Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions

A Contribution to IEA EBC Annex 72

February 2023

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Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of IEA EBC Annex 72. Its contents complement the report “Context-specific assessment methods for life cycle-related environmental impacts caused by buildings” by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of “Assessing Life Cycle Related Environmental Impacts Caused by Buildings” (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on influence of future climate change on prediction of operational energy consumption (Guarino et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

Buildings' expected service life usually spans over at least several decades of even centuries and produce further emissions not only when they are being constructed, but also in the operational phase (including repair and replacement) and at the end of life. The problem of emissions discounting is the problem of present and future importance of GHG emissions released into atmosphere or captured for a certain period over time. The current LCA practice does not consider such temporal aspects. With the typical approach, emissions occurring at different times are aggregated, but in reality, the total emission is not present in the environment at one time, but it is spread over time.

This report summarises the most relevant approaches and their implications regarding the time-related aspects of emissions. It deals with time horizons, physical discounting, carbon budget approach, discounting, economic discounting and monetization of environmental impacts.

If temporal differentiation is considered in LCA, the following recommendations are provided:

Time in life cycle inventory
A prerequisite for considering time in impact assessment and weighting is that life cycle inventory data should be temporally differentiated. It is recommended to indicate the time when emissions occur in the inventory to make it possible that temporal issues are later considered.

Physical discounting
Physical discounting is based on the modelling the actual behaviour of emissions in the environment. While this is an important issue, it is not recommended to apply this approach to future emissions.

Carbon budget approach
The carbon budget approach is recommended. In this approach it is irrelevant whether the emission occurs now or in the future. This makes physical temporal differentiation unnecessary, but scarcity considerations might be applied.

Physical discounting based on increasing scarcity considerations
There is a (residual) budget of emissions determined using scientific methods that may still be emitted if the goal of limiting global warming is met. The amount of emissions that are still permitted to be released is therefore smaller and scarcer. Increasing scarcity can be expressed by increasing the weighting factor (e.g. ecological scarcity method).

Monetization of environmental impacts and discounting
Although physical discounting of future impacts is not recommended, in some approaches, monetization of environmental impacts is used. Once the environmental impacts are monetized, it is possible to apply discounting on the environmental external cost. However, a discount rate of zero or near zero shall be applied considering the perspective/interest of future generations. It is recommended to perform a sensitivity analysis to check how sensitive the results are to the discount rate.

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Abbreviations

Abbreviations	Meaning
EOL	End of life
EU ETS	The European Union Emissions Trading System
GHG	Greenhouse gas emission
GWP	Global warming potential
IAM	Integrated assessment model
ISO	International Organization for Standardization
IPCC	The Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
MCA	Marginal cost approach
MMG	Milieugerelateerde Materiaalprestatie van Gebouwelementen: Environmental Material Performance of Building Elements
OECD	The Organisation for Economic Co-operation and Development
OVAM	Public Waste Agency of Flanders
SCC	Social cost of carbon
TH	Time horizon
UN	The United Nations

1. General Context and Scope

1.1 General

Emissions over the life cycle of a construction product occur at different points in time and significance of their impact may vary. A typical example is waste incineration where immediate emissions to the air have to be weighed against future emissions of slag landfills (Hellweg, Hofstetter, & Hungerbiihler, 2003). In the built environment the service life may span over decades or even hundreds of years, therefore the consideration of temporal issues may become relevant. However, in general no temporal differentiation of impacts is considered in LCA. There have been attempts to adopt the approach of economic discounting where future cash flows are weighted differently than today's cash flows to account for the time value of money. The possibility of applying "physical discounting" based on the modelling the actual behaviour of emissions in the environment has also been discussed. Currently, there is no consensus on whether discounting should be applied in LCA or not. It can and must therefore be discussed whether and to what extent it is possible and sensible to transfer the discounting approach to life cycle assessment.

1.2 Context: Relation to LCA

Climate change is one of our largest challenges today. As buildings are responsible for nearly 40 % of carbon emissions and have high potential for savings, the society shall consider greenhouse gas (GHG) and other emissions in all life cycle phases of construction projects. It is especially important in buildings, as their expected service life usually spans over at least several decades of even centuries and produce further emissions not only when they are being constructed, but also in the operational phase (including repair and replacement) and at the end of life.

If there is a case, that the importance of GHG and other emissions changes over time, such fact shall definitely be considered in optimization approaches and assessment methods, because the change shall impact the optimization result.
The problem of emissions discounting is the problem of present and future importance of carbon emissions released into atmosphere or captured for a certain period over time. The current LCA practice is not to consider such temporal aspects. With the typical approach, emissions occurring at different times are aggregated, but in reality, the total emission is not present in the environment at one time, but it is spread over time.

The question arises whether the temporal aspect should be incorporated into the LCA of buildings and whether today's emissions should be evaluated differently from future emissions. Depending on the chosen approach, this may have a significant influence on the assessment results and thus influence the decision-making process in construction.

2. Status of the Discussion

Temporal issues appear at all stages of an LCA (Stefan Lueddeckens, Saling, & Guenther, 2020):

- Goal and scope definition: the temporal system boundary (time horizon) is defined and the regarded life cycle stages
- Inventory: the inventory data may have a temporal resolution
- Impact characterisation: time dependent characterisation mechanisms
- Normalisation: time dependent normalisation factors
- Weighting: temporal weighting (discounting)

In current LCA practice, the life cycle inventory is usually an aggregated total value of emissions over the service life of the product. Some time-related information is included in some databases. For example, the ecoinvent database (Wernet et al., 2016) distinguishes very long-term emissions for disposal processes. Further disaggregation in time is usually not applied.

Characterization factors of impact assessment are usually generic (average values) without temporal differences (Hellweg & Frischknecht, 2004), (C. Yuan, Wang, Zhai, & Yang, 2015). For example, no difference is considered whether an emission contributes to global warming potential today or in 150 years.

Temporal differentiation could be especially relevant for long-term emissions (slowly released over a long period of time) where the impact of long-term emissions could be very large if the same impact factors are used as for short-term emissions. This problem occurs, for example, in waste treatment processes in landfills (Hellweg & Frischknecht, 2004). Also, there is ongoing debate on carbon capture and storage technologies, that would take exhaust waste carbon emissions from industrial processes or energy production and store them for shorter or longer period of time (Marshall & Kelly, 2010). While weighting of impact categories is well established in LCA, there is a lack of consensus on temporal weighting or discounting. In this report, the most relevant approaches are summarised.

2.1 Time Horizons: Temporal System Boundary

In current LCIA practice, generally there is no explicit differentiation between emissions occurring at different points in time, but some form of implicit discounting is common practice, for example the use of temporal system boundaries or time horizons (TH). Time horizons can be applied for the whole assessment, for the life cycle inventory and for the impact characterization (S. Lueddeckens, Saling, & Guenther, 2021).

Are discounting and time horizons equivalent?

In the early 1990s there has been a discussion on discounting for global warming assessment, but the IPCC instead adopted the concept of time horizons because of its presumed simplicity (Fearnside, 2002) In the literature, setting a time horizon (temporal cut-off) for the assessment is generally regarded as equivalent to the application of discounting (Almeida, Degerickx, Achten, & Muys, 2015; Boucher, 2012; Fearnside, Lashof, & Moura-Costa, 2000; HU, 2018; Stefan Lueddeckens et al., 2020; Mallapragada & Mignone, 2017). (Hellweg et al., 2003) states that time horizon is a special discounting case with a zero rate during the considered time horizon and an infinite rate after the time horizon. On the other hand, in the opinion of (S. Lueddeckens et al., 2021) discounting and time horizons are not equivalent, as in case of time horizons some kind of standardization is possible while discounting is highly individual and fully dependent on a decision maker's utility at different points in time (S. Lueddeckens et al., 2021).

Length of time horizon (TH)

The choice of the time horizon in LCA will significantly influence the results. For example, (Finnveden, 2000) showed how results change depending on the time horizon when assessing long-term heavy metal emissions of municipal waste sites.

The choice of TH is regarded by many as an ethical question about the rights of future generations. Very short THs are against the principle of intergenerational equality, while very long ones marginalize short-term actions and thereby reduce incentives to act (Herzog, Caldeira, & Reilly, 2003; Stefan Lueddeckens et al., 2020). For example, with an infinite TH no benefit of any sequestration measure could be shown (Brandão et al., 2013) but this would avoid problem shifting to the future (Lebailly, Levasseur, Samson, & Deschênes, 2014).

According to (S. Lueddeckens et al., 2021) an LCA can be action-oriented and measurement-oriented. Action-oriented LCA would have a short time horizon to show the consequences of actions and the responsibility of people living today. However, their opinion is that LCA should be measurement-oriented and therefore have a long TH. They recommend the use of discounting to express time preference instead of setting a short TH.

In impact assessment, pre-defined time horizons can be selected in the fate model for temporal system boundaries (e.g. GWP 20, 100, 500). There is a debate whether these time horizons are realistic, as 20 years are too short, while 500 years too long, meaning most LCA studies choose the 100-year TH (Fearnside, 2002).

The Eco-indicator 99 and ReCiPe methods also consider time according to the cultural theory (Hofstetter, Baumgartner, & Scholz, 2000). The archetypes in society are fatalist, individualist, hierarchist and egalitarian with fatalist having the shortest TH and egalitarian the longest. For example, in climate change calculations, the individualist has a 20-year perspective, the hierachist 100-year and the egalitarian an infinite TH. Most assessments apply the hierarchist perspective.

An option is to use strict time horizons. This would mean that if the impact of CO_2 emitted today is determined for a time horizon of 100 years, then the impact of CO_2 emitted in 20 years should be determined based in a time horizon of 80 years (suggested by Ollivier Jolliet in (Hellweg & Frischknecht, 2004)). Such an approach is possible by using a dynamic LCA (Pehnt, 2006).

2.2 Physical Discounting

Hellweg, Hofstetter and Hungerbiihler (2003) introduced the idea that changes in the environment can be expressed with discounting, similarly to economics where price level changes (inflation or deflation) are included in the nominal discount rate. The background concentration of pollutants values or the sensitivity of the ecosystem may change and impacts depend on doses or threshold. For example, soil has a certain buffer for acidic substances until exhaustion occurs (S. Lueddeckens et al., 2021) or the accumulation of heavy metals may trigger a change in the damage produced by an additional unit of emission (Hellweg et al., 2003).

Yuan *et al.* (2015) proposed a theoretical framework for temporal discounting in LCA. Their conclusion was that the inventory analysis stage is advantageous for addressing temporal homogeneity issue. They recommend a methodology following five steps and in their paper they summarize the possible solutions and challenges encountered in each step:

1. Calculating the temporal scale of LCA: the length of each activity when emissions are released must be determined (e.g. product production time, usage time, EOL time + time lags in between). This usually follows a stochastic pattern due to variability, so the result of this step is an expected minimum and maximum time duration of each activity (possible methods to use: fuzzy logic method, Critical Path Method, scenario analysis, statistical analysis, stochastic modelling, predictive models, degradation analysis)
2. Compiling temporally differentiated life cycle emissions: the inventory data must be temporally differentiated, which requires an activity-based modelling.
3. Modelling the actual behaviour of emissions in the environment: released emissions have an initial concentration in the environment, but through various routes and pathways their concentration is dynamically changing (e.g. transported by the fluid flow, chemical reaction, degradation by itself, interaction with other medium for interphase transport and change, absorption in the environmental sinks, precursors). The changes in the amount can be mathematically determined through appropriate fate and transport models, but this involves complex modelling.
4. Discounting emissions to a selected reference time point: the reference point can be any time, e.g. starting or ending point of the life cycle.
5. Aggregating discounted emissions at the reference time point: calculating the equivalent amount.

According to the authors, the difference between the discounted total amount and the directly aggregated amount can be significant. For example, the total discounted amount of CO_2 emissions was 19.78% lower than the total amount of CO_2 emissions in the conventional life cycle inventory in the case of a Volkswagen Golf A4 car (Yuan et al. 2015).

The concept of physical discounting was, however, rejected by (O'Hare et al., 2009) who stated "the discounting model applies to costs and benefits, not to physical phenomena that generate them, unless their economic value is otherwise stable over time". (S. Lueddeckens et al., 2021) agrees that only utility and not physical things can be discounted. According to their opinion, changing background concentration should be modelled with dynamic characterization and normalization and the use of the term "discounting" is not appropriate for this issue.

2.3 Carbon Budget Approach

Carbon budget can be utilized for setting of national or regional benchmarks for the amount of CO_2 emissions produced by buildings over their life cycles. An emissions budget, carbon budget, emissions quota, or allowable emissions, is an upper limit of total carbon dioxide (CO_2) emissions associated with remaining below a specific global average temperature (Meinshausen et al., 2009; UN Environment, 2018).

Governments of some countries already use carbon budgets on daily bases. In the UK, for instance, "under the Climate Change Act (2008) the Government is committed to legally binding carbon budgets. These are five-year period targets for the UK's GHG emissions set fifteen years ahead. The first four Carbon Budget periods have been legislated for: 2008-12; 2013-17; 2018-22 and 2023-2027." (Department for Business, 2018)

The development of remaining carbon budget is monitored by UN and the results are continuously reported in the Emission Gap Reports. The latest report (UN Environment, 2018) concludes, that although most of the nations provided their Nationally Determined Contributions to the Paris Agreement, the actual commitments are not sufficient for bridging the emissions gap in 2030. Moreover, the global GHG emissions showed no signs of peaking in 2017.

The problematics of allocation of the carbon budget from the global level to national buildings-related activities is available in (Habert et al., 2020).

In the carbon budget approach, it is irrelevant whether the emission occurs now or in the future. They are considered equal. This makes physical temporal differentiation unnecessary, but scarcity considerations might be applied.

Physical discounting can be based on increasing scarcity considerations. There is a (residual) budget of emissions determined using scientific methods that may still be emitted if the goal of limiting global warming is met. This remaining budget is getting smaller and smaller as a result of continued release of emissions, and the amount of emissions that are still permitted is therefore smaller and scarcer. In some impact assessment methods, such as the ecological scarcity method, increasing scarcity is expressed by increasing the weighting factor.

2.4 Economic Discounting

Discounting in economics is common practice. A key publication that introduced the concept of discounting in LCA was the publication of Hellweg et al in 2003 (Hellweg et al., 2003), which was followed by some other papers. Discounting is still seldom applied in LCA studies and there is no consensus in the literature on its application.

2.4.1 Discounting Approaches in Economics

In economics, temporal variability is addressed with a temporal discounting approach. The motivation for discounting can be time preference, productivity of capital (related to economic growth/decline) and uncertainty/ risk perception (Hellweg et al., 2003). The basic idea behind is that money available today is worth more than the same amount in the future, because money is already there, certain and can earn interest.

In economics, cash flows occurring over time are discounted to a common metric – present values or future values. A discount rate is applied to describe the change of the value of the money during an interval. Cash flows at different points in time are projected to the reference time and then aggregated to the total value. The reference time is usually the present, but sometimes the future. The general formula for calculating the present value is:

$$PV = CFV / (1+r)^n$$

where

PV	is present value
CFV	is future cash flow value
N	is number of years between present time and occurrence time
r	is discount rate

2.4.2 Reasons for the application of discounting in LCA

Due to time preference: There is a general agreement that discounting because of pure time preference should not be applied in LCA as it is against fundamental ethical values (Hellweg et al., 2003) (S. Lueddeckens et al., 2021). Time preference would mean that environmental damage may be regarded worth less in the future than today. From a moral aspect, all people including those not yet born should be treated equally. However, in real life decision makers often apply an implicit discounting and most people have a short planning horizon. Ethical issues do not mean that all kinds of temporal weighting should be rejected. Weighting of damages at different times can be regarded similarly to weighting of different damage types (Hellweg et al., 2003).

Due to uncertainty: Discounting is sometimes used to reflect uncertainty. For example, some environmental damages may become less important in the future if technological breakthroughs help to reverse the damage but could become more important if they affect more people (S. Lueddeckens et al., 2021). There is a general agreement, however, that discounting is not the right method for considering uncertainty in LCA, which should rather be handled with scenario and sensitivity analysis.

Supporting decisions: According to Lueddeckens, Saling and Guenther (2021), discounting is a tool for intertemporal decision making. It is only useful if alternatives need to be compared to support decision making. They do not recommend discounting in informative assessments, e.g. in single-product LCA or labels. However, in comparative LCA, discounting may help to answer temporal decision problems, for example, a question on whether to use resources now or later. Lueddeckens, Saling and Guenther (2021) provides an example that natural gas reserves can be used now or later. Today there is plenty of solar power available which could be used to produce electricity or heat. In a worst case scenario, after a major volcanic eruption in the future, the available solar energy may be limited and without any fossile reserves energy supply would be hindered. They suggest applying the discounted utility theory for developing a discounting framework, which means that any utility can be discounted and not just money. Discounting can be regarded as a decision instrument that gives information on the difference from opportunities. The discounting function depends on the evaluated utility and personal criteria (S. Lueddeckens et al., 2021).

2.4.3 Discount rate

In most applications of discounting in environmental science, a standard exponential discount function is applied like in financial mathematics, for example in (Hellweg et al., 2003) and (C. Y. Yuan, Simon, Mady, & Dornfeld, 2009).

The discount rate will influence the weighting between present and future and it is a question to which impacts to give a higher weight. The higher the discount rate, the lower the present value of the future cash flows. Similarly, a high positive discount rate would reduce the present value of future environmental impacts. For example, regarding the use of energy source, on the one hand, the scarcity of fossil fuels and the prospect of their complete depletion in the near future say that future energy is more valuable. On the other hand, the marginal cost of extracting energy increases over time. Hence, present saving of energy should be preferred in order that today's relatively easily extractable energy is available as long as possible and other energy fields requiring more complex and more expensive exploration techniques do not have to be used. Using the discounting method makes it possible to take into account emissions concentrated over a shorter period starting in the present, such as manufacturing of materials. Due to improving technologies future energy production is expected to correspond to lower emission levels (Zöld & Szalay, 2007).

The determination of the appropriate discount rate is a challenge. In economics it could be the average bank interest rate, bond rate during the time interval, or the social discount rate used in computing the value of funds spent on social projects (Harrison, 2010). In the standard theory, the discount rate is the sum of time preference and opportunity costs or utility of economic growth (Gowdy, Rosser, & Roy, 2013).

With regards to environmental damages, the application of the social discount rate is proposed, as these damages harm all of society (Richards, 1997; J. Wang, Zhang, & Wang, 2018). This rate is typically lower than the private discount rate as society has a longer time horizon and less time preference than individuals (S. Lueddeckens et al., 2021).

According to ISO 14008:2019 (ISO, 2019), the discount rate:

$$r = d + g \cdot \mu$$

where

d is the pure rate of time preference

g is the growth rate of per capita consumption

μ is the elasticity of social marginal utility of consumption.

The ISO 14008:2019 suggests that for inter-generational (i.e. long-term) considerations from a societal perspective, the pure rate of time preference should be set to zero.

Many authors propose a small discount rate near 0% as the rate has a very large influence on the results (Bakas, Hauschild, Astrup, & Rosenbaum, 2015) In the Cultural Theory, a hierarchist would apply a discount rate of close or equal to 0%, while an individualist would choose the private discount rate and an egalitarian would prefer zero or even negative discount rate (Hellweg et al., 2003). In the opinion of (C. Y. Yuan et al., 2009), underestimation of impacts would be more critical than overestimation, hence discounting should be handled very conservatively. On the other hand, according to (S. Lueddeckens et al., 2021), the choice of the discount rate is not arbitrary and depends on the opportunity cost of the exact case. The discounting function depends on the use case and must be developed individually.

Lueddeckens, Saling and Guenther (2021) raises the possibility of using declining discount function (hyperbolic discounting) instead of the usual exponential function in certain cases, for example for long time horizons and taking into account *"individual rights to utilize parts of the natural capital (as equity) and emission rights "borrowed" from others, especially from future generations (debt)".*

It is recommended to check the sensitivity of the results to different discount rates. For example, in Germany, a discount rate of 3 percent can be expected for short-term periods (up to approx. 20 years). For claims that extend further into the future, the discount rate applied by default is 1.5 percent. Furthermore, a sensitivity calculation with a discount rate of 0 percent must be carried out for cross-generational considerations. The discount rates are to be applied for the entire period (constant discount rates). The values selected for the method convention are within the ranges that are scientifically common (Bünger & Matthey, 2018; Matthey & Bünger, 2019; Umwelt Bundesamt, 2021).

2.5 Monetization of Environmental Impacts

In economics, one reason for discounting is capital productivity, as capital can be invested so that it grows in the future. This does not apply directly to environmental issues as they cannot be stored in a fund. However, if we accept that there is a relationship between monetary values and environmental impacts, discounting could also be applied to environmental impacts (Hellweg et al., 2003; O'Hare et al., 2009; J. Wang et al., 2018).

Monetization of impacts can be based for example on the prevention or abatement costs. Arguments against monetization are that monetization of human lives or natural assets is often perceived as unethical, as future generations are left with no option to decide whether they accept compensation payment for a natural asset. Global, irreversible, critical damages are difficult to monetize (Temel, Jones, Jones, & Balint, 2018). Also, it cannot be guaranteed that the payment will be passed on by the intermediate generations (Hellweg et al., 2003).

Hellweg reached the conclusion that discounting due to capital productivity leads to an overall discount rate of close to 0%, as both compensation and discount rate relate to economic growth. The discount rate may even be negative if natural assets become scarce and a very high compensation is required.
According to Lueddeckens, Saling and Guenther (2021), discounting of monetized impacts is a valid approach but monetization is not a prerequisite for discounting. In their opinion, "discounting is independent from monetary values. Every kind of utility can be discounted. Avoided negative impact is always a utility, and negative impact is always disutility.

In the following section, a summary is provided on the available monetization approaches, with a special focus on the social cost of carbon.

2.5.1 Monetization approaches

A brief summary of monetization of environmental impacts was provided by Le Pochat (Le Pochat, 2013). The short paper also provides a general classification of methods used for the monetization of environmental impacts: a) economic valuation of biodiversity and/or ecosystem services; b) monetization of environmental impacts; and c) environmental accounting. For GHG calculation, typical approach for doing so is to calculate so called social cost of GHG emissions, sometimes shortly referred to the social cost of carbon, or SCC (class b – monetization of environmental impacts). The recommended approaches are provided in the international standard ISO 14008:2019 Monetary valuation of environmental impacts and related environmental aspects (ISO 14008:2019). ISO 14008:2019 provides an overview of procedures and requirements for monetary valuation. The list of available procedures comprises market price proxies (market proxies of traded goods and labour; cost-of-illness method); revealed preference methods (individual and public averting cost methods; hedonic pricing method; travel cost method; and evaluation based on data derived from public referendums); stated preference methods (contingent valuation; choice experiment); and value transfer (spatial value transfer; temporal value transfer).

Another approach that can be traced in the field of economy is not to use the GWP indicator with monetizing GHG emissions, but to have use other indicators such as Global Cost Potential or Cost-Effective Temperature Potential (Johansson, 2012).

2.5.2 Cost of GHG emissions arising from emission trading schemes

The minimum cost of carbon for the industry sectors covered by emission trading is given by the prices in the emission trading markets. An overview of the emission trading schemes worldwide is provided in the report of ICAP (ICAP, 2018). The report states that in 2018 15 % of global GHG emissions were covered by the emission trading schemes and provide overview of covered sectors per region and scheme. The report does not present any figures for the cost of emissions traded, but it provides an overview of various emissions trading schemes in operation or with planned launch. It covers the emissions trading schemes in force by 2018 at various levels:

- supranational level: European Union Emissions Trading System (EU ETS);
- country level: China, Kazakhstan, Korea, New Zealand, Switzerland;
- provinces and states levels: Western Climate Initiative (including California, Québec, Manitoba, Ontario, British Columbia), Regional Greenhouse Gas Initiative (including Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, Vermont) and Saitama;
- city level: Tokyo.

The report also mentions different schemes in preparation (by 2018).

2.5.3 Social cost of carbon

The external climate cost (also called ‘social cost of carbon’ in literature) is increasing over time and this can be discounted.

There are various methods to evaluate the social cost of carbon (SCC).
The SCC can be set as a result of Cost-Benefit Approach by seeking for socially optimum levels of emissions through time. The shadow price of emissions is then defined as the pollution tax required to keep emissions at the optimal level (Clarkson & Deyes 2002).

Another method is the Marginal Cost Approach (MCA) represents an attempt to calculate directly the difference in future damage levels caused by a marginal change in baseline emissions (Clarkson & Deyes

2002). It is the monetized damage from emitting one additional unit of CO_2 or its equivalent to the atmosphere, often obtained from various computational Integrated Assessment Models (IAMs) (Marshall & Kelly, 2010) or the cost of actions needed to recovery the damage. There are claims that monetization of damages is essential for the determination of optimal climate policies (Nordhaus, 2017; van den Bijgaart, Gerlagh, & Liski, 2016). The MCA is used also with the abatement costs, i.e. cost of reducing emissions (Ackerman & Stanton, 2012).

There is a considerable body of literature that discuses SCC. Two main groups of sources are briefly discussed in this chapter: scientific papers that present various background calculations of SCC; and documents of public domain that proposes, prescribe or use some levels of SCC for the policy and decision-making in the public sector.

Range of SCC presented in scientific papers

Various studies propose different levels of SCC. Literature research made in this project considered research papers and reports published in the past five years, i.e. in 2014 and later. The research was made during January and February 2019 using research databases (mainly Web of Science and Elsevier) supplemented by inputs provided by the Annex 72 members. Since the topic of the cost of carbon develops rapidly, in June 2021 more sources and new updates were added. Details of all the aspects of estimations of SCC are beyond the limited scope of this text, so the review was not focusing on single studies, but rather on papers presenting outcomes of broader reviews of papers and reports in order to provide basic idea on ranges of SCC and provide links to sources of further references for deeper study.

The IPCC WGIIAR5 report (IPCC, 2014) includes chapter 10.9.3. *Social cost of carbon* which discusses the estimates published in research studies published before and after IPCC AR4, discusses the figures, used discount rates and presents statistic charts of SCC for various pure rates of time preferences. Average cost in all set of considered studies ranged between \$40 for 3 % discount rates and \$655 for 0 % discount rates (page 690, Table 10-9, prices in dollar per tonne of carbon).

A paper by Nordhaus (Nordhaus 2017) proposes SCC per tonne of CO_2 of $\$31.2_{2010}$ for baseline scenario and $\$184.4_{2010}$ for scenario of 2.5 degree maximum (for year 2015). The paper provides more figures for 2015, 2020, 2025, 2030 and 2050 for various scenarios. For scenario of 2.5 degree maximum proposes \$351.0 for emissions in 2030, and 1,006.2 for emissions in 2050.

The team of Chinese authors (P. Wang, Deng, Zhou, & Yu, 2019) made a review of the current research on the SCC and discussed model choice of models for its calculation. They made a meta-analysis above data from 58 studies. In the conclusions they state that "*in all collected data, the estimated SCC ranged from –50 to 8752\$/tC (–13.36e-2386.91\$/tCO₂), with a mean value of 200.57\$/tC (54.70\$/tCO₂). Specifically, it equaled to 112.86\$/tC (30.78\$/tCO₂) with a PRTP at 3% in peer-reviewed studies*".

The authors of another paper (Yang et al., 2018) discuss the role of socioeconomic assumptions in the estimations of future SCC. They use DICE model and results of the China Climate Change integrated assessment model to update SCC in five Shared Socioeconomic Pathways. For 2020, the average SCC estimations under SSP1, SSP2, SSP4 and SSP5 were 10 \$/tCO_2, 19 \$/tCO_2, 18 \$/tCO_2 and 12 \$/tCO_2, respectively. The SSP3, which represents high mitigation and adaptation challenges, has the highest SCC early in this century, reaching 45 \$/tCO_2 in 2020 and increasing to 108 \$/tCO_2 by 2050. The paper also provides a wide variety for SCC in 2100 for different scenarios.

The authors of a working paper (Havranek, Irsova, Janda, & Zilberman, 2015) examine potential selective reporting in the literature on the social cost of carbon (SCC) by conducting a meta-analysis of 809 estimates of the SCC reported in 101 studies. Their results indicated that estimates for which the 95% confidence interval includes zero were less likely to be reported than estimates excluding negative values of the SCC, which might create an upward bias in the literature. Their estimates of the mean reported SCC corrected for the selective reporting bias are imprecise and range between USD 0 and 130 per ton of carbon at 2010 prices for emission year 2015.

Another paper (van den Bergh & Botzen, 2015) presents a critical review of the reported SCC estimates by examining some neglected consequences of climate change, uncertain and extreme scenarios of climate change, the discounting of future climate change effects, the treatment of individual risk aversion, and assumptions about social welfare. The text does not provide its own levels of SCC, but provide a long list of references to other studies.

Examples of use of SCC by public authorities

The examples of public authorities use the comprise USA, UK, Germany and Belgium. These documents are relevant for construction GHG as well, as they shall apply also to new legislation (incl. construction) and to public investments.

In the USA, the Interagency Working Group on Social Cost of Greenhouse Gases (or IWG) of the United States Government has a task to ensure that the social cost of carbon estimates provided to the U.S. government reflect the best available science and methodologies, so that these estimates can be used in cost-benefit analyses of regulatory actions. In its report (Interagency Working Group on Social Cost of Greenhouse Gases, 2016) IWG calculated SCC ranging from \$31 (USD_{2007}) for 2010, through \$42 for 2020 upward to \$69 for 3 percent discount rate. The report also provides ranges for 2.5 and 5 percent discount rate and for lower-probability, higher-impact outcomes and 3 percent discount range. The SCC in the report ranges between \$10 (for 5% in 2010) and \$212 (for 3%, high impact). The U.S. EPA on its website (US EPA, 2017) and in its factsheet (US EPA, 2016) on SCC referred to the levels from IWG report as well. In the new 2021 report (Interagency Working Group on Social Cost of Greenhouse Gases, 2021) IWG presents for the period 2020-2050 costs between \$14 and \$260 per metric ton of CO_2 in 2020 dollars.

In the UK, the central government uses for appraisal and evaluation in decision-making The Green Book (HM Tresaury, 2018). The document describes the principles and procedures used for public appraisal and evaluation in various segments and in *Chapter 6 Valuation of Costs and Benefits* in it specifically lists GHG emissions and energy efficiency and provides guidelines for valuing effects on the natural environment. A supplementary document (Department for Business, 2018) provides a specific guidance for valuation of energy use and GHG and makes link to the toolkit that the British government provides for valuing changes in GHG emissions. The document also provides practical guide with examples that shows how to value GHG under traded price (for the valuation of GHG under trading scheme it prescribes to calculate with traded price from EU ETS system) and under non-traded price. For the non-traded price, the example uses value 66 £/tCO_{2e} (in $£_{2017}$), the authors currently working on valuing shall use actual numbers from the provided toolkit.

In Germany, the German Environment Agency (Umwelt Bundesamt) provides Methodological Convention 3.0 for the Assessment of Environmental Costs (Matthey & Bünger, 2019). In its Table 1 on page 8, the report presents a table of SCC (in $€_{2016}$) for 1% pure rate of time preference of €180 for 2016, €205 for 2030 and €240 for 2050. It also shows figures for 0% pure rate of time preference of €640 for 2016, €670 for 2030 and €730 for 2050. For the years not indicated, the figures shall be interpolated. The recommended value of $€180_{2016}$/t $CO_{2eq.}$ is close to value determined in the 5th Assessment IPCC report of 173.5 $€_{2016}$ /tCO_2[1]. In the 12/2020 update (Matthey & Bünger, 2020) the costs range between 195 and 765 $€180_{2020}$/t CO_{2eq}.

In Belgium, Public Waste Agency of Flanders (OVAM) published a series of reports on MMG method (Milieugerelateerde Materiaalprestatie van Gebouwelementen: Environmental Material Performance of Building Elements) which is based on a first 2012 report (Debacker et al., 2012). The latest MMG report (De Nocker, L., Debacker, 2018) describes the updates in methods and presents monetary values of several

[1] IPCC (2014), p. 691, Average of all available studies with a 1% pure time preference rate and different assumptions regarding Equity Weighting, compounded for 2016, currency conversion via purchasing parities of the World Bank.

environmental indicators based of combination of damage costs and prevention/abatement costs methods. For GWP it provides cost of 1 kg of $CO_{2eqv.}$ in three levels for Western Europe: low €0.025, central €0.050 and high €0.100, whilst the central is recommended as most representative. The central cost was estimated from prevention costs, because damage costs were highly uncertain and prevention cost information was good. The value of future impacts was discounted using a social discount rate 3 %. In chapter 4.1.1 the study cites two tables from VITO 2014 (details on the original source is not mentioned in the report references) which provide also different costs for construction phase, use phase, and end of life phase and make difference in SCC depending on the purpose of calculation – a monetary indicator for global warming for studies focusing on the comparison of impacts from different building materials or building lines; and monetary indicator for global warming, for assessment of external costs of buildings in cost-benefit analysis (e.g. for comparison with costs of emission reduction measures).

Example of use of SCC policy papers

An example of use of the SCC in policy papers is the OECD document Effective Carbon Rates 2018 (OECD, 2018a) and accompanying brochure (OECD, 2018b). The documents represent detailed and comprehensive account of how 42 OECD and G20 countries, which are responsible for 80 % of the global carbon emissions, price carbon emissions from energy use. The reports describe so-called carbon pricing gap, which measures the difference between price of emissions (combining price of emission permits, carbon taxes and specific taxes on energy use) produced in each country with two reference levels: EUR 30/t CO_{2e} and EUR 60/t CO_{2e} and describes that the carbon gap for the EUR 30 level in 2018 was 76.5%. That means that 76.5 % of emissions in the countries responsible for 80 % of global GHG emissions are valued bellow 30 EUR/t CO_{2e}.

The documents also present outcomes of an analysis, which claim, that the negative economic motivation works – those countries with a low carbon pricing gap tend to have less carbon intensive economies.

3. Recommendations

If temporal differentiation is considered in LCA, the following recommendations are provided:

Time in life cycle inventory
A prerequisite for considering time in impact assessment and weighting is that life cycle inventory data should be temporally differentiated. In building LCA, production of materials and construction happen is a relatively short time period, which is followed by a long period of operation. It is recommended to indicate the time when emissions occur in the inventory to make it possible that temporal issues are later considered.

Physical discounting
Physical discounting is based on the modelling the actual behaviour of emissions in the environment. While this is an important issue, it is not recommended to apply this approach to future emissions. These effects do hardly apply to CO_2 because of its chemical stability and thus long-term presence in the atmosphere.

Carbon budget approach
The carbon budget approach is recommended. In this approach it is irrelevant whether the emission occurs now or in the future. They are considered equal. This makes physical temporal differentiation unnecessary, but scarcity considerations might be applied.

Physical discounting based on increasing scarcity considerations
There is a (residual) budget of emissions determined using scientific methods that may still be emitted if the goal of limiting global warming is met. This remaining budget is getting smaller and smaller as a result of continued release of emissions, and the amount of emissions that are still permitted is therefore smaller and scarcer. Increasing scarcity can be expressed by increasing the weighting factor (e.g. ecological scarcity method).

Monetization of environmental impacts and discounting
Although physical discounting of future impacts is not recommended, in some approaches, monetization of environmental impacts is used (i.e. when there is need for a single indicator integrating various interests). Once the environmental impacts are monetized, it is possible to apply discounting on the environmental external cost. However, a discount rate must be chosen that considers the perspective/interest of future generations, in line with IPCC's recommendations. Hence, a zero or near zero (1% or less) discount rate is recommended. It is also recommended to perform a sensitivity analysis to check how sensitive the results are to the discount rate.

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