. M. J. Ragas, and V. D. M. Dik, “Human-Toxicological Effect and Damage Factors of Carcinogenic and Noncarcinogenic Chemicals for Life Cycle Impact Assessment,” *Integr. Environ. Assess. Manag.*, vol. 1, no. 3, pp. 181–244, 2005.

[41] C. A. Pope *et al.*, “Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution,” *J. Am. Med. Assoc.*, vol. 287, no. 9, pp. 1132–1141, 2002.

Appendix A

Normalisation factors at midpoint from Prosuite Project 2013 [33] **and related end-point LCIA methods, indicators and classifications (ILCD** [7]**)**

Mid-point impact category	Normalisation factor	Unit	End-point LCIA method	Indicator	Classification
Climate change	8.10E+03	kg-CO_2eq per person	No methods recommended		Interim
Ozone depletion	4.14E-02	kg-CFC-11eq per person	No methods recommended		Interim
Human toxicity (cancer effects)	5.42E-05	cases per person per year	DALY calculation applied to USEtox midpoint (Adapted from [40])	Disability Adjusted Life Years (DALY)	II/Interim
Human toxicity (non-cancer effects)	1.10E-03	cases per person per year	No methods recommended		Interim
Particulate matter/ respiratory inorganics	2.76E+00	kg-$PM_{2.5}$eq per person	DALY calculation applied to midpoint (adapted from [27], [41]	Disability Adjusted Life Years (DALY)	I/II
Ionising radiation (human health)	1.33E+03	kBq U-235 air-eq per person per year	No methods recommended		Interim
Ionising radiation (ecosystems)	None recommended		No methods recommended		
Photochemical ozone formation	5.67E+01	kg-NMVOCeq per person per year	Model for damage to human health [27]	Disability Adjusted Life Years (DALY)	II
Acidification (terrestrial)	4.96E+01	Accumulated Exceedance per person per year	No methods recommended		Interim
Eutrophication (terrestrial)	1.15E+02	Accumulated Exceedance per person per year	No methods recommended		

Eutrophication (freshwater)	6.20E-01	Kg-P-eq per person per year	No methods recommended	Interim
Eutrophication (marine)	9.38E+00	Kg-N-eq per person per year	No methods recommended	Interim
Ecotoxicity (freshwater)	6.65E+02	PAF.m^3.d per person per year	No methods recommended	
Ecotoxicity (marine and terrestrial)	None recommended		No methods recommended	
Land use	2.36E+05	kgC-yr per person per year	No methods recommended	Interim
Resource depletion (water)	1.11E+02	m^3 per person per year	No methods recommended	
Resource depletion (mineral, fossil and renewable)	3.13E-01	kg-Sb-eq per person per year	No methods recommended	

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