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Environmental Unit Cost Lists

A Methodological Comparative Analysis

by:
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On behalf of the German Environment Agency.

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Abstract: Environmental Unit Cost Lists: A Methodological Comparative Analysis

The aim of this report is to compare the different methodologies applied in lists/databases of environmental unit costs for use in CBAs and environmental/sustainability reporting. The analysis is based on a core set of lists/databases from a scoping exercise performed by the German Environment Agency supplemented with other recent lists/publications that include relevant data for Germany. 15 unit costs lists and their supporting documents are compared methodologically across 6 main environmental topics: i) greenhouse gases, ii) Local/regional air pollutants (PM_{10} (including $PM_{2.5}$), NO_X, SO_2, NH_3, and NMVOC), iii) Eutrophication (N and P) , iv) Other local/regional water and soil pollutants, v) Traffic noise and vi) Land use changes affecting biodiversity and ecosystem services.

Kurzbeschreibung: Umweltkostenlisten: eine vergleichende Methodenanalyse

Ziel dieses Berichtes ist der Vergleich unterschiedlicher Methodiken, die in Listen oder Datenbanken von Umweltkosten (environmental unit costs) verwendet werden. Diese werden u.A. für Kosten-Nutzen-Analysen und Umwelt- oder Nachhaltigkeitsberichterstattung genutzt. Die Analyse basiert auf einem Kernset von Listen und Datenbanken, das aus einer Sondierung des Umweltbundesamtes hervorging. Ergänzt wurde dies um weitere aktuelle Listen und Veröffentlichungen, die für Deutschland relevante Daten enthalten. Insgesamt 15 Umweltkostenlisten und ihre ergänzenden Dokumente werden innerhalb des Berichts methodisch verglichen. Der Vergleich vollzieht sich entlang von sechs zentralen Umweltthemen: i) Treibhausgase, ii) lokale/regionale Luftschadstoffe (PM10 einschließlich PM2,5, NOx, SO2, NH3 und NMVOC), iii) Eutrophierung (N und P), iv) andere lokale/regionale Wasser- und Bodenschadstoffe, v) Verkehrslärm, sowie vi) Landnutzungsänderungen, die Biodiversität und Ökosystemleistungen beeinflussen.

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List of abbreviations

AC	Avertive /Avoidance Costs
BT	Benefit Transfer
CBA	Cost-Benefit Analysis
CC	Climate Change
CF	Characterization Factor (in LCA)
CO_2	Carbon dioxide
COI	Cost-of-Illness
CRF	Concentration-response function
DALY	Disability Adjusted Life Year
dBA	Decibel A (A= adjusted for human sensitivity to different sound frequencies)
DEFRA	UK Department for Envorinment, Food & Rural Affairs
DFA	Damage Function Approach
DRF	Dose-response function
ENCA	Enabling a Nature Capital Approach (UK Defra)
EPS	Environmental Priority Strategies
ERF	Exposure-response function
EU ETS	European Union Emission Trading System (for CO_2)
GBD	Global Burden of Disease
GHG	Greenhouse gas
GWP	Global Warming Potential
HP	Hedonic Pricing
IAM	Integrated Assessment Model
IPA	Impact Pathway Approach
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
MAC	Marginal Abatement Costs

MD	Marginal Damage (Costs)
N	Nitrogen
NEEDS	New Energy Externalities Developments for Sustainability (EU FP7--project)
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_X	Nitrogen oxides
NPP	Net Primary Production
P	Phosphorous
p.a.	Per annum (per year/yearly)
PAF	Potentially Affected Fraction (of species)
PDF	Potentially Disappeared Fraction (of species)
$PM_{2.5}$	Particulate Matter 2.5 micrometer or smaller
PM_{10}	Particulate Matter 10 micrometer or smaller (includes $PM_{2.5}$)
PPP	Purchase Power Parity
QALY	Quality Adjusted Life Year
RP	Revealed Preference
SDR	Social Discount Rate
SCC	Social Costs of Carbon
SO_2	Sulphur dioxide
SP	Stated Preference
T	Time horizon (in years); analysis period
VOLY	Value of a Statistical Life Year
VSL	Value of a Statistical Life
YLD	Years of Life with Disability
YOLL/YLL	Years of Life Lost

Summary and Conclusions

The aim of this report is to compare the different methodologies applied in lists/databases of environmental unit costs for use in CBAs and environmental/sustainability reporting. The analysis is based on a core set of lists/databases from a scoping exercise performed by the German Environment Agency supplemented with other lists/databases that include relevant data for Germany.

The comparative analysis looked at emissions from transport and power generation (heat and electricity) and pollutants that are included or planned to be included in the UBA Methodological Convention for Estimating Environmental Costs. These pollutants include:

- Greenhouse gases (GHG)
- Local/regional air pollutants
  - Particulate matter PM_{10}, which includes fine particles $PM_{2.5}$
  - Nitrogen oxides (NO_X)
  - Sulphur oxide (SO_2)
  - Ammonia (NH_3)
  - Non-methane volatile organic compounds; NMVOC
- Local/regional water and soil pollutants
  - Nitrogen and phosphorous (Eutrophication),
  - Other water and soil pollutants
- Traffic noise
- Land use changes affecting biodiversity and ecosystem services

The analysis compares the unit cost methodologies applied, data sources used, system boundaries, discount rates, equity weighting schemes and uncertainty assessments (e.g., point estimates versus ranges; and catastrophic risk considerations).

Results show that environmental unit cost lists and CBA guidelines recommend the use of the Impact Pathway Approach (IPA) as the welfare theoretic correct approach, and the application of benefit transfer of estimates from revealed and stated preference studies in the final valuation step of this damage function approach. However, some impacts are left out either because they are not quantified and/or valued, and thus the resulting unit cost estimates are subtotals. This is true also where lower and upper estimates are provided along central estimates. Thus, the use of unit value ranges can be somewhat misleading as some damage components are left out, and thus the ranges do not fully reflect the uncertainty. Further, catastrophic risks are often not considered explicitly in the unit value ranges. Even though the unit cost lists are explicit about the assumptions their central estimates and ranges are based on, they could be more explicit on stating that the estimates are subtotals as not all environmental and health impacts are covered in the assessments. Identifying these knowledge gaps, and which factors have the potential to influence the unit costs the most, can also provide valuable input to research agendas to improve unit damage costs lists based on IPA.

LCA methodologies have the advantage over external costs reports of having estimates of health effects for hundreds of hazardous substances including many toxics and heavy metals, whereas external costs estimates exist for 10-20 environmental pollutants. However, in LCA, impacts are reported in terms of e.g. human toxicity impacts (as a "midpoint" impact) rather than as a final health impact that can be valued. Further, LCA methodologies build on expert assessment rather than individual preferences, do usually not apply discount rates (which are important for e.g., carcinogens with long-term effects), implicitly assuming a zero discount rate which is not in agreement with current practise in external costs reports and CBAs in Europe which typically use social discount rates in the range of 2% - 4 %.

Applying monetary valuation methods to LCA methodologies according to the ISO 14008 standard, as e.g. the LCA methodology EPS is aiming for, does seems like a fruitful way of utilizing the data from LCAs in both CBAs and environmental/sustainability reporting, in a way which is compatible with the welfare economic underpinnings of CBA. However, lack of data and knowledge gaps for many steps of the IPA for the large number of heavy metals, toxins and chemicals currently precludes the full use of LCA data in IPA-based environmental unit cost assessments.

Application of IPA to more pollutants, and more comprehensive coverage of impacts for the pollutants already included in environmental unit cost lists, requires more biophysical, ecological and epidemiological research as well as new environmental valuation studies designed for national benefit transfer, along with a structured overview of already existing data useful for application of IPA. An example of the latter with respect to the most incompletely covered topic in environmental unit cost lists is the UK Defra's ENCA (Enabling a Natural Capital Approach) guidelines for biodiversity and ecosystem services. These guidelines (UK Defra 2021b) include benefit transfer methodology, lists of suggested unit values for different habitats and ecosystem services (with low and high values reflecting varying values of the same environmental goods at different locations rather than uncertainty in the IPA), a list of case studies using ENCA, and an excel template for undertaking ENCA in accordance with national CBA manuals.

Zusammenfassung

Ziel dieses Berichts ist der Vergleich der verschiedenen Methoden, die in Listen/Datenbanken zu Umweltkosten zur Verwendung in Kosten-Nutzen-Analysen und Umwelt-/Nachhaltigkeitsberichterstattung angewendet werden. Die Auswertung basiert auf einem Kernset von Listen und Datenbanken aus einer Sondierung des Umweltbundesamtes. Dieses Kernset wurde um andere Listen und Datenbanken ergänzt, die relevante Daten für Deutschland enthalten.

Die vergleichende Analyse betrachtet Emissionen aus Verkehr und Energieerzeugung (Wärme, Elektrizität) und Schadstoffe. Diese sind entweder derzeit in die UBA-Methodenkonvention zur Ermittlung von Umweltkosten integriert, oder sollen künftig eingebunden werden. Hierzu gehören:

- Treibhausgase (THG)
- Lokale/Regionale Luftschadstoffe
  - Feinstaub PM_{10}, welche auch $PM_{2.5}$ Partikel beinhalten
  - Stickoxid (NO_X)
  - Schwefeloxid (SO_2)
  - Ammoniak (NH_3)
  - Nicht-Methanhaltige flüchtige organische Verbindungen (NMVOC)
- Lokale/Regionale Wasser und Bodenschadstoffe
  - Stickstoff und Phosphor (Eutrophierung)
  - Andere Wasser- und Bodenschadstoffe
- Verkehrslärm
- Landnutzungsänderungen, die Biodiversität und Ökosystemleistungen verändern

Der vorliegende Bericht vergleicht die verwendeten Methoden zur Ermittlung der Kostensätze. Ebenfalls verglichen werden die Datenquellen, Systemgrenzen, Diskontierungsraten und Equity Weighting der ausgewählten Listen und Datensätze. Ferner werden unterschiedlicje Methodiken zur Berücksichtigung von Unsicherheit verglichen (bspw. Punktschätzer verglichen mit Bandbreiten, sowie die Berücksichtigung von Katastrophenrisiken).

Die Ergebnisse zeigen, dass sich für Umweltkostenlisten und Richtlinien für Kosten-Nutzen-Analysen die Verwendung des Wirkungspfadansatzes (Impact Pathway Approaches, IPA) als wohlfahrtstheoretisch korrekten Ansatz empfiehlt. Darüber hinaus unterstreichen die Ergebnisse die Relevanz der Anwendung des Benefit Transfers von Schätzungen aus Studien zur geoffenbarten und bekundeten Präferenz innerhalb des letzten Bewertungsschritts des Schadensfunktionsansatzes. Aufgrund fehlender Quantifizierungen oder ausgebliebener Bewertungen werden einige Wirkungen hierbei ausgelassen. Daher stellen die resultierenden Schätzungen der Kostensätze nur Teilsummen dar. Dies gilt auch dort, wo niedrigere und höhere Schätzung um einen zentralen Schätzwert angegeben sind. Die Nutzung von Bandbreiten von Kostensätzen kann daher etwas irreführend sein. Dies resultiert aus Auslassungen von Schadensbestandteilen und einer unvollständigen Widerspiegelung der Unsicherheit durch

angegebene Bandbreiten. Darüber hinaus werden Katastrophenrisiken oft nicht explizit in den Bandbreiten berücksichtigt. Grundsätzlich stellen die Listen der Kostensätze die Annahmen, die ihren zentralen Schätzungen und Bandbreiten zugrunde liegen, explizit dar Allerdings wäre eine konkretere Darstellung der ermittelten Werte als Teilsummen sinnvoll. Dass Teilsummen ermittelt werden liegt insb. daran, dass nicht alle Umwelt- und Gesundheitswirkungen abgedeckt werden. Für zukünftige Forschungsagenden wäre eine Identifikation dieser Wissenslücken ein wichtiger Input. Zugleich wäre es hilfreich herauszufinden, welche Faktoren die vorliegenden Kostensätze potentiell am stärksten zu beeinflussen. So ließen sich zukünftig die auf Wirkungspfadanalysen basierenden Listen von Kostensätzen verbessern.

Lebenszyklusanalysen (LCA-Methodiken) haben gegenüber Berichten zu externen Kosten den Vorteil, dass sie Schätzungen der Gesundheitseffekte von hunderten gefährlichen Substanzen einschließlich vieler Gifte und Schwermetalle, ermöglichen. Dem gegenüber existieren Schätzungen externer Kosten für lediglich 10 bis 20 umweltverschmutzende Stoffe. Allerdings werden in LCAs Wirkungen in Form von bspw. humantoxischen Wirkungen berichtet (als „midpoint" Wirkungen) anstatt einer bewertbaren, am Ende der Kette stehenden Gesundheitswirkung. Darüber hinaus bauen Methoden der Lebenszyklusanalyse auf Experteneinschätzungen anstelle von individuellen Präferenzen auf. Sie verwenden in der Regel keine Diskontraten (welche bspw. bei krebserregenden Stoffen mit Langzeitwirkungen wichtig sind) und nehmen daher implizit Diskontraten von 0% an. Dies steht nicht in Einklang mit der herrschenden Praxis für Berichte zu externen Kosten und Kostennutzenanalysen in Europa. Diese verwenden typischerweise soziale Diskontraten in der Bandbreite von 2% bis 4%.

Die Anwendung monetärer Bewertungsmethoden auf LCA-Methoden gemäß der Norm ISO 14008, wie es bspw. die LCA Methode EPS anstrebt, scheint ein effizienter Weg zu sein. Hierdurch wäre es möglich die Daten aus LCAs sowohl in Kostennutzenanalysen als auch in der Umwelt- und Nachhaltigkeitsberichterstattung auf eine Weise zu nutzen, die mit der wohlfahrtstheoretischen Fundierung von Kostennutzenanalysen kompatibel ist. Allerdings verhindern aktuell (noch) der Datenmangel und Wissenslücken bei vielen Schritten der Wirkungspfadanalysen die umfängliche Nutzung von Lebenszyklusdaten in wirkungspfadbasierten Ermittlungen von Umweltkostensätzen. Dies gilt für eine große Zahl von Schwermetallen, Toxinen und Chemikalien.

Die Anwendung von Wirkungspfadanalysen auf mehr Schadstoffe und eine weitreichendere Abdeckung von Wirkungen der bereits in Kostensatzlisten erfassten Schadstoffe erfordert daher verstärkte biophysikalische, ökologische und epidemiologische Forschung. Auch neue Umweltbewertungsstudien, die für einen nationalen Benefit Transfer zugeschnitten sind, sind hierzu notwendig. Diese sollten mit einem strukturellen Überblick über bereits existierende Daten, die für die Anwendung von Wirkungspfadanalysen nützlich sind, kombiniert werden. Ein Beispiel für letztere ist ENCA (Enabling a Natural Capital Approach), eine Richtlinie für Biodiversität und Ökosystemleistungen des britischen Department for Environment, Food & Rural Affairs (DEFRA). Diese Richtlinien (UK Defra 2021b) beinhalten Benefit Transfer-Methoden sowie Listen mit vorgeschlagenen Kostensätzen für verschiedene Habitate und Ökosystemleistungen (mit niedrigen und hohen Werten, die verschiedene Werte des gleichen Umweltgutes an unterschiedlichen Orten widerspiegeln, anstelle der Unsicherheit der Wirkungspfadanalyse). Darüber hinaus stellt DEFRA eine Liste von Fallstudien bereit, die ENCA verwenden, sowie eine Excel-Vorlage um ENCA in Einklang mit nationalen Kosten-Nutzen-Analyse-Handbüchern zu verwenden.

1 Introduction

1.1 Background

Cost-benefit analyses (CBAs) of environmental regulations as well as of transport and energy projects with emissions to air, water and soil require the social benefits and social costs to be compared on the same monetary scale (here: in euro). Whereas the costs of mitigating (or adapting to) pollution can be monetized by market prices of private goods; market prices do often not exist for the benefits in terms of increased quantity and quality of public goods like air, soil, and water and related public health effects; stable climate; and biodiversity and ecosystem services. Thus, the assessment of impacts on these environmental goods requires other monetization techniques than market prices for valuing the welfare improvements (or avoided welfare losses) people experience from marginal changes in the quality or quantity of these public goods. Environmental valuation methods have been developed and frequently applied to fill this gap, and the increased use of CBAs as a decision support tool has led to the development of lists of standardized environmental unit costs for ease of use in CBAs. With the recent ISO standard for monetization of environmental impacts (ISO 14008), there is now also an increasing interest in applying such environmental unit costs in environmental /sustainability report at the firm level.

1.2 Aim

The aim of this report is to compare the different methodologies applied in lists/databases of environmental unit costs for use in CBAs and environmental/sustainability reporting. The analysis is based on a core set of lists/databases from a scoping exercise performed by the German Environment Agency supplemented with other lists/databases that include relevant data for Germany.

The comparative analysis will look at emissions from transport and power generation (heat and electricity) and pollutants that are included or planned to be included in the UBA Methodological Convention for Estimating Environmental Costs (UBA 2019). These pollutants include:

- Greenhouse gases (GHG)
- Local/regional air pollutants
  - Particulate matter PM_{10}, which includes fine particles $PM_{2.5}$
  - Nitrogen oxides (NO_X)
  - Sulphur oxide (SO_2)
  - Ammonia (NH_3)
  - Non-methane volatile organic compounds; NMVOC
- Local/regional water and soil pollutants
  - Nitrogen and phosphorous (Eutrophication),
  - Other water and soil pollutants
- Traffic noise
- Land use changes affecting biodiversity and ecosystem services

The analysis compares the unit cost methodologies applied, data sources used, system boundaries, discount rates, equity weighting schemes and uncertainty assessments (e.g., point estimates versus ranges; and catastrophic risk considerations).

The rest of this paper is organized as follows. Chapter 2 provides an overview of the main methodologies used to derive unit values for different air, water and soil pollutants, noise and biodiversity/ecosystem services. Chapter 3 provides an overview of the reports, lists, and databases considered and compared in this analysis. Chapter 4 reports and discusses the comparative methodological analysis for each group of pollutants.

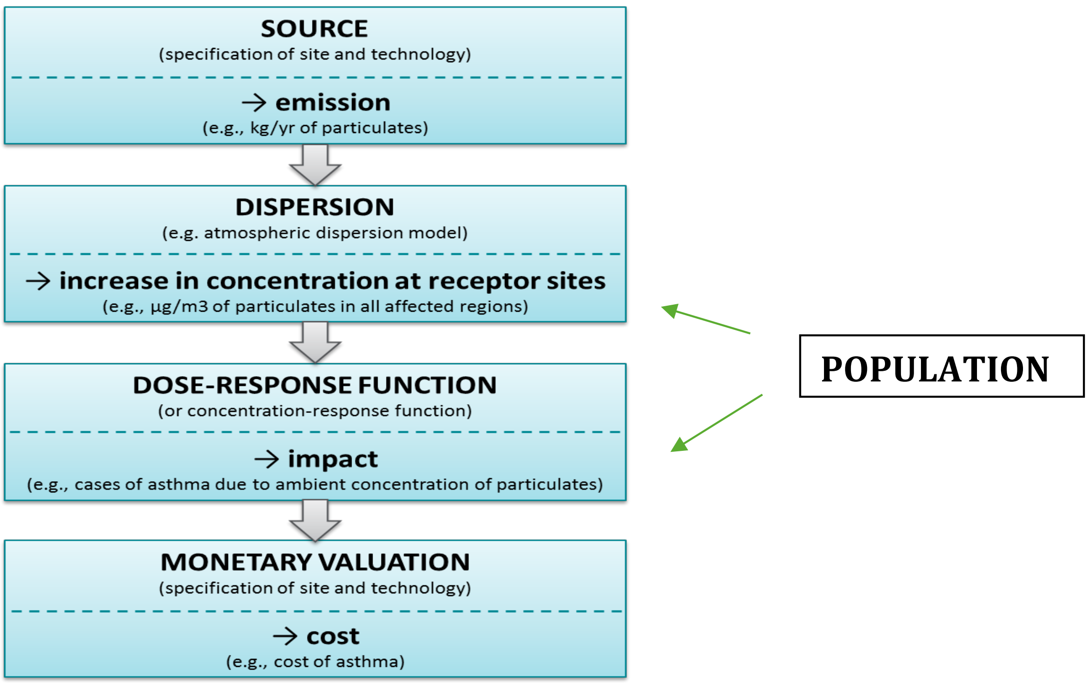
2 Methodologies for environmental unit values

There are three main methodologies for constructing unit costs per tonne of emission: i) Impact Pathway Approach (IPA), ii) Life Cycle Assessment (LCA) and iii) Marginal Abatement Costs (MAC).

2.1 Impact Pathway Approach (IPA)

The Impact Pathway Approach (IPA), often termed the Damage Function Approach (DFA) by economists, is illustrated in figure 1. IPA consists of the following four main steps: i) Mapping emissions from a specified activity to air, water, or soil, ii) Spatial dispersion modelling to calculate increased pollutant concentrations (in air, water or soil), iii) Environmental and health impact assessment based on dose-response functions (DRF) (for health impacts, concentration-response functions (CRF) and exposure-response functions (ERF)[1] are often used), and iv) Economic valuation of environmental and health impacts. The estimated total damage cost is then divided by the amount of emission to calculate unit damage costs in euro/kg or ton of pollutant. These unit costs are often presented as marginal damage costs while they are often average damage costs over the emission changes in question.

Figure 1 Impact Pathway Approach (IPA). An example.



Source: Modified from Bickel and Friedrich (2005, figure 1.1)

A very important input in both the impact assessment and the monetary valuation is *the number of people affected* in terms of getting their wellbeing/welfare reduced, as this would greatly influence the total damage costs. As greenhouse gasses will have the same impact independent

[1] Dose–response functions (DRFs) , or exposure–response functions (ERFs), describe the magnitude of the response of an organism, as a function of exposure (or doses) to a stimulus or stressor (e.g. an air pollutant or chemical) after a certain exposure time. DRFs and ERFs are usually used for environmental and public health impacts, respectively. Concentration-response functions (CRFs) relate concentrations of pollutants in ambient air to mortality risks or other adverse health effects as opposed to ERFs that take exposure time into account.

of where they are emitted, and affect the global climate, the affected population will be the global population. Even for CBAs performed at the national level, the global damage costs (including environmental and health costs) in terms of the Social Costs of Carbon (SCC) are therefore often used in order not to underestimate the damage costs of climate change from greenhouse gas emissions. For other pollutants, public health impacts would be aggregated over the exposed population. For environmental impacts both the *use value* and *non-use value* should be accounted for. Use value impacts includes reduced recreational experience among locals and tourists of fishing and swimming from eutrophication of lakes, and homeowners experiencing traffic noise or negative landscape aesthetic impacts from wind turbines. *Non-use value* applies to a wider population, also those not directly affected or using the affected environmental goods. They can experience a welfare loss in terms of reduction in their existence and bequest values of the environmental goods affected by the polluting emissions or land use changes causing e.g. biodiversity loss.

IPA is considered a best practise method for monetizing environmental and health impacts (see e.g., UBA 2019, Defra 2021a), and it is in accordance with the welfare economic underpinnings of CBA (Boardman et al 2018, OECD 2018). However, there are often incomplete information and uncertainties in all steps of the IPA; from emissions through dispersion modelling, concentration and exposure modelling, dose-response functions (DRFs) (or concentration-response function CRF)/exposure-response function (ERF) for health impacts), and the economic valuation of the endpoints of the DRFs/CRFs/ ERFs. In the last step, these endpoints sometimes need to be converted to units that can be valued using market prices or environmental or health valuation methods, which adds uncertainty. Lack of DRFs/CRFs/ERFs for some pollutants makes a complete IPA impossible. Then inputs from Environmental Impact Assessments (EIAs) and expert assessments are often used instead to shortcut the IPA (i.e., going directly from emission or concentration to impact) for the pollutants in question.

2.1.1 Environmental valuation methods and benefit transfer

In the last step of the IPA, environmental and environmentally related health impacts of the emissions of the pollutants are valued in monetary terms. Table 1 provides an overview of the two main groups of primary valuation methods, Stated Preference (RP) and Revealed Preference (RP) methods. SP methods are used to capture both use and non-use values, whereas RP techniques capture mostly use values[2].

Table 1: Environmental Valuation methods

i) **Primary Valuation methods** = Revealed Preference (RP) and Stated Preference (SP) methods
ii) **Benefit transfer methods** = Unit value transfer, Function transfer, Meta analysis, Delphi method

Primary Valuation methods	Indirect	Direct
Revealed Preference (RP)	Household Production Function - Travel Cost (TC) method - Averting Costs (AC) method (Avoidance/Defensive costs) Hedonic Price (HP) method	Simulated market Market prices Replacement costs (RC) (Restoration costs)

[2] More recently, the Subjective well-being (SWB) method has also been applied to environmental impacts. Here, people report in surveys how environmental goods impact on self-reported measures of well-being such as life satisfaction, which is then converted into a monetary measure from their trade-off between environmental goods and income (OECD 2018, Chapter 7).

Primary Valuation methods	Indirect	Direct
Stated Preference (SP)	Choice Experiments (CE)	Contingent Valuation (CV)

Source: Own illustration, Norwegian University of Life Sciences

Economic valuation in environmental unit cost lists is often based on transfer and generalization of results from previous RP or SP studies, which have usually not been designed specifically to provide values to be used in these lists. This procedure is commonly termed benefit transfer (BT), even if both environmental costs and benefits can be transferred and "value transfer" could be a more appropriate term (Johnston et al. 2021).

According to Navrud (2004), to perform BT, there are four requirements:

1. Databases of primary valuation studies (to transfer values from)
2. Guidelines for assessing quality of primary valuation studies
3. BT techniques
4. BT guidelines

The first requirement is a *database* for primary valuation studies with sufficient and detailed information of the studies to allow for judgement of the similarity (and thus the transferability) between the impacts valued and the population valuing the impacts in the primary studies and the impacts and affected population of the policy case to be evaluated. Instead of having to conduct detailed literature searches and reviews every time the environmental and health impacts of different pollutants are updated, a complete database of valuation studies of relevant environmental and health impacts would greatly ease this task. While such detailed databases have been constructed for meta-analyses of valuation studies of specific environmental and health impacts, they are usually not updated nor publicly available.

The Environmental Valuation Reference Inventory (EVRI) www.evri.ca is the most comprehensive and updated international database for both primary studies and meta-analyses valuing both environmental and environmentally related health impacts. EVRI contains more than 5200 studies. Examples of more specialized databases of valuation studies include: i) the Ecosystem Services Valuation Database (ESVD) www.esvd.net, extending a database developed under TEEB (The Economics of Ecosystems and Biodiversity) http://teebweb.org/, now covering 950 studies of the benefits of ecosystem services and biodiversity; ii) the Recreational Use Value Database (RUVD) http://recvaluation.forestry.oregonstate.edu/database of North-American SP and RP studies of use values of different recreational activities, and iii) the OECD Value of Statistical Life (VSL) database https://www.oecd.org/env/tools-evaluation/env-value-statistical-life.htm with global coverage of Stated Preference (SP) studies of mortality risk reductions and constructed for a global meta-analysis of VSL estimates from SP studies (Lindhjem et al., 2011; OECD, 2012; Lindhjem and Navrud, 2015). A challenge for all databases is that they need to be continuously maintained and updated by adding new valuation studies.

Databases constructed for use in meta-analysis usually contains more detailed information, which all databases and BT exercises would benefit from. For example, the information collected about each primary valuation study in EVRI will in some cases not be sufficient for the BT techniques and guidelines. Thus, the reporting of the valuation estimates and data for variables known to affect the value estimates should be more detailed when studies are published (e.g., as electronic appendices to the journal articles and reports), and reported in a way that allows for both a detailed quality assessment of the primary study and best practise BT. With regards to requirement no. 2 above on quality assessment of primary valuation studies, there are updated comprehensive guidance on e.g., SP methods (Johnston et al., 2017). For requirements 3 and 4 on BT techniques and guidelines, Johnston et al. (2021) provide an overview of techniques and recent guidance on BT.

2.1.2 Health Valuation Methods

Both SP and RP methods have been used to value mortality and morbidity impacts. Among RP methods, both hedonic price (HP) and averting cost (AC) analyses have been conducted. Hedonic wage studies estimate workers' willingness-to-accept (WTA) higher wages to compensate for higher mortality risks, whereas AC studies look at households' investments in measures that averts/reduces the mortality risk; typically traffic related measures like buying and wearing motorcycle and bicycle helmets and car seat belts. SP methods (both CV and CE) have been used to elicit people's willingness-to-pay (WTP) for reduced mortality risks and calculate the Value of a Statistical Life (VSL). Assuming that VSL is the present value of the remaining life years (typically with a remaining life expectancy of 40 years and discount rate of e.g., 2 % p.a.), the Value of a Life Year (VOLY)[3] is derived. VOLY can be used to directly value years of life lost (YLL) from dying prematurely due to e.g., respiratory or cardiovascular diseases caused by local air pollutants; often expressed in Quality Adjusted Life years (QALY) or Disability Adjusted Life Years (DALY). VSL is often used to value climate change related premature deaths from e.g., increased frequency and intensity of extreme weather events like droughts, flooding, landslides and hurricanes. While there are no general rule as to when to use VSL versus VOLY, CBA manuals often recommend using VSL and then VOLY for sensitivity analysis.[4]

2.2 Life Cycle Assessment (LCA) methods

Life Cycle Assessments (LCAs) are based on life cycle inventories (LCI) of emission of different pollutants. Life cycle impact assessment (LCIA) is the phase of an LCA that aims "at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system" (Nieuwlaar 2004, 647).In the final stage of LCIA the different pollutants can be aggregated using a set of weights in order to express the total impacts in one single number.

There are a range of LCA methods and weighting techniques, and they can be based on expert assessment, abatement costs, implicit valuation based on previous policy decision and regulations (e.g., environmental taxes and charges); and monetisation of impacts. The latter approach has recently become an ISO-standard; ISO 14008:2019: "Monetary Valuation of environmental impacts and related environmental aspects"[5]. The monetary valuation methods listed in the standard are the same as the environmental valuation techniques listed in figure 2; including both primary valuation techniques of SP and RP, and benefit transfer/value transfer. Note, however, that LCAs usually have a much wider scope than the IPA, as both upstream and downstream emissions and impacts of producing a good are included. Compared to IPA, LCAs are usually performed for a product, and are not policy evaluations (e.g., CBAs of stricter air quality standards and implied programs that can be used to achieve this) where IPA is often used.

[3] VOLY is also termed Value of a Statistical Life Year (VSLY): there have also been attempts to value VOLY directly in multi-country CV studies; see e.g, Desaigues et al. (2011).

4 It is also very much an ethical question whether we count and value lost lives (VSL) or lost life years (VOLY), as the latter approach implicitly assign a lower value to elderly people dying prematurely compared to young people that would lose more life years.

[5] ISO 14008: 2019; see https://www.iso.org/standard/43243.html

The development of ISO 14008 was initiated by Bengt Steen at the Swedish Life Cycle Center at Chalmers University of Technology. In 1989 he developed the Environmental Priority Strategies in product design (EPS), which was the first LCA method to apply a type of IPA to LCA with aggregation in damage categories (eutrophication, acidification etc.) and monetarization of endpoints to come up with a single score for each product analyzed. EPS, and selected other LCA weighting techniques seeking to use monetary measures will be listed and reviewed in chapter 3 and 4, respectively. For recent comprehensive reviews of LCA methods; see Arendt et al. (2020) and Amadei et al. (2021). These reviews show differences in monetized impacts of several orders of magnitude across weighting methods for a wide range of pollutants. The differences can be attributed partly to differences in weighing techniques in terms of design and whether the weights are based on the preferences of experts, citizens or politicians (through their decisions on regulatory measures), the costing/monetization method and whether future damages were discounted; and partly by factors like the geographical references area, population size and environmental conditions.

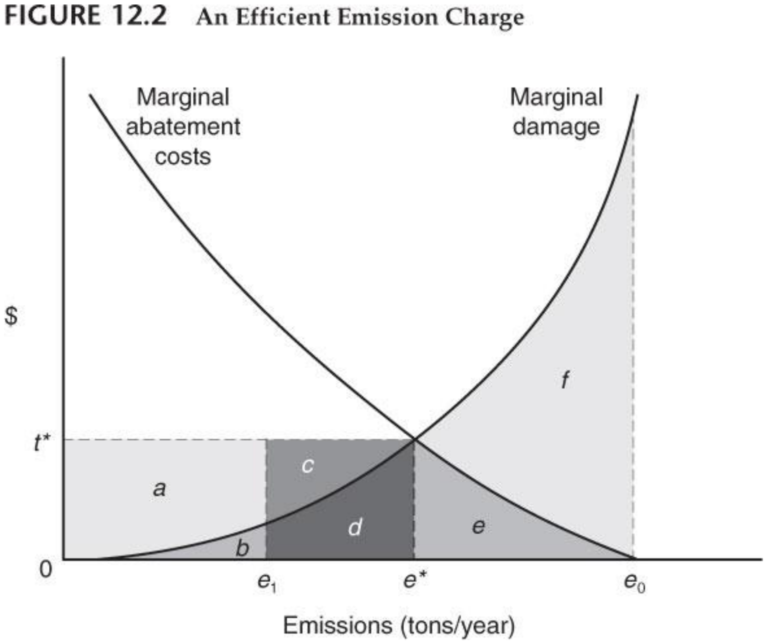
As opposed to CBA manuals, LCA approaches typically do not apply discount rates, and uncertainty and catastrophic risks are usually not addressed explicitly. CBA manuals recommends the use of IPA, specify social discount rates (SDRs), and recommends ways to present uncertainty. In practice, this is usually in terms of sensitivity analysis and/or applying scenario analysis (often with worst, central, best case scenarios); but sometimes simulation models (e.g., Monte Carlo simulation) assuming a probability distribution for the possible outcomes of each input factor to the CBA are also used.

2.3 Marginal Abatement Costs (MAC)

Marginal abatement costs (MAC) or mitigating costs of reaching a specified political target have also been used to monetize the marginal damage costs (MD)[6]. This approach is sometimes also termed the *Implicit Cost* approach as politicians by deciding on an emission target and its associated abatement costs implicitly value the benefits, in terms of the avoided damage costs, to be equal to or exceed the abatement costs. Thus, MAC is here used as an approximation for MD, but they are only equal if the political target for emission reduction is set at the social optimal level where MAC=MD. Figure 2 shows that if the emission target is set at a higher or lower emission level than the level corresponding to MAC=MD, the marginal abatement cost approach would under- or overestimate the marginal damage costs, respectively. Note that the MD curve would typically be calculated using the IPA approach shown in figure 1. To reflect the uncertainties inherent in each of the steps of IPA, the MD curve in figure 2 should be drawn as a brushstroke, reflecting the possible range of damage costs, rather than the current thin line based on midpoint estimates of MD at different emission levels. Then the socio-economic optimal emission level (e* in figure 2) would also be a range rather than one specific level.

[6] As «damage» in the environmental economics literature always refers to costs, marginal damage (MD) here refers to the monetized damage or damage costs per unit of emission of a pollutant (or unit of an environmental aspect).

Figure 2: Marginal Abatement Costs and Marginal Damage



Source: Field and Field (2021, figure 12.2)

In figure 2 the total damages at the initial emission level e_0 is the area under the MD curve at that point i.e. areas *b+d+e+f.* Reducing emissions from the initial level e_0 (i.e. moving to the left on the x-axis towards zero emissions), we see that the benefit in terms of avoided damages per ton of emission (represented by the MD curve) exceeds the cost of reducing emissions by 1 ton (represented by the MAC curve) all the way until we reach e* where the MAC and MD curves intersect and MAC=MD. This is the socio-economic optimal emission level, since reducing emissions further would incur net costs for each ton of emission reduced when MAC>MD. Thus, reducing emissions from e_0 to e* provides the highest net benefits of any emission reduction (smaller or larger). Net benefits are equal to the area *f*, as total abatement costs are equal to area *e* and total benefits (avoided damage costs) are equal to area *e+f*.

In theory, the MD curve can be derived using the damage function approach in terms of IPA (see figure 1). Unit damage costs are usually computed by dividing the estimated avoided damage costs for a specific, small reduction (or increment) in emissions of a pollutant by the reduced (or increased) number of tons of the pollutant emitted. This yields an average estimate of the marginal damage costs of the pollutant for the specified change in emissions. Thus, environmental unit costs typically provide *average* rather than marginal damage costs. Thus, they will not fully reflect that the marginal damage costs vary with the initial emission level, the size and direction of the change in emissions, and the shape of the MD curve. However, if the change in emissions is small and the MD-curve at that point is relatively flat, average damage costs will be a good approximation of the marginal damage costs. For large changes in emissions of a pollutant and steep MD curves, there could be larger deviations.

With regards to uncertainty, some environmental unit value publications have low, central and high estimates but recognize that this range of estimates might still not fully cover the range of uncertainties in the different steps of the IPA applied.

3 Environmental unit cost publications

3.1 Overview of publications reviewed

The following documents, guidelines, and lists of environmental unit costs for use in CBAs or in monetized sustainability assessments of organizations have been identified in a scoping exercise by the German Environment Agency; and the latest versions of these papers have been subjected to a comparative methodological assessment. For ease of exposition, each publication has been assigned a short name; shown in bold (All weblinks last accessed May 2022).

a) **UBA Method Conv –** UBA (2019) Methodological Convention 3.0 and 3.1 (UBA 2020). Umweltbundesamt (UBA), Dessau-Roßlau, Germany. https://www.umweltbundesamt.de/en/publikationen/methodological-convention-30-for-the-assessment-of

b) **CE Delft** – CE Delft (2018): Environmental Prices Handbook EU 28 version

   https://cedelft.eu/publications/environmental-prices-handbook-eu28-version/

c) **LIME 3** (LCA Society of Japan) https://lca-forum.org/english/lime/

d) **GIST** https://www.gistimpact.com/quantifying-impacts

   Supporting document: Case study (in coperation with Truecost): Yara Valley Integrated Profit and Loss Report https://www.longfinance.net/programmes/sustainable-futures/london-accord/reports/yarra-valley-water-integrated-profit-and-loss-ipl-report/

e) **EPS** – Environmental Priority Strategies (EPS) https://www.ivl.se/english/ivl/our-offer/our-focus-areas/consumption-and-production/environmental-priority-strategies-eps.html

   Supporting documents:
   Steen, B. (2016): Calculation of Monetary Values of Environmental Impacts from Emissions and Resource Use. The Case of Using the EPS 2015d Impact Assessment Method. *Journal of Sustainable Development*; 9 (6); doi:10.5539/jsd.v9n6p15

   Steen, B. (2015): The EPS 2015d impact assessment method – an overview. Swedish Life Cycle Center, Report 2015:5. Department of Energy and Environment, Div. of Environmental Systems Analysis. Chalmers University of Technology, Gothenburg, Sweden. 6 pp.

   Steen, B, (1999a) A Systematic Approach to Environmental Priority Strategies in In Product Development (EPS). Version 2000 – General System Characteristics. Chalmers University of Technology, Centre for Environmental Assessment of Products and material Systems (CPM), Report 1999:4, Gothenburg, Sweden. 66 pp

   Steen, B, (1999b) A Systematic Approach to Environmental Priority Strategies in In Product Development (EPS). Version 2000 – Models and Data. Chalmers University of Technology, Centre for Environmental Assessment of Products and material Systems (CPM) Report 1999:5, Gothenburg, Sweden. 312 pp.

f) **PWC LCA** – PricewaterhouseCoopers LCA e.g., Forest products https://www.pwc.com/gx/en/forest-paper-packaging/pdf/fpac-lca-white-paper.pdf

g) **Harvard BS –** Harvard Business School – Impact Weighted Accounts

   https://www.hbs.edu/impact-weighted-accounts/Pages/default.aspx

   https://www.hbs.edu/impact-weighted-accounts/Documents/corporate-environmental-impact.pdf

h) **UNEP LCIA** United Nations Environment Program (UNEP) Life Cycle Initiative: Global Guidance for Life Cycle Impact Assessment Indicators Volume 1 and 2 https://www.lifecycleinitiative.org/applying-lca/lcia-cf/

i) **US IWG SCC –** US Government Interagency Working Group on Social Costs of Greenhouse Gases (2021): Technical Update of the Social Cost of Carbon, Methane and Nitrous Oxide. Interim Estimates under Executive Order 13990. Technical Support Document, Feb. 2021 https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

j) **OECD CBA** – OECD (2018): Cost-benefit analysis and the environment: further developments and policy use, OECD Publishing, Paris. https://www.oecd.org/governance/cost-benefit-analysis-and-the-environment-9789264085169-en.htm

k) **US EPA CBA** – US EPA (2014): Guidelines for preparing economic analysis. Washington, DC, US Environmental Protection Agency (EPA) , Office of Policy, National Center for Environmental Economics. https://www.epa.gov/environmental-economics/guidelines-preparing-economic-analyses

l) **UK CBA –** UK HM Treasury (2022): The Green Book. Appraisal and Evaluation in Central Government. London: TSO. Her Majesty's Treasury, London. 114 pp. Updated March 2022. https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent.

Valuation of Greenhouse Gas Emissions (2 September 2021) Valuation of greenhouse gas emissions: for policy appraisal and evaluation - GOV.UK (www.gov.uk)

Enabling a Nature Capital Approach (ENCA) (27 October 2021). Department for environment, food & rural affairs (Defra). Enabling a Natural Capital Approach - data.gov.uk

Additionally, the following three recent documents were identified, and considered relevant for this comparative analysis (All weblinks last accessed May 2022):

m) **EC Transport** – European Commission DG MOVE (2019): Handbook on the external costs of transport https://op.europa.eu/en/publication-detail/-/publication/9781f65f-8448-11ea-bf12-01aa75ed71a1

n) **EEA Industry Air –** European Environment Agency (2021): Costs of air pollution from European industrial facilities 2008–2017. Eionet Report – ETC/ATNI 2020/4. January 2021

https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-04-2020-costs-of-air-pollution-from-european-industrial-facilities-200820132017

o) **UK Defra Air** – UK Defra (2021a): Air quality appraisal: Damage costs appraisal (updated March 26 2021), Department for environment, food & rural affairs (Defra).

https://www.gov.uk/government/publications/assess-the-impact-of-air-quality/air-quality-appraisal-damage-cost-guidance

The above list of publications can be divided into three main categories:

- CBA manuals
- External costs reports with environmental unit costs
- LCA methodologies

3.2 CBA manuals

Items j), k) and l) belongs to the first category as these are CBA manuals for OECD, US and the UK, respectively. These CBA manuals (especially the two national ones) also contains quite detailed descriptions of environmental valuation tools, see e.g., Appendix 1 of the UK HM Treasury's (2022) Green Book, and the description of the UK Enabling a Nature Capital Approach (ENCA); see Defra (2021b)).

3.3 External cost reports with environmental unit costs

Items a), b), i), m), n) and o) all belong to the second category as they provide unit damage costs estimates for a large range of pollutants. However, item i) deals only with climate change and SCC estimates; and items n) and o) deal only with emissions to air (and o) only with local/regional air pollutants). While items a), b) and i) look at emissions from all sectors; items m) and n) look at emissions from specific sectors; transport (*EC Transport*) and industry (*EEA Industry Air*), respectively. External cost estimates for many pollutants are based on the impact pathway methodological approach (IPA; see figure 1), but the MAC approach is also used in terms of mitigation costs to reach national (or global) targets for some pollutant; especially for greenhouse gases.

3.4 LCA methodologies

The remaining items on the list belong to the third category. This include items c), d), e), f), g) and h), which are all different LCA methodologies (although many are based on EPS), applying weights to assess the contribution of different impact categories or the overall impact of the functional unit (usually a product) which is analyzed. Thus, these methodologies have primarily been developed to support the sustainability reporting of companies, rather than CBAs and regulatory impact analyses at the national or international level. LCA methodologies assess impacts over the life cycle of the product (cradle-to-grave or cradle-to-cradle), and thus usually have a broader scope than CBA manuals and External cost reports.

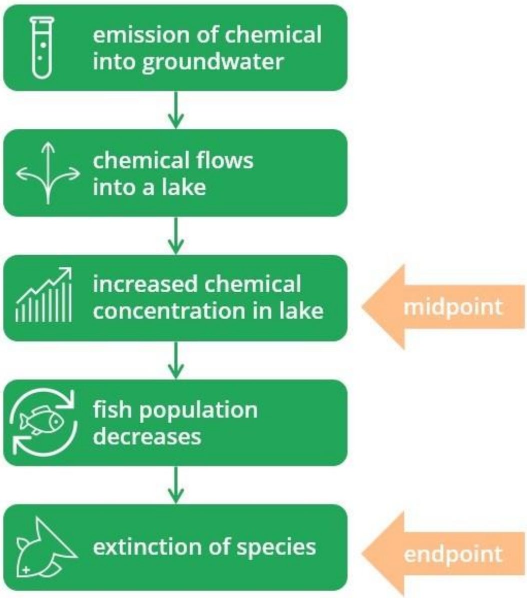
The impact assessment part of LCA, termed Life Cycle Impact Assessment (LCIA), is illustrated in figure 3. According to Golsteijn (2014), LCIA consists of four steps:**"1. Classification**. All substances are sorted into classes according to the effect they have on the environment. A cause-effect pathway shows the causal relationship between the environmental intervention (for instance, the emission of a certain chemical) and its potential effects. LCA professionals can choose impact indicators at different stages in this pathway, for example, the midpoint or endpoint [shown in figure 3] [...]. **2. Characterization.** All substances are multiplied by a factor that reflects their relative contribution to the environmental impact, quantifying how much impact a product or service has in each impact category.[7][...] **3. Normalization.** The quantified impact is compared to a certain reference value, for example, the average environmental impact of a European citizen in one year.[8] **4. Weighting.** Impact categories are assigned an importance value, and the resulting figures are used to generate a single score." (Golsteijn 2014, para 3). This last step is optional and also the step where most LCA methodologies deviate from economic welfare theory as the weighting is usually not based on individual preferences, but on expert judgement. A notable exception is EPS, which have strived to monetize environmental

[7] An example of a characterization factor is the Global Warming Potential (GWP) for greenhouse gases, which for e.g., methane is 22 kg. CO2-eq./kg. "For a small number of impact categories, such ready-made characterization factors from authoritative bodies are available [...] For many impact categories, however, characterization factors are not directly available. In these cases, they must be constructed from models, either existing or self-constructed" (Heijungs et al. 2004, 16).

[8] See, e.g., Sala et al 2017 for further information.

and health impacts based on benefit transfer from SP and RP methods in sustainability accounting exercise (Brandt 2016).

Figure 3: Cause-effect pathway in Life Cycle Impact Assessment (LCIA). An Example. LCA impact indicators can be chosen at midpoint level (pollutant concentration) or at the endpoint/impact level.



Source: https://pre-sustainability.com/articles/consider-your-audience-when-doing-lca/

In terms of sources of data and approaches, there are also lessons to be learned for CBA from LCA. This includes the aggregation into categories of impacts through their process of characterization for e.g., eutrophication and acidification. The substance-specific characterization factors combine environmental fate, exposure and effects into one quantitative measure like kg SO_2-equivalents /year for acidification.

The LCA methodologies are compared and assessed with regards to what extent they adhere to the welfare theoretic foundation of CBA (which is based on citizens' preferences; and not the preferences of scientific experts or politicians often used for weighting categories of impacts in the last stage of the LCIA, and whether they apply the IPA approach Among these six approaches (*LIME 3, GIST, EPS, PWC LCA, Harvard BS and UNEP LCIA*), only EPS and *UNEP LCIA* apply an IPA-like assessment framework where the weighting takes place at the endpoint/impact stage (and not at the midpoint/concentration stage). Weighting is increasingly performed in monetary units in many LCA approaches, especially in EPS, GIST and LIME3, but not always at the endpoint stage.

Interestingly, within the External Cost reports rooted in LCA frameworks there seems to be a shift over time from environmental prices based on marginal abatement costs to reach specified national environmental targets, towards the use of IPA and damage costs based on SP and RP approaches (often restoration cost approaches). This is the case for e.g., the CE Delft Handbook of Environmental Prices when the 2010 version was updated in 2019 (which is the version evaluated here).

4 Comparative methodological analysis

For each publication, the system boundaries, social discount rates (SDR), equity weighting schemes and uncertainty assessments (e.g., point estimates versus ranges; catastrophic risk considerations) have been reviewed, and will be compared here for each group of pollutants and environmental aspects; to the extent these issues are reported in the documents. Each publication is assessed in terms of the approach used: Impact Pathway Approach (IPA), Marginal Abatement Cost (MAC), LCA weighting with monetization, and LCA weighting with other metrics. Chapters 4.1- 4.6 and respective tables 2-7 provide the comparative analysis for each of the six groups of pollutants. In tables 2-7, **"X"** means the listed approach is applied. "**X-**" means the approach is incompletely applied. **"(X)"** means the approach is discussed but not recommended. "**nc**" (i.e., not covered) means the publication does not specifically cover the pollutant(s) in question.

4.1 Greenhouse gases (GHG)

Table 2 reviews the methodology used to value greenhouse gas emissions (GHG). In all source lists, unit values for emissions of different GHGs are converted to, and expressed in terms of, CO_2- equivalents using Global Warming Potential (GWP) weights. How the CO_2- equivalents are valued do, however, vary between the different publications. So does the treatment of uncertainty, and overall the publications mention catastrophic risk but do not account explicitly for this in the recommended unit damage costs based on SCC. The ability of CBA to handle catastrophic risks is also questioned; see e.g., OECD (2018, Ch. 14.4). The difficulty in accounting for catastrophic risks in IAMs and the resulting SCC estimates is also used as an explanation in some publications (e.g., *EC Transport*) for moving from estimates based on IPA and SCC to using the MAC approach and the mitigation costs of avoiding a rise in global mean temperature above + 1.5 – 2.0 C which is believed to avoid catastrophic risks (according to the Paris agreement). Other explanations for using the MAC approach are: i) to have a "target-consistent approach" nationally or globally, and ii) the large uncertainties in several parts of the theoretically correct IPA approach of IAMs (see e.g., *UK CBA*).

Table 2: Methodological comparison: Greenhouse gases (GHG)

Source/ Publication	Damage Function – Impact Pathway Approach (IPA)	Marginal Abatement Cost (MAC)	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UBA Method Conv	**X** IAM (FUND 3.0), SCC as present value of global damage costs over T=100 years, equity weighting, sensitivity analysis with SDR = 0 %.			
CE Delft	**X** **Lower** value, simplified damage function approach, median SCC from Monte Carlo simulation, T=100 years and a range of SDRs, no equity weighting. 37 €/t CO_2 in 2030	**X** **Central and Upper** values based on abatement costs of current policy plans and reaching		

Source/ Publication	Damage Function – Impact Pathway Approach (IPA)	Marginal Abatement Cost (MAC)	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
		+2C target, respectively 95 and 160 €/t CO_2 in 2030		
LIME 3			**X** Monetization of categories of damages from CC i.e., selected human health impacts (using DALY), biodiversity (increasing number of extinct species; vascular plants);	**X** Weighting of damage categories based on national citizen SP surveys in all G20 countries and 11 emerging countries.
GIST	**X** SCC valuation based on US Interagency Working Group on the Social Cost of Carbon. 95th percentile values, SDR= 3%, no equity weighting, point estimate			
EPS	**X** Apply IPA to a wide range of impacts identified by IPCC 5th Assessment Report. Value impacts on health (using YOLL= 50.000 euro; based only on productivity loss and DALYs. Values for different illnesses from ExternE/NEEDS EU-project). Agricultural product, wood, fish, irrigation and drinking water are valued by market prices. Migration of people (valued at AC/Defensive costs) and habitat loss (in terms of share of all red-listed species threatened and assigned an impact in CO_2-equivalents), T=100 years, SDR = 3 %. A set of uncertainty factors applied to all valued impacts.	**X** MAC approach for biodiversity impacts of CC; valued as financial costs of meeting Global Biodiversity conservation targets		
PWC LCA				**X** GWP and Carbon footprint tool for aggregating life

Source/ Publication	Damage Function – Impact Pathway Approach (IPA)	Marginal Abatement Cost (MAC)	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
				cycle carbon emissions. No weighting with other emission categories.
Harvard BS	**X** Refer to and use same approach as EPS (SCC, SDR= 3 %, T = 100 years)			
UNEP LCIA	**X -** Apply IPA-like approach, but no monetization of CO_2-equivalents			**X** Focus on characterization factors. Use GWP for GHG to estimate kg of CO_2-equivalents
US IWG SCC	**X** SCC from running 3 IAMs (DICE, PAGE, FUND). Range of SCCs presented based on SDR= 2.5, 3 and 5 % (but note that there is new evidence for lower SDR). Unit values for CO_2, CH4, N_2O for 2020-2050. Uncertainty addressed by Monte Carlo simulations providing frequency distributions of SCC. Climate risk, environmental justice, and intergenerational equity to be adequately addressed in revision later in 2022.			
OECD CBA	**X** SCC from review of IAMs (Ch. 14) Range of SCCs presented based on different scenarios for SDR, uncertainty and discuss catastrophic risks. Equity weighting and other guiding principles for distributional analysis presented (Ch. 11.4)	**(X)** Discuss costs of reaching domestic emission targets, trading goals, to traded carbon emission (EU ETS) and non-traded.		**(X)** Expert assessment of SCC discussed
US EPA CBA	**X** Refers to recommended set of values from US IWG SCC			

Source/ Publication	Damage Function – Impact Pathway Approach (IPA)	Marginal Abatement Cost (MAC)	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UK CBA		**X** MAC to achieve UK targets; IPCC Climate Model for + 1.5 C target by 2100. Carbon prices for 2020-2100 per ton CO_2-equivalent. Uncertainty range: +/-50 %		
EC Transport		**X** MAC to avoid more than + 1.5-2.0 C. Low, central and high estimates		
EEA Industry Air		**X** Same MAC-approach as EC Transport		
UK Defra Air	**nc**			

Source: authors' compilation

4.2 Local/regional air pollutants

Particulate matter PM_{10} (including $PM_{2.5}$), NO_X, SO_2, NH_3, and NMVOC are local and regional air pollutants, as opposed to the global greenhouse gases considered above. Table 3 reviews the methodologies used to value these local and regional air pollutants. These air pollutants cause health impacts (both premature deaths/mortality and morbidity), which is the focus of most publications, but some also cover impacts on crops (e.g., crop loss due to ozone production caused by NOx and VOC emissions), material and buildings (from soiling and corrosion) and ecosystems/biodiversity (from acidification and eutrophication leading to decreased biodiversity). For valuation of health impacts, mortality impacts are often valued both in terms of VSL (Value of Statistical Life) and in terms of VOLY (Value of a Life Year) combined with YOLL (Years of Life Lost) estimates (as upper and lower estimates, respectively). Morbidity impacts are valued either by unit costs per case of different illnesses and per symptom day of lighter respiratory illnesses; or by using illness specific estimates of Quality Adjusted Life Years (QALYs) or Disutility Adjusted Life Years (DALYs; from the Global Burden of Disease (GBD)[9]) for living with the illness combined with VOLY estimates.

[9] For Global Burden of Disease (GBD); see https://www.healthdata.org/gbd/about , and for GBD data for 2019 https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)30925-9/fulltext

Table 3: Methodological comparison: Local and Regional air pollutants. PM10 (includes PM2.5 and PMcoarse), NOX, SO2, NH3, and NMVOC.

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UBA MethodConv	**X** Average environmental costs per ton of emission from IPA. Covers all pollutants. Covers health damage (VOLY for mortality; morbidity values per illness episode), biodiversity loss, crop damage (market prices) and material damages. Average rates for Germany, but also differentiated rates for different emissions sources (higher values for lower emission sources in areas with higher population density; especially for PM)			
CE Delft	**X** Average damage costs per kg of emissions for each of all these five air pollutants. Lower, central and upper estimates. Lower and upper (range) recommended for CBA; Central estimate for Sustainability reporting at firm level. Covers health damage costs, but for PM_{10} also damages to buildings (valued as restoration costs). Average EU-28 damage costs per kg of pollutant. SDR = 0 % p.a.			
LIME 3			**X** Air pollution impacts considered as one group of pollutants.	

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
			Chronic death, acute death and respiratory illnesses covered in DALY. Valued by VOLY. Estimate for Germany.	
GIST	**X-** Covers SOx, NOx and PM. Methodology not publicly available but seems to be based on an IPA-type approach			
EPS			**X-** All air pollutants covered. Top-down approach, with weighting based on WTP for protecting the safeguard of subjects (e.g. human health, biodiv.) among OECD inhabitants. Human health impacts; DALY valued as loss of economic productivity. Biodiversity impacts valued as prevention costs of extinction of species (based on the risk of becoming red listed). Valued in ELU (Environmental load units), where 1 ELU is equal to 1 €	

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
			under specific conditions. SDR = 0 % p.a. Use a log-normal distribution to derive a factor of 3 to account for uncertainty.	
PWC LCA			**X** EPS methodology used for air pollutants (see above).	
Harvard BS			**X** EPS methodology used for air pollutants (see above).	
UNEP LCIA			**X-** Covers all pollutants, except NMVOC. Impacts only on human health. Calculated in DALY (w/wo age weighting and w/wo discounting, summing up YOLL and YLD).	
US IWG SCC	**nc**			
OECD CBA	**nc** Recommends IPA			
US EPA CBA	**nc** Recommends IPA			
UK CBA	**nc** Recommends IPA			
EC Transport	**X**			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
	Covers all air pollutants. Covers emissions from transport only, but all transport modes. Emission factors in tons per vehicle-km as basis for IPA (based on updating results from EU-project NEEDS with new valuation estimates etc.). Total, average and marginal unit damage costs for EU-28, and individual countries (incl. Germany) for road transport. Unit value transfer with income adjustment.Differentiated on vehicle characteristics (e.g. fuel type, size class, etc.) and traffic situation (type of road, day/night, thin/dense traffic, etc.). Covers aviation emissions at selected airports (Munich, Frankfurt **a. M.**), and maritime transport emissions at selected freight ports (Hamburg, Bremerhaven) & ferry ports (Travemünde). Recommends use of upper and lower estimates (not central estimates) for CBA.			
EEA **Industry Air**	**X** Covers all air pollutants. Covers EEA38 + UK. EU average and national (incl. Germany) marginal unit damage costs per ton of pollutant based on IPA. Covers only industrial facilities. Separate numbers for damage costs occurring in the			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
	emission country and the rest of EEA38+UK. "Low" and "High" estimates based on VOLY and VSL, resp. Sectoral adjustment factors for each country based on the SHERPA air dispersion model for PM2.5 and NO_2. Covers mainly health impacts but also impacts on crops and forests (ozone), building materials (SO_2, NO_x) ecosystems (eutrophication from NH_3 and NOx, critical load exceedance Natura 2000 areas only). SDR = 3% p.a.			
UK Defra Air	**X** Covers all air pollutants. National (UK) average damage costs based on IPA**.** Diversified unit damage costs from large industrial plants For NOx and $PM_{2.5}$ ($PM_{2.5}$ calculated from PM_{10}): 9 categories with unit costs estimates depending on average population density and height of smokestack. UK emission factors for road traffic. Relative increase in damage costs 2 % p.a. SDR = 3.5 % p.a. High and low unit damage costs for sensitivity analysis.			

Source: Authors' compilation

4.3 Eutrophication (Nitrogen and Phosphorous)

Table 4 reviews the methodologies used to value eutrophication impacts. This topic covers eutrophication effects by nitrogen (N) and phosphorous (P) emissions to aquatic (i.e., lakes and rivers) and marine ecosystems (coast and ocean). As most of the external cost reports reviewed here concentrate on emissions to air, eutrophication from NOx emissions is usually what is covered. Some of the LCA reports also cover emissions to water bodies, and aggregate P and N emissions in eutrophication equivalents. As eutrophication impacts is dependent on the local environmental state of the affected water bodies, external cost assessments would benefit good local biophysical data as well as carefully conducted benefit transfer from national or Europe-wide Stated Preference studies covering both use and non-use values of water quality changes caused by eutrophication (see e.g. Bateman et al. (2011)). *UK CBA* in their Greenbook (UK HM Treasury 2022) refers to their ENCA Services and Assets Databook (UK Defra 2021b) where they combine biophysical data with benefit transfer to construct eutrophication unit cost lists which can be used to derive site-specific estimates of damage costs from eutrophication.

Table 4: Methodological comparison: Eutrophication

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UBA MethodConv	**n.c.** Recommends IPA			
CE Delft	**X** Total N, total P and phosphate emissions to freshwater, unit damage costs as euro per kg/pollutant. Average value for EU28. Lower and upper estimates for CBA.	**X** Impacts of N on marine ecosystems (excessive algal growth) based on Dutch water pollution charge (set to reach a policy target); average EU28 value		
LIME 3			**n.c.**	
GIST	**(X)**	**X** Eutrophication assessed in terms of Biological Oxygen Demand (BOD) and Suspended Solids (SS). Valued using the greywater	**X**	

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
		footprint approach, i.e. calculating the amount of freshwater required to dilute BOD and SS back to safe levels, i.e. treatment costs /MAC	Human health impacts from nitrate in drinking water estimated in YLL and country-specific VOLY. Recreational and amenity loss from eutrophication valued as property value loss (Hedonic Price method)	
EPS	**(X)**		**X** Impacts from eutrophication (in phosphate (PO4) -equiv.); impacts on fish production valued at market prices	
PWC LCA				**X** EPS methodology used for eutrophication (Stated in phosphate (PO4) -equiv.; but not monetized)
Harvard BS				**X** EPS methodology used for eutrophication, (but not monetized)

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UNEP LCIA	**(X)** Discuss midpoint level in IPA (level eutrophication emission), and endpoint (ecosystem/biodiversity impact in PDF). No monetization.			**X** Freshwater eutrophication emission in phosphorous equivalents (Peq) and damages in PDF/m^3/year and effects of total P on primary production invertebrates and fish. Marine eutrophication emissions in Neq, and damages to benthic ecosystems in PDF/m^3/year
US IWG SCC	**nc** Recommends IPA			
OECD CBA	**nc** Recommends IPA			
US EPA CBA	**nc** Recommends IPA			
UK CBA	**X** Refers to Defra's ENCA Services Databook which provides unit values per kg of nitrates and per kg of phosphates in water based on benefit transfer			
EC Transport	**X** Eutrophication (NO_x from air pollution) impacts valued indirectly in terms of causing biodiversity loss, valued as PDFs (cf. *EC Transport,* table 4)			
EEA	**X**			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
Industry Air	Marginal unit damage costs of NH_3 and NO_x emissions to air include ecosystem impacts from eutrophication.			
UK Defra Air	**nc** Recommends IPA			

Source: Authors' compilation

4.4 Other water and soil pollutants

This group of pollutants here includes acidification of river, lakes and soils (caused primarily by sulphur and nitrogen depositions), heavy metals, toxins, radionuclides, and chemicals to the extent they are included in the list of publication of unit values considered here. Table 5 reviews the methodologies applied. LCA manuals typically aggregate emissions leading to acidification of water and soils in terms of kg SO_2-equivalents/year using characterisation factors, but usually do not assess nor monetize the impacts of the emissions. Most externality reports with environmental unit costs lists and CBA manuals do not cover these other water and soil pollutants. The exception being acidification, which is covered in some reports that assess the environmental impacts of atmospheric depositions of SO_2 and NO_x (but often only health impacts of these local/regional air pollutants are covered) LCA methodologies cover heavy metals, toxins and chemicals; and two of the external costs reports with environmental unit cost lists, *CE Delft* and *EEA Industry Air*, utilize this and attempt to monetize the impacts using an LCA weighting technique and IPA, respectively. However, the very large number of different substances in this group and the lack of data and knowledge in many steps of IPA for most of these pollutants limits the number of substances it is possible to cover with the welfare theoretic consistent IPA.

Table 5: Methodological comparison: Other water and soil pollutants

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UBA MethodConv	**n.c.** IPA recommended			
CE Delft	**X** Ionizing radiation:		**X**	

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
	EU-28 average unit damage costs (euro per kBq U235-equivalent for 14 radionuclides and unspecified radioactive aerosols. COI for non-fatal cancer; COI and DALYs lost for fatal cancer valued with VOLY (high and low estimate). Data from NEEDS project.		CFC, Cd, As, Hg, Pb and dioxins: Characterization factors from the ReCiPe method (Huijbregts et al. 2017). "Human-toxicological effect factors were derived for carcinogenic and non-carcinogenic effects separately, reflecting the change in lifetime disease incidence due to a change in intake of the substance" (Huijbregts et al. 2017, 142).	
LIME 3			**X** Health impacts (DALY) from waterborne infectious diseases, valued by VOLY (Acidification not considered)	
GIST			**X** Organic and inorganic pollutants, and heavy metals. Environmental impacts valued using Ecosystem service values (Int $/ha/year) from ESVD. Health impacts valued using DALY (continent-specific for inorganic and	

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
			heavy metal; country-specific for organic pollutants). Valued w/country specific VOLY.	
EPS	**(X)**		**X** Acidification monetized as damage costs to fish and meat (using market prices)	
PWC LCA				**X** Acidification, stated in kg SO_2-equiv/year, but not monetized
Harvard BS				**X** Acidification, stated in kg SO_2-equiv/year, but not monetized
UNEP LCIA	**X-** Apply IPA-like approach, but no monetization			**X** Ecotoxicological effects of chemicals and heavy metals in coastal seawater, freshwater sediment and soil assessed with PAF (potentially affected fraction) of species, and link to PDF.
US IWG SCC	**n.c.**			
OECD CBA	**n.c.** Recommends IPA			
US EPA CBA	**n.c.** Recommends IPA			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UK CBA	**X** Acidification damages; refers to Defra's ENCA Services Databook which provides unit values per kg of sulphate based on benefit transfer			
EC Transport	**X** Acidification damage costs from SO_2 and NO_x to materials (valued as increased maintenance costs) and biodiversity (valued as PDFs; see *EC Transport* table 4)			
EEA **Industry Air**	**X** Marginal damage costs; selected health impacts, for heavy metals: arsenic, cadmium, chromium VI, lead, mercury, nickel, organic pollutants: 1,3 butadiene, benzene, formaldehyde, benzo(a)pyrene, dioxins and furans. "Low" and "High" estimates based on VOLY and VSL, resp.			
UK Defra Air	**n.c.** Recommends IPA			

Source: Authors' compilation

4.5 Traffic noise

LCA methodologies tend not to cover traffic noise whereas the externality handbooks do, and of course especially those specialized in transport like "EC Transport". Table 6 reviews the methodologies used to assess traffic noise. Traffic noise causes disutility and health impacts in terms of: i) medical costs of treating health impacts (both private and public), ii) productivity loss, and iii) annoyance (nuisance) of being exposed. Cost of Illness (COI) estimates usually would cover the first two categories. Category iii), however, need to be elicited in SP surveys (CE or CV), Hedonic Price (HP) surveys (where the Noise Sensitivity Depreciation Index (NSDI) tells the percentage reduction in house prices per dBA increase in noise level (above 50 dbA); or, more recently, using disability weights to calculate DALYs and multiply with VOLY. All these approaches apply IPA, but SP surveys adhere closest to this approach as NSDI derived from HP surveys might capture also other externalities from transport than just noise (e.g. visual amenity losses, barrier effects, dust/air pollution etc.) and DALYs for noise are still little researched and uncertain. For noise annoyance there is a movement away from using NSDI from HP studies to using DALY (e.g., the *UK CBA*) or benefit transfer from SP studies (e.g., *CE Delft* and *EC Transport*).

Table 6: Methodological comparison: Traffic noise

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UBA MethodConv	**X** Unit damage costs euro/person/year for different dBA classes (based on L_{DEN} values; average noise level for day, evening night); separate for rail, road and air; combined with assessment of number of people affected. Annoyance costs (including self-reported sleep disturbance) dominate, but physical health and cognitive/mental health also valued. (mileage - related noise costs not calculated as reduced mileage does not necessary mean reduced noise pollution)			
CE Delft	**X**			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
	Unit damage costs separately for rail, road and aircraft noise. Valued in the same way as in **EC Transport**, see below (SP survey meta analysis for noise annoyance, and disutility and medical expenses for health costs)			
LIME 3			**n.c.**	
GIST			**n.c.**	
EPS			**n.c.**	
PWC LCA			**n.c.**	
Harvard BS			**n.c.**	
UNEP LCIA	**(X)**		**n.c.**	
US IWG SCC	**n.c.**			
OECD CBA	**n.c.** Recommends IPA			
US EPA CBA	**n.c.** Recommends IPA			
UK CBA	**X** Road, rail, aircraft noise. Refers to Defra's ENCA Services Databook for Noise; which provides central marginal values per dBA/ household /year from 45 dbA for amenity (annoyance) and health impacts (with and without sleep disturbance); health impacts in DALY valued at VOLY = 60,000 £; UK study. Increasing marginal values to 65 dbA, and then constant value per dBA. Separate values for Day and Night. Increase in			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
	relative prices/unit values (above inflation) = 2 % p.a..SDR= 3,5 % p.a.			
EC Transport	**X** Road, rail, aircraft noise. Health costs and annoyance costs valued separately. Annoyance unit cost in euro/ person /year/ db (above 50 dBA) based on meta-analysis of SP surveys (Bristow et al. 2015). Health costs based on Defra (2014), using an IPA approach, capturing both disutility and medical expenses; productivity loss not included. Average environmental noise costs (defined as annoyance and health) in euro/ person /year/ db (above 50 dBA) for EU28; separately for road, rail and air; for road differentiated by vehicle type, time of the day, traffic situation and area type/ population density)			
EEA **Industry Air**	**n.c.**			
UK Defra Air	**n.c.**			

Source: Authors‘ compilation

4.6 Land use changes affecting biodiversity and ecosystem services

LCAs were originally developed to assess emissions of pollutants, and land area was assessed in terms of just the size of land area influenced by the activities, and not the impacts on biodiversity or ecosystem services. However, some of LCA methodologies assessed here have used the Potentially Disappeared Fraction (PDF) of species as an indicator of species richness, which measures the change in species diversity and is integrated over a certain time and area. This characterization factor (CF) is usually not carried over to economic valuation. However, in some external cost publications (e.g., *CE Delft* and *EC Transport*) PDF are valued in monetary terms using a restoration cost approach, i.e. the costs of restoring lost habitat so they can support the lost species. Still, most LCAs reviewed here do not assess effects of land use change on biodiversity, but rather assess the ecotoxicological effects from emissions of chemicals and heavy metals in terms of PDF or PAF (see chapter 4.4)

In other external cost reports and the CBA manuals, IPA and benefit transfer /value transfer are recommended for valuation of biodiversity and ecosystem services. The UK CBA manual "Green Book" (UK HM Treasury 2022) is the most comprehensive one in this regard with its reference to UK Defra (2021b). This publication describes the ENCA (Enabling a Natural Capital Approach) guidelines with benefit transfer methodology, lists of suggested unit values for different habitats and ecosystem services (with low and high values reflecting varying values of the same environmental goods at different locations rather than uncertainty in the IPA), a list of case studies using ENCA, and an excel template for undertaking ENCA in accordance with the "Green Book" guidance. The ENCA Services and Assets Databooks together cover around 400 UK data sources, tools and studies for 8 natural habitat categories, and 25 environmental effect categories. In the UK, the LEEP (Land, Environment, Economics and Policy) Institute at the University of Exeter, with support from Defra, has also developed the map-based online tool *Orval* (Outdoor Recreation Valuation tool; see https://www.leep.exeter.ac.uk/orval/) for assessment of recreational values in greenspaces in England and Wales; and *NEVO* (Natural Environment Valuation Online tool; see https://www.exeter.ac.uk/research/leep/research/nevo/) for assessing the economic value of impacts from land use changes on a range of ecosystem services: agricultural production, woodlands and timber production, greenhouse gas emissions, recreation, biodiversity, water quantity and water quality. Both the *ORVAL* and the *NEVO* tools produce spatially explicit values for ecosystem services based on IPA, biophysical data and valuation using benefit transfer of estimates from previous UK SP and RP valuation studies as well as use market prices for e.g., agricultural and timber production, and for restoration and replacement costs estimates.

Table 7: Methodological comparison: Land use changes affecting biodiversity and ecosystem services

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UBA MethodConv	**X** Replacement cost approach used. Habitat loss valued at the costs of restoring lost biotype or ecosystem areas. Based on INFRSA en Ecoinvest (2019).			
CE Delft	**X**			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
	Restoration costs approach used to value PDF. Based on INFRAS en Ecoplan (2019).			
LIME 3				**X** Effects on terrestrial ecosystems/vascular plants; in NPP
GIST			**X** Change in Net primary Production (NPP) for terrestrial ecosystem services; valued based on unit values per ha of biomes from De Groot et al. (2012). Refers to Ecosystem Service Valuation Database (ESVD) www.esvd.net	
EPS	**(X)**	**X** Total value of biodiversity estimated by McCarthy et al. (2012) as total financial costs of meeting global biodiversity conservation targets to be 56 billion €/year.State indicator for biodiversity is "NEX" (normalized extinction of		

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
		species); measured as share of all red-listed species. If 1% of all red-listed species are threatened by a certain land use type, NEX is 0.01 (McCarthy et al. 2012).		
PWC LCA			**n.c.**	
Harvard BS			**n.c.**	
UNEP LCIA			**n.c.**	
US IWG SCC	**X-** Addressed indirectly in SCC estimate; partly based on IAM FUND model that also covers impacts on biodiversity from increased global mean temperature by global unit value benefit transfer of WTP from SP studies			
OECD CBA	**X** Monetary values for each biome for each service (list of provisioning, regulating, cultural and habitat services (i.e., nursery services and genetic diversity); (in International $/ha/year, tab. 13.3), revised from de Groot et al. (2012).			
US EPA CBA	**n.c.** Recommends IPA			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
UK CBA	**X** Refers to Defra's ENCA Services Databook which provides UK biophysical and valuation data sources for benefit transfer of provisioning and abiotic, regulating and cultural ecosystem services, bundled services and negative environmental impacts of 8 habitat types: i) Enclosed farmlands, ii) Urban natural capital, iii) Mountains, moor and heath, iv) Freshwater, v) Woodlands, vi) Coastal Margins, vii) Marine, and viii) Semi-natural grasslands			
EC Transport	**X** CRF for NO_x, taken from the NEEDS project. Habitat damage assessed using the Potentially Disappearing Fraction (PDF) approach; and valued at restoration costs of lost land area (lower estimate) and WTP to avoid biodiversity loss (lower estimate). Annual relative increase in price of nature / biodiversity: 1 % p.a.	**X** Restoration costs approach used to value PDF		
EEA Industry Air	**n.c.** IPA recommended, but ecosystem impacts considered			

Source/Publication	Damage Function - Impact Pathway Approach (IPA)	Marginal Abatement Cost	LCA Weighting; Monetisation	LCA Weighting; Other metrics than money
	too uncertain to be included.			
UK Defra Air	**X** Environmental impact value in £/ton of pollutant for NO_2, NH_3 and SO_2; and £/ unit of ozone. Impacts on agricultural production (market price), and recreational fishing biodiversity (benefit transfer for SP studies); based on Jones et al. (2014)			

Source: Authors‘ compilation

5 References

Amadei, A.M., V. De Laurentiis and S. Sala (2021): A review of monetary valuation in life cycle assessment: State of the art and future needs. *Journal of Cleaner Production*, Volume 329, 20 December 2021, 129668. https://doi.org/10.1016/j.jclepro.2021.129668.

Arendt, R, T.M. Bachmann,M. Motoshita, V. Bach, and M. Finkbeiner (2020): Comparison of different monetization methods in LCA: A review. *Sustainability*, 12 (24),10493; https://doi.org/10.3390/su122410493

Bateman, I. J., R. Brouwer, S. Ferrini, M. Schaafsma, D.N. Barton, A. Dubgaard, B. Hasler, S. Hime, I. Liekens, S. Navrud, L. De Nocker, R. Sceponaviciute, and D. Semeniene. (2011): Making Benefit Transfers Work: Deriving and Testing Principles for Value Transfers for Similar and Dissimilar Sites Using a Case Study of the Non-Market Benefits of Water Quality Improvements Across Europe. *Environmental and Resource Economics* 50 (3);365-387. https://doi.org/10.1007/s10640-011-9476-8.

Bickel, P. and R. Friedrich [eds.] (2005): ExternE Externalities of Energy Methodology 2005 Update, European Commission DG for Research Sustainable Energy Systems. Report EUR 21951 EN, Office for Official Publications of the European Communities, Luxembourg. https://op.europa.eu/en/publication-detail/-/publication/b2b86b52-4f18-4b4e-a134-b1c81ad8a1b2.

Bristow, A. L., Wardman, M. & Chintakayala, V. P. K., (2015): International meta-analysis of stated preference studies of transportation noise nuisance. *Transportation,* 42(1), pp. 71-100. https://doi.org/10.1007/s11116-014-9527-4.

Boardman, A.E, D.H Greenberg, A.R. Vining & D.L. Weimer (2018): *Cost-Benefit Analysis. Concepts and Practice*. (5th ed.). Cambridge University Press*;* Cambridge, UK and New York, USA. https://doi.org/10.1017/9781108235594

De Groot, R., L. Brander, S. van der Ploeg, R. Costanza, F. Bernard, L. Braat, M. Christie, N. Crossman, A. Ghermandi, L. Hein, S. Hussain, P. Kumar, A. McVittie, R. Portela, L. C. Rodriguez, P. ten Brink, and P. van Beukering (2012): Global estimates of the value of ecosystems and their services in monetary units. *Ecosystem Services*, 1 (1); 50-61. https://doi.org/10.1016/j.ecoser.2012.07.005.

Desaigues, B., D. Ami, A. Bartczak, M. Braun-Kohlová, S. Chilton, M. Czajkowski, V. Farreras, A. Hunt, M. Hutchison, C. Jeanrenaud, P. Kaderjak, V. MácA, O. Markiewicz, A. Markowska, H. Metcalf, S. Navrud, J. S. Nielsen, R. Ortiz, S. Pellegrini, A. Rabl, R. Riera, M. Scasny, M. E. Stoeckel, R. Szántó, and J. Urban (2011): Economic valuation of air pollutants: A 9-country contingent valuation survey of value of a life year (VOLY). *Ecological Indicators* 11 (3); 902-910. https://doi.org/10.1016/j.ecolind.2010.12.006.

INFRAS and Ecoplan (2018): External Effects of Transport 2015 in Switzerland ('Externe Effekte des Verkehrs 2015'). Update study of the calculations of environment, accident and health costs of road, rail, air and water transport 2010-2015, Bern: Swiss Federal Office for Spatial Development. https://www.infras.ch/media/filer_public/a6/24/a624c88d-581c-4554-a102-dcefef85b1bd/externe_effekte_verkehr_aktualisierung_2015_schlussbericht.pdf

Field, B.C. and M.K. Field (2020): Environmental Economics. An Introduction. 8. edition McGraw-Hill, New York.

Golsteijn, L. (2014): Characterization: new developments for toxicity. https://pre-sustainability.com/articles/characterisation-new-developments-for-toxicity/

Heijungs, R., A. de Koning, T. Ligthart and R. Korenromp (2004): Improvement of LCA characterization factors and LCA practice for metals, TNO-report R 2004/347. https://web.universiteitleiden.nl/cml/ssp/projects/finalreportmetals.pdf.

Huijbregts, M.A.J., Z. J.N. Steinmann, P.M.F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander and R. an Zelm (2017). ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. *International Journal of LCA* 22; 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Jones, L., G. Mills,.and A. Milne. (2014): Assessment of the Impacts of Air Pollution on Ecosystem Services – Gap Filling and Research Recommendations (Defra Project AQ0827) Final Report July 2014. https://uk-air.defra.gov.uk/assets/documents/reports/cat10/1511251140_AQ0827_Asessment_of_the_impacts_of_air_pollution_on_Ecosystem_Services_Final_report.pdf (4 July 2022)

Johnston, R. J., K.J. Boyle, W. Adamowicz, J. Bennett, R. Brouwer, T.A. Cameron, W.M. Hanemann, H. Hanley, M. Ryan, R. Scarpa, R. Tourangeau, and C.A. Vossler (2017): Contemporary Guidance for Stated Preference Studies. *Journal of the Association of Environmental and Resource Economists* 4 (2); 319-405. https://doi.org/10.1086/691697.

Johnston, R.J., K.J. Boyle, M.L. Loureiro, S. Navrud and J. Rolfe (2021): Guidance to Enhance the Validity and Credibility of Environmental Benefit Transfers. *Environmental and Resource Economics* 79 (3); 575-624. https://doi.org/10.1007/s10640-021-00574-w.

Lindhjem, H., S. Navrud, N.A. Braathen, and V. Biausque (2011): Valuing lives saved from environment, transport and health policies. A meta-analysis. *Risk Analysis* 31 (9); 1381-1407. https://doi.org/10.1111/j.1539-6924.2011.01694.x.

Lindhjem, H. and S. Navrud (2015): Reliability of Meta-analytic Benefit Transfers of International Value of Statistical Life Estimates: Tests and Illustrations. In: R. Johnston, J. Rolfe, R. Rosenberger and R. Brouwer (eds.) 2015: Benefit Transfer of Environmental and Resource Values: A Handbook for Researchers and Practitioners. Springer Science+Business Media, Dordrecht, The Netherlands; 441-464. https://doi.org/10.1007/978-94-017-9930-0_19.

McCarthy, D., P. Donald, J. Scharlemann, G. Buchanan, A. Balmford, J. Green, L. Bennun, and S. Butchart (2012): Financial Costs of Meeting Global Biodiversity Conservation Targets: Current Spending and Unmet Needs. *Science* 338(6109), 946-949. https://doi.org/10.1126/science.1229803

Navrud, S. 2004: Value transfer and environmental policy. In: T. Tietenberg and H. Folmer (eds.): The International Yearbook of Environmental and Resource Economics 2004/2005. A survey of Current Issues. Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA; 189-217

Nieuwlaar, E (2004): Life Cycle Assessment and Energy Systems. In: C. J. Cleveland (ed.): Encyclopedia of Energy. Elsevier, Amsterdam, 647-654. https://doi.org/10.1016/B0-12-176480-X/00233-3.

OECD (2012): Mortality risk valuation in Environment, Transport and Health Policies. Organization for Economic Co-operation and Development (OECD), Paris, France. https://www.oecd.org/env/tools-evaluation/mortalityriskvaluationinenvironmenthealthandtransportpolicies.htm (14 May 2022)

OECD (2018): Cost-benefit analysis and the environment: further developments and policy use, OECD Publishing, Paris. https://www.oecd.org/governance/cost-benefit-analysis-and-the-environment-9789264085169-en.htm (4 July 2022)

Sala, S., E. Crenna, M. Secchi, and R. Pant (2017): Global normalisation factors for the Environmental Footprint and Life Cycle Assessment, EUR 28984 EN, Publications Office of the European Union, Luxembourg, https://www.doi.org/10.2760/88930.

Steen, B. (2016): Calculation of Monetary Values of Environmental Impacts from Emissions and Resource Use. The Case of Using the EPS 2015d Impact Assessment Method. *Journal of Sustainable Development* 9 (6); https://www.doi.org/10.5539/jsd.v9n6p15

UBA (2019): Methodological Convention 3.0 for the Assessment of Environmental Costs - Cost Rates, February 2019. Dessau-Roßlau: German Environment Agency. https://www.umweltbundesamt.de/publikationen/methodenkonvention-30-zur-ermittlung-von-0.

UBA (2020): Methodological Convention 3.1. December 2020. Dessau-Roßlau: German Environment Agency. https://www.umweltbundesamt.de/publikationen/methodenkonvention-umweltkosten.

UK HM Treasury (2022): The Green Book. Appraisal and Evaluation in Central Government. London: TSO. Her Majesty's Treasury, London. 114 pp. Updated March 2022. https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent (4 July 2022)

UK Defra, 2014. *Environmental noise: Valuing impacts on: sleep disturbance, annoyance, hypertension, productivity and quiet,* London: Defra. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/380852/environmental-noise-valuing-imapcts-PB14227.pdf(30 May 2022).

UK Defra (2021a): Air quality appraisal: Damage costs appraisal (updated March 26 2021). Department for the Environment, Food and Rural Affairs (Defra), London, UK. https://www.gov.uk/government/publications/assess-the-impact-of-air-quality/air-quality-appraisal-damage-cost-guidance

UK Defra (2021b): Enabling a Nature Capital Approach (ENCA) (updated 27 October 2021) Department for the Environment, Food and Rural Affairs (Defra), London, UK. https://www.data.gov.uk/dataset/3930b9ca-26c3-489f-900f-6b9eec2602c6/enabling-a-natural-capital-approach (4 July 2022)