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Evaluating the monetary values of greenhouse gases emissions in Life Cycle Impact Assessment

Yan Dong[a*], Michael Hauschild[a], Hjalte Sørup[b], Rémi Rousselet[c], Peter Fantke[a]

[a]Quantitative Sustainability Assessment, Department of Management Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

[b]Urban Water Systems, Department of Environmental Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

[c]Engineering School, Ecole Centrale de Marseille, 13013 Marseille, France

*Corresponding author: E-mail yado@dtu.dk; tel: +45 4525 4417

Highlights

- Human health damages contribute to 70-97% of the GHG monetary value in assessed methods
- Comprehensive and robust modelling for ecosystem damages is lacking in LCIA
- Monetary values of CO_2-eq are 16, 160 and 140 US$$_{2017}$/ton in LIME, EPS and ReCiPe
- GHG monetary values in EPS and ReCiPe are in line with social costs of carbon (SCC)
- The uncertainty of GHG monetary values is at least 1-2 orders of magnitude

Abstract

It is commonly acknowledged that greenhouse gas (GHG) emissions from anthropogenic sources accelerate climate change impacts. Efforts are made by governments and companies to reduce GHG emissions via policies and actions. In order to determine which actions to prioritize among many options, benefits of emission reductions are often monetized, to compare with the costs of action or with benefits that can be obtained from other actions. Life cycle assessment (LCA) is a commonly used tool to assess the amount of GHGs emitted over the life cycle of a service, policy or product system. However, the damage modeling of GHGs in life cycle impact assessment (LCIA) and its monetary values have not been separately evaluated. This hinders the application of LCA in relevant decision contexts. This study evaluates the cause-effect chains and associated monetary values of GHG in three LCIA methods LIME2, EPS2015 and ReCiPe2016. Among these three, EPS2015 covers most damage categories, including the ones on human health, ecosystem and social assets. ReCiPe2016 does not include social assets damages and LIME2 does not consider ecosystem damages in climate change impact. Human health damages are well estimated in all three methods, contributing to 70-97% of the GHG monetary values. The lack of data is a clear obstacle across methods. Further research is needed to develop comprehensive and robust modelling approach for ecosystem damages, which are not well covered in current LCIA methods. Moreover, due to the scope of environmental LCA, there is a lack of consideration on socio-economic consequences, which may not be negligible for climate change. The resulting monetary value of GHG, expressed in per tonne CO_2-eq are 16, 160 and 140 $US\$_{2017}$ respectively in LIME2, EPS2015 and ReCiPe 2016. These monetary values are reasonable for use in decision contexts where LCA is applied. Further research is, however, needed to reduce the current uncertainty of at least 1-2 orders of magnitude.

KEYWORDS: life cycle assessment, climate change, monetary valuation, cost of carbon, damage modelling

1. Introduction

In recent years, global average temperature has increased (IPCC, 2014a). Greenhouse gases (GHGs), defined as gases with a potential to trap heat in the atmosphere, are considered likely to be the major driver behind the phenomenon (IPCC, 2014a). Both the United Nations Sustainable Development Goals (SDGs) (UN, 2015) and the Paris agreement (UNFCCC, 2015) bring countries together to combat climate change. In response to these calls, many countries have started to develop and adopt climate change adaptation and mitigation actions (IPCC, 2014b; OECD, 2009). In those actions, often qualitative approaches are used to assess climate change impacts, using damage-based approaches (ICAT, 2017; WRI, 2014). Sometimes, quantitative methods are used to quantify GHG reductions, where GHG emissions may be monetized for decision support (van den Bergh and Botzen, 2014). Companies also start to include the assessment of climate change related damages in their decision support tools, e.g. cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA), where results are often expressed in monetary terms (Nas, 2016). In order to incorporate climate change-related impacts into such decision support tools, GHG emissions are often monetized to be accounted as costs, as illustrated in Danish Ministry of Transport (2015) and European Commission (2014).

Among GHGs, the common ones are CO_2, CH_4, N_2O and industrial halogenated gases like HFC-134a, CF4 and CFC-11. Each of them has a different capacity to trap heat in the atmosphere (radiative forcing). In the last century, GHG emissions have led to a change of radiative forcing, accompanied by an increase of global atmospheric temperature that eventually causes damages on Areas of Protections (AoPs) such as human health and natural ecosystems. Quantification of GHG monetary values of a project or policy should proceed through three steps (Figure 1): 1) Quantification of GHG emissions associated with the project or policy; 2) Characterization of the GHG emissions according to their potential of contributing to global warming; and 3) Conversion of the global warming potentials into monetary values. The 1st step involves a modelling of the system changes resulting from the project or policy implementation with focus on quantification of changes in GHG emissions. The 2nd step is performed according to guidance offered by IPCC. Among different indicators such as Global Temperature change Potential (GTP) and Global Warming Potential (GWP), IPCC recommends the use of GWP. "It is defined as the accumulated radiative forcing within a specific time horizon (e. g., 100 years — GWP100s), caused by emitting one kilogram of the gas, relative to that of the reference gas CO_2. This metric is used to transform the effects of different GHG emissions to a common scale CO_2-eq (CO_2-equivalents), caused by emitting one kilogram of the gas, relative to that of the reference gas CO_2" (IPCC, 2014a, page 47). The 3rd step is to estimate the monetary value per unit emitted CO_2-eq. Three mainstream approaches are distinguished. The first one (3a in figure 1) is to assess the monetary values based on the potential damages caused by GHG emissions, namely damage cost. The second approach (3b in figure 1) is the indirect costs that aims at regulating GHG emissions by existing carbon policies, such as pollutant taxes and trading prices (Mandell, 2011). The last approach is the marginal abatement cost (MAC) approach, which considers the costs needed to reduce a certain amount of GHG, in order to meet a target (Isacs et al., 2016).

In many decision contexts, the first step is often done following formal guidelines. For example, the EU CBA guidelines suggest to use emission factors from recommended economic literature, such as EMEP/EEA air pollutant emission inventory guidebook (EEA, 2016) and TREMOVE database (Leuven and DRI, 2007), to derive emission quantities when project-specific data is not available (European Commission, 2014). The emission factors developed by IPCC (IPCC, 2017) and corresponding factors developed by individual countries are also often used. Though convenient to use, this practice of applying IPCC emission factors has been criticized for being too generic and not accounting for the whole life cycle of the relevant project or policy. To address these shortcomings, life cycle assessment (LCA) has been used in recent years to assess the project or policy specific GHG emissions.

LCA is an ISO standardized methodology that aims at quantify the damages on AoP such as human health, ecosystem quality and services and resource depletion that are associated with the life cycle of products or services. It is often used to compare the environmental performances of two products, or identify hotspots along the assessed life cycles. In the first phase of LCA- life cycle inventory (LCI), GHG emissions, as well as other emissions (e.g. chemicals and radiation) and resources used (e.g. land and water use) associated with the entire life cycle of a policy or product are quantified, taking a systemic perspective. The environmental emissions are translated into impact scores in several impact categories, including climate change. Those different impact scores are sometimes weighted to deliver the result on a common matrix for decision support. Weighting, however, is optional in LCA, and is often conducted following non-monetary weighting principles, such as “proxy methods, distance to target and panel weighting methods” (Ahlroth et al., 2011). Monetary valuation of emissions is not a common practice in LCA, but rather performed for other decision support contexts. For example, the environmental emissions are often monetized and accounted as external costs/benefit in CBA projects, following EU CBA guidelines (European Commission, 2014). This has been applied in e.g. transport sector (Annema et al., 2017), waste management (Eshet et al., 2006), and renewable energy decision making (Owen, 2006). It is challenging to use monetary based weighting approaches in LCA. As stated by Pizzol et al. (2015), LCA assesses impacts on a rather abstract and general level, which means it is difficult to derive an approach that is robust across different impact categories at both midpoint and endpoint on the cause-effect chain. In the cases where monetary valuation based weighting is performed, we consequently see a big variation in the results. For example, Møller et al. (2013) used LCA to quantify GHG emissions and fossil fuel energy consumptions, which are monetized using “welfare economic accounting prices” recommended by Danish Energy Agency. The prices fluctuate with market situation, thus the monetary evaluated LCA results vary over times. Jones et al. (2017) used LCA to quantify few pollutants emissions in transport projects and applied monetary valuations. They find it difficult to assign costs to the emissions due to limited data availability and lack of reliability. Ferreira et al. (2014) assessed the economic impacts of recycling systems in Portugal, where environmental impacts are quantified using LCA and then converted into monetary values using three methodologies. The monetary results vary 60% between applied valuation methods. These studies show that uncertainty associated with the monetary valuation results in LCA may hinder its application in decision support, if not well evaluation and explained. In the present study, we will therefore specifically focus on climate change impact category in LCA and evaluate different monetary valuation methods applied to GHG emission related impacts in order to strengthen the potential of using monetization in LCA for better decision support.

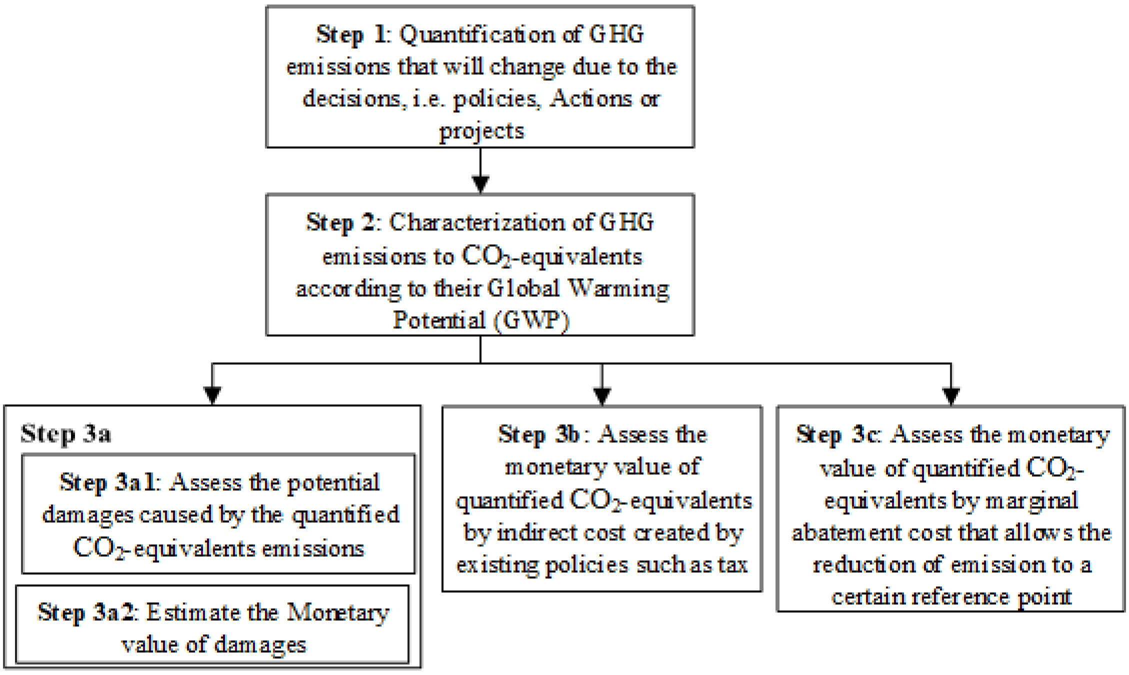


Figure 1 Steps for deriving monetary values of GHG emissions

Monetary valuation, or monetarization, is to convert consequences on society and ecosystems into a common metrics by using conversion factors. In this way, they can be compared and combined with other benefits and costs (Pizzol et al., 2015). Different approaches for monetizing damages exist, e.g. approaches based on observed, revealed, or stated preferences, approaches focusing on abatement costs, and approaches using budget constraints (Pizzol et al., 2015). The monetary value of GHG, expressed as CO_2-eq, has been studied intensively. Public awareness has been risen especially after the publication of the Stern review (Stern, 2006). As shown in figure 1, three mainstream approaches exist. Ideally, the monetary values estimated by the three methods should reach the same value (Isacs et al., 2016). However, this is rarely the case.

Among the three monetary valuation approaches, it is recommended to use MAC approaches when binding GHG emissions with reduction targets (Department of Energy & Climate Change, 2009; Isacs et al., 2016). MAC approach has been used increasingly in policy making, especially after the publication of MAC curves by McKinsey (2010). It has been used in UK extensively to shape climate change policies, such as setting carbon budget and recommending cost-effective measures (AEA Energy & Environment, 2008). MAC has also been used in CEA to identify cost effectiveness of mitigation policies in e.g. agriculture sector (Eory et al., 2013), energy efficiency in maritime (IMO, 2014) and transport sector (Tomaschek, 2015). Tol (2012) used the MAC and marginal impacts of climate change to conduct a CBA for EU 2020 targets. The GHG values derived by MAC approaches are sometimes also used in transport CBAs (VTPI, 2017). In addition to the abundant application of MAC in policy contexts, the MAC approach has been combined with LCA to derive eco-efficiency on product level-- the so-called eco-costs/value ratio (EVR) model. This model was introduced by Vogtländer et al. (2002, 2001), and has been used for assessing the eco-efficiency of products such as cork (Mestre and Vogtlander, 2013) and bamboo products (Vogtländer et al., 2010).

When it comes to estimating potential future impacts that is not bond with targets in short-terms, it is recommended to use damage costs (Isacs et al., 2016). Sometimes damage costs is criticized for “not simple enough or not known with enough precision to allow quantitative cause-effect modeling” (UNEP Setac Life Cycle Initiative, 2009, page 70). However, it assesses the potential future damages, which fits the scope of LCA. Thus the traditional LCA modelling falls into this category, which is also the focus of the present study. Two steps are required to derive damage costs. The first step (3a1) is to identify the potential damages that are caused by a unit emission of CO_2-eq. This is largely natural-science-based modelling, where uncertainty may arise related to e.g. the scenario settings, the magnitude of expected impacts, or the time horizon. The second step is to determine the monetary values of the considered damages (step 3a2 in figure 1). IPCC report (IPCC, 2014c) gives a comprehensive overview of the potential damages on AoPs, which may all be linked to GHG emissions. Based on the IPCC report, models have been developed to assess the monetary value of GHG. One of the most used monetary valuation of carbon dioxide is social cost of carbon (SCC), which represents “the net present value of the incremental damage due to a small increase in carbon dioxide emissions” (Tol, 2009). In a North American contexts the most used models for assessing SCC are PAGE (Hope, 2011a), DICE (Nordhaus and Sztorc, 2013) and FUND (Waldhoff et al., 2014). In European contexts, the monetary values of CO_2-eq developed in the ExternE project series (European Commision, 2005) and in the NEEDS project (Preiss and Klotz, 2007) are often used, especially in CBA (European Commission, 2014). LCA supports damage assessment for a variety of environmental impacts including the one caused by GHG, as well as monetary valuation of GHG emissions in few methods.

In LCA, GHG emissions are quantified in the LCI phase (step 1 in figure 1). Subsequently, the emissions are characterized in terms of their potential damages on AoPs in the life cycle impact assessment (LCIA) phase. In LCIA, GHG emissions are firstly all converted to CO_2-eq (step 2 in figure 1). Damages associated with a unit emission of CO_2-eq are then characterized considering different impact pathways in different LCIA methods. In several LCIA methods, such as ReCiPe2016 (Huijbregts et al. 2016, referred as ReCiPe), IMPACT 2002 (Jolliet et al., 2003) and TRACI (Bare et al., 2003), only step 3a1- damage modelling (see Figure 1) is performed, without further monetizing the resulting damages. In a few LCIA methods, such as LIME2 (Itsubo and Inaba 2012a, referred as LIME) and EPS2015 (Steen 2015, referred as EPS), damages are further monetized and hence expressed in economic terms.

In recent years, there are many studies that advances the development of climate change impact assessment methods. IPCC AR5 (IPCC, 2014a) has summarized recent updated knowledge on climate change, where the physical mechanisms, observed changes and future potential impacts are identified. This is used as basis for LCIA climate change impact characterization methodology development. Joos et al. (2013) conducted multi-model analysis to better estimate the response of climate variables in the atmosphere to the pulsed emission of GHG. De Schryver et al. (2009) updated the coverage of diseases caused by climate change and corresponding severities on human health and ecosystems, within the context of LCIA. Hanafiah et al. (2011) estimated damage on freshwater ecosystem due to climate change related changes on water discharge. Urban (2015) summarized the climate change related extinction rate on terrestrial ecosystems. The above methodology development has been adapted by different LCIA models such as ReCiPe, IMPACT World+ (Bulle et al., 2018), LIME and EPS. However, each of the LCIA methodology made its own adaptations to fit into its model framework. This brings differences such as the choice of damage coverages and time perspectives. There is currently a lack of evaluation and comparison of LCIA climate change impact characterization methodologies, as well as their monetary valuation, where available. Such work is needed in order to support the use of LCA result in certainty decision contexts. In the present study, we looked into damage assessment of CO_2-eq (also called climate change impacts in LCA) in the three LCIA methods LIME2, EPS2015 and ReCiPe2016. The first two methods are chosen because they integrate monetary valuation directly in their damage characterization factor modelling, where both steps 3a1 and 3a2 (see Figure 1) are included. ReCiPe is chosen because it has been identified as the currently "scientifically most robust endpoint method" (EC-JRC, 2011) for LCIA climate change impacts in the European context. However, ReCiPe only performs step 3a1-quantifying damages to AoPs, which are human health, ecosystem quality, and natural resources. In order to compare the ReCiPe results with results from the other two methods, we paired it with a monetizing approach developed in (Weidema, 2009) that executes Step 3a2 in figure 1 to translate the damages on AoPs into monetary values.

Using three LCIA methods as demonstration, the aim of the present study is to evaluate and discuss how monetized climate change related damages are considered in LCIA methods. To achieve this aim, we focus on three specific objectives: 1) to identify damage pathways of GHG and corresponding CO_2-eq monetary value of the damages as it is modelled in the three LCIA methods; 2) to compare the identified damage pathways with recommendations from the latest IPCC report (IPCC, 2014c) to discuss potentially missing pathways in LCIA; and 3) to evaluate the CO_2-eq monetary value in LCA by analyzing uncertainty and in comparison with studies from other science-policy fields. The CO_2-eq monetary values in LCIA are derived with assumptions. Whether the assumptions are acceptable for decision support highly depends on the decision context (Dong et al., 2018). Examples are whether system boundary is consistent between the models used for deriving CO_2-eq monetary values and the decision contexts, and decisions under pre-cautionary principle prefer to cover potentially significant consequences that has high uncertainties (Aven, 2008). Therefore the applicability of CO_2-eq monetary values derived by LCIA in the relevant decision contexts will also be discussed. Future research needs for LCIA climate change impact assessment will be identified.

2. Climate change damage modelling in LCIA methods

In this section we will present how climate change damage modelling is done in the three chosen LCIA methods to derive the monetary value of GHG.

2.1 The general methodology of climate change damage modeling

In the three selected LCIA methods, the monetized damages associated with GHG emissions are calculated as demonstrated in equation 1.

$$Monery\ value\ of\ GHG = CF_{mid} \times Cost_{CO_2-eq} = CF_{mid} \times \sum_{i=1}^{n}(Damage_{mid-end,i} \times Cost_{end,i})$$

Eq. 1

Where:

CF_{mid}: midpoint characterization factor, expressed in kg CO_2-eq/kg GHG emission

$Cost_{CO_2\text{-}eq}$: The monetary value of damage per unit emission of CO_2-eq, expressed in monetary values such as US$/kg CO_2-eq

i: a numeric representation of AoP. It varies in different LCIA methodology and can be human health, ecosystem, resources and social assets, etc.

n: number of AoPs in the specific LCIA method.

$Damage_{mid\text{-}end,i}$: damage caused by a unit emission of CO_2-eq on the AoP i, expressed in the corresponding metrics such as DALY for human health.

$Cost_{end,i}$: The monetary value per $Damage_{mid\text{-}end}$, expressed in monetary values such as US$/DALY.

First, midpoint Characterization Factor (CF_{mid}) is derived for per unit emission of each GHG, describing the GWP of that GHG in CO_2-eq, similar to step 2 in figure 1. Afterwards, the monetary value of damage related to a unit emission of CO_2-eq are quantified. Here according to the AoPs and corresponding pathways identified, damages are firstly quantified in each AoP, and their associated monetary values are estimated and summed up. The following section will focus on the monetary value of CO_2-eq ($Cost_{end,i}$) in the selected LCIA methods.

LIME2 (Japanese life-cycle impact assessment method based on endpoint modeling) is the second version of LIME (Itsubo and Inaba, 2012b). It has four AoPs: Human health (with relevant damages expressed in DALY/kg emitted), Social assets (with relevant damages expressed in Japanese Yen/kg emitted), Biodiversity (with relevant damages expressed in EINES that is based on the extinction risk assessment) and Primary Production (with relevant damages expressed in Net Primary Production, NPP). The monetary value per damage ($Cost_{end,i}$) is derived by conjoint analysis. It is a questionnaire based methodology to investigate people's willingness to pay for a non-market good. Firstly a questionnaire-based survey of Japanese people's opinion on the importance of AoPs was conducted. Statistical analysis of the results was carried out to derive average monetary values for the four AoPs.

The EPS (Environmental Priority Strategies) method was originally developed for assessing companies' internal product development processes based on the ISO 14044 Standard (iso.org, 2017; Steen, 2015). It was developed in a top-down manner to inform decision makers (mostly product developers) of the environmental costs of choosing a particular product design. The AoPs in EPS include ecosystem services, access to water, abiotic resources, biodiversity and human health. Each of the AoPs is associated with a state indicator. For human health, the state indicators are life expectancy described by Years of Life Lost (YOLL), disability caused by diseases described in person.years and cases, and migration in persons. For ecosystem services and access to water, the state indicators are provisions of crops, fruits and vegetables, fish and meat, wood, drinking and irrigation water, expressed in weight (kg). Biodiversity is described by Normalized Extinction of Species (NEX). Abiotic resources includes the depletion of reserves such as fossil fuels and rare earth metals, expressed in weights (kg). The Monetary values are determined by market values or estimated market values depending on availability (Steen, 2016). Values on biodiversity are calculated from prevention costs to reach Global Biodiversity Conservation Targets (McCarthy et al., 2012).

The ReCiPe endpoint method quantifies the damages to three AoPs: human health, ecosystem quality and resource depletion, expressed in DALY, species.year and monetary terms respectively. It develops the impact assessment results in three different scenarios reflecting different cultural perspectives. In the present study, we specifically looked into the Hierarchist perspective, which considers mid-term time frames and common policy principles. We applied monetary values developed in Weidema (2009), in combination with ReCiPe damage modelling for deriving monetized results. Weidema (2009) used the budget constraint approach for estimating the damages on human health, assuming that the maximum spending on extending a life with one year is the annual income. Monetary valuation on ecosystem damages is extrapolated from the damage on human life, and the share that "we are willing to sacrifice to protect the ecosystems" (Weidema, 2009).

2.2 Climate change impact assessment methods in LIME, EPS and ReCiPe

Table 1 summarizes the damage assessments in the three selected LCIA methods, and their corresponding characterization factors and monetary values. Note that different climate change models and scenario were used in the three LCIA methods to estimate the temperature rise, as summarized in Appendices. However, due to the scope of this study, we do not further analyze the uncertainty associated with the climate change models and scenarios, but focus on the damage coverage in the LCIA methods and their monetary values.

2.2.1 Monetary value of human health damages

The metrics DALY is used to quantify human health damages in both LIME and ReCiPe. It includes disabilities caused by disease and the affected life expectancy. In EPS, the affected life expectancy is described by YOLL, where the disability is calculated separately. Note that YOLL usually dominates DALY estimates. Thus the related monetary values are in the same orders of magnitude. They are 14.7 million JPY_{2012}/DALY (approximately 133000 $US\$_{2017}$/DALY) in LIME (Itsubo et al., 2012), 50000 $€_{2015}$/YOLL (59900 $US\$_{2017}$/YOLL)_in EPS (Steen, 2016) and 74000 $€_{2003}$/DALY (109000 $US\$_{2017}$/DALY) in Weidema (2009).

EPS has the highest monetary value per kg CO_2 emission on human health, by a factor of 2 and 12 higher than ReCiPe and LIME, respectively. This is largely due to its inclusion of working capacity decrease, which is not assessed in the other two LCIA methods, yet contributes 53% of the monetary value of human health damage in EPS. Nutrition-related damages are divided into undernutrition and malnutrition in EPS, which are the 2nd and 3rd highest contributors. This is in accordance with ReCiPe, where malnutrition is the predominant contributor to human health damages (60%). EPS and ReCiPe have similar monetary values for nutrition damages, both of which are one order of magnitude higher than the damage values of malnutrition in LIME. Malaria is also considered an important contributor to human health damages, ranked the 1st (80%) in LIME and 3rd (19%) in ReCiPe. Mainly due to the lack of damage on working capacity, and the lower estimation on nutrition-related damages, the monetized value of human health damages in LIME is by a factor of 12 and 6 lower than EPS and ReCiPe, respectively.

2.2.2 Monetary value of social assets damages

Damages on social assets are assessed in LIME, representing damages on services that our society obtain from ecosystems, such as agricultural field crops, fruits and water. The damage on ecosystem services in EPS is addressed within the contexts of social assets damages in LIME. Thus, we consider them in the same category. The damage coverages are different in the two methods except for one common category: crop productivity, which is assessed via market prices. Damages on crop productivity reach similar values in both methods and it is the predominant contributor to monetary value of social assets damages in both methods. ReCiPe, in contrast, does not include any damages on social assets.

2.2.3 Monetary value of ecosystem quality damages

Ecosystem damages caused by GHGs are assessed in EPS and ReCiPe, but not in LIME. LIME claims that due to the complexity of the cause-effect chain, it is difficult to define a proper biodiversity endpoint relating to GHG emissions. Note that the ecosystem damages may be included in the upcoming LIME3 (Itsubo et al., 2015), but not in the LIME2 version that we are currently assessing. EPS assumes that 70% of birds will be affected by changing habitats (IPCC, 2014c). This fraction is extrapolated to represent the red-listed species, resulting in a NEX value of 0.7 (Steen, 2016). The monetary value for biodiversity is 5.5×10^{10} $€_{2015}$/NEX, derived from prevention costs (McCarthy et al., 2012). In ReCiPe, the difference of estimated extinction rate between now and 100 years into the future is used to calculate the damage CF (Urban, 2015). The monetary value for potential disappearance of species is 9.5×10^{6} $€_{2003}$/species.year (Weidema, 2009). The resulting monetary value per CO_2-eq in ReCiPe is thus three orders of magnitude higher than the one in EPS. This is due to both differences in the estimation of damages and the different methods to derive monetary values.

2.2.4 Summary of assessed monetary value of damages

Human Health is clearly the main contributor in the assessment of climate change related damages associated with GHG emissions in all three LCIA methods, contributing 70-97% to the monetary value of damages related to GHG in the three assessed methods. This may reflect reality, but could also be caused by the fact that we do not have sufficient knowledge on damages on social assets and ecosystems to provide as evident damage or related monetary valuations as for human health.

The lack of data is a clear obstacle across all methods. LIME for instance enlists all the subcategories of damages that they could not assess due to lack of quantitative information on the subject. This includes air pollution for human health, wood production, fishery production, water resources, immigration, assets loss and impact on insurance for social assets, and the damages on primary production and biodiversity. Even though ecosystem-related damages are estimated in EPS, it extrapolates the fraction of birds that may be affected by climate change to all red-listed endangered species, which is not evidentially appropriate. The three orders of magnitude difference between monetary value of ecosystem damage in ReCiPe+Weidema and EPS shows that there is uncertainty on the modelling and variety on the estimation method. This can be explained by the fact that ecosystem damages are difficult to quantify and highly differ according to the regions under study, hence a real problem when trying to generalize. Moreover, the monetary valuation of biodiversity varies among different methods, where uncertainty may also be high.

Table 1 Climate change related damages assessed in the three selected LCIA methods and their associated monetary values. Note that the monetary values are converted to the corresponding US$ values in 2017.

	LIME			**EPS**			**ReCiPe （Hierarchist perspective）**		
	Damage/ kg CO_2	Unit	Damage converted to $\$_{2017}$/kg CO_2	Damage/ kg CO_2	Unit	Damage converted to $\$_{2017}$/kg CO_2	Damage/ kg CO_2	Unit	Damage converted to $\$_{2017}$/kg CO_2
Damages on Human Health									
Heat stress	3.90E-09	DALY	5.17E-04	1.35E-07	YOLL	8.10E-03			
Cold stress*	-4.30E-09	DALY	-5.70E-04	-1.28E-09	YOLL	-7.68E-05			
Natural disasters	1.02E-09	DALY	1.35E-04	1.18E-08	YOLL	7.05E-04	-2.02E-08	DALY	-2.20E-03
Malaria	7.70E-08	DALY	1.02E-02				1.77E-07	DALY	1.93E-02
Dengue	9.30E-10	DALY	1.23E-04						
Malnutrition	1.80E-08	DALY	2.39E-03	2.39E-06	person.years	2.74E-02	5.49E-07	DALY	5.99E-02
Undernutrition				5.00E-07	YOLL	3.00E-02			
Diarrhea				2.79E-09	YOLL	1.67E-04	1.85E-07	DALY	2.02E-02
				1.59E-08	person.years	1.00E-04			
Working capacity				1.17E-06	person.years	8.21E-02			
Migration				2.27E-07	persons	6.78E-03			
Cardiovascular diseases							3.79E-08	DALY	4.13E-03
Total	**9.66E-08**	**DALY**	**1.28E-02**			**1.55E-01**	**9.28E-07**	**DALY**	**1.01E-01**
Damages on Ecosystem Quality									
Terrestrial ecosystems							2.80E-09	species.year	3.91E-02
Freshwater ecosystems							7.65E-14	species.year	1.07E-06
Total				**2.27E-16**	**NEX**	**1.52E-05**	**2.80E-09**	**species.year**	**3.91E-02**
Damages on Social Assets									
Land price Dryland			1.10E-04						
Wetland			1.20E-04						

Crops	Rice	2.70E-01	g	5.87E-04						
	Corn	6.10E-01	g	7.40E-05						
	Wheat	1.50E+00	g	2.36E-03						
	Total			3.03E-03	1.09E-02	kg	**2.87E-03**			
Energy costs	Heat decrease*	5.10E+00	kcal	-1.71E-04						
	Cooling increase	1.30E+00	kcal	2.80E-04						
Fruit and Vegetables					1.31E-03	kg	6.10E-04			
Meat and Fish					5.14E-04	kg	1.29E-03			
Drinking water					6.28E-02	kg	1.51E-04			
Irrigation water					1.26E-01	kg	1.51E-04			
Total				**3.36E-03**			**5.08E-03**			
Aggregated Damages										
US$$_{2017}$/ kg CO_2 emitted		1.62E-02			1.60E-01			1.40E-01		
US$$_{2017}$/ton CO_2 emitted		16.2			160			140		
Contribution	Human health	79.20%			96.82%			72.17%		
	Ecosystem Quality	<0.01%			0.01%			27.83%		
	Social assets	20.80%			3.17%			<0.01%		

*Damage or monetary values below zero mean that the CO_2 emissions will result in a positive impact in that category. For example, CO_2 emissions cause temperature rise that will decrease damages on human health from cold stress. It will also increase the energy need for heating.

3. GHG related damages acknowledged by IPCC AR5

In its Technical Summary of the 5th Assessment Report (WG II, AR5), the IPCC presents a comprehensive set of impacts that is (potentially) related with climate change, both currently observed ones and predicted ones as being future major issues during the 21st century. In the context of our study, it is fruitful to compare the IPCC assessment with those carried out by the three selected LCIA methods, especially because IPCC is the main source of pathways used for the estimates in the LCIA methods. We have sketched the impact pathways from CO_2 emissions to the damages on ecosystems and human health that are covered in IPCC AR5 (IPCC, 2014a) in Figure 2.

Damages on human health is by far the most thoroughly assessed in the three LCIA methodologies. The health effects listed in IPCC are mostly also found in ReCiPe, LIME and EPS. For the increased mortality caused by climate-related natural disasters, we can observe that LIME has the most complete coverage. Wildfires are excluded from all the three methods (Figure 2). For all three LCIA methods, the contribution from natural disaster damages only accounts for less than 2.5% to the monetary value of human health damages. It appears that knowledge on the potential for natural hazards is poorly represented and the related monetary valuations are probably underestimated (Stern, 2013). In IPCC it is stated that "at present the worldwide burden of human ill-health from climate change is relatively small comparing with effects of other stressors and is not well quantified" (IPCC, 2014a). As 70-97% of the monetary value of GHG related damage in the three LCIA methods are associated with this pathway, there is a good chance that we are missing some damages from social and ecosystem due to the current lack of data and quantification methods.

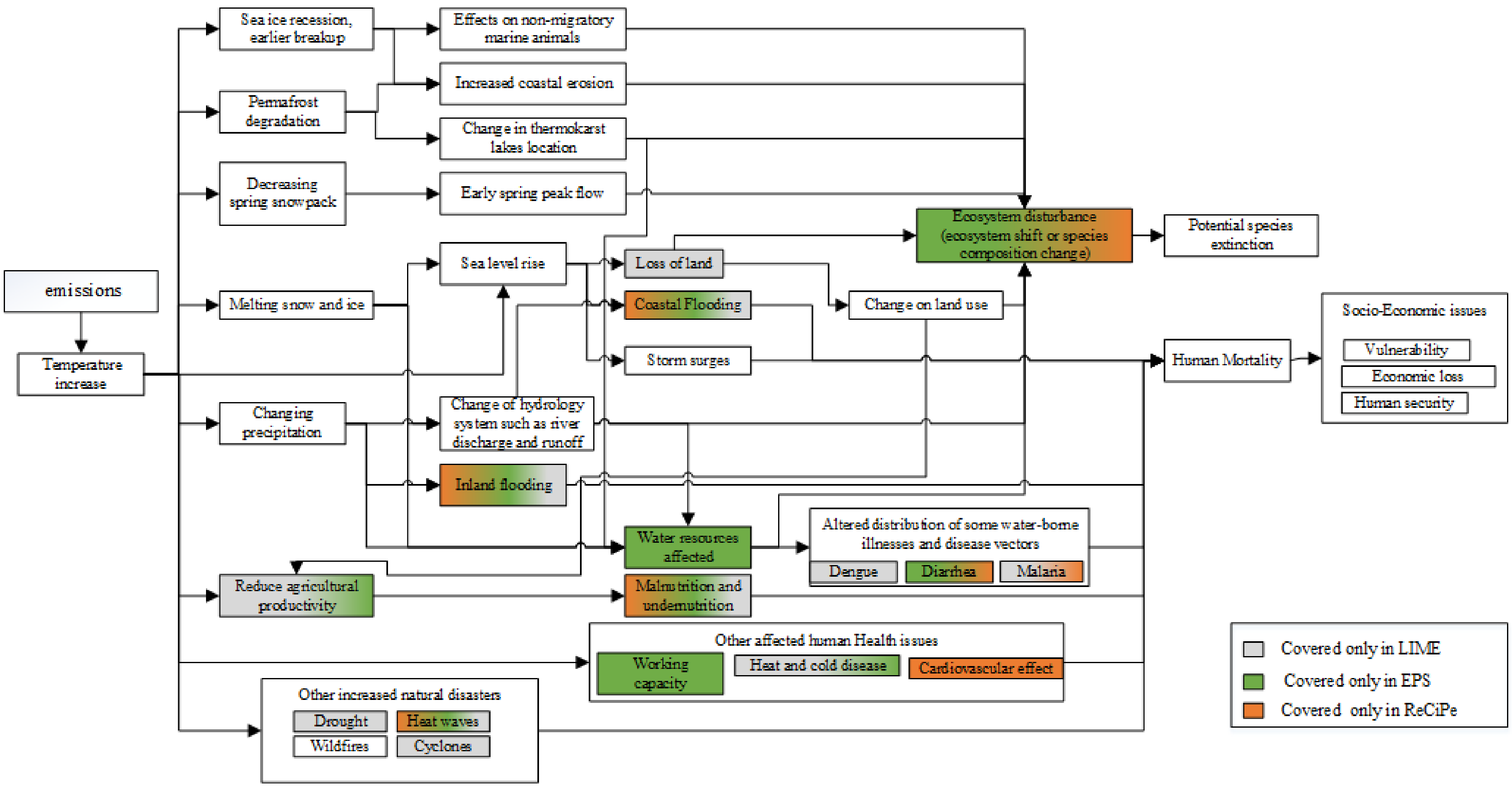
Monetary value of damages on ecosystems are poorly quantified in EPS and ReCiPe, with only one integrated indicator provided in each of the methods. The indicator is calculated from extinction rate changes in ReCiPe and the extrapolated fraction of affected red-list species in EPS. As shown in Figure 2, IPCC lists many pathways that cause disturbances on ecosystems, e.g. natural disasters such as droughts, wind storms and fires, sea ice recession, permafrost degradation, decreasing spring snowpack, melting snow and ice and change of precipitation. They are presently not easy to quantify, and neither ReCiPe nor EPS includes them in the damage assessment. LIME does not account damages on ecosystems.

Social assets damages seem better covered in EPS than in the other two LCIA methods (Figure 2). For food security, LIME follows a similar approach to IPCC recommendations, where the fertilizer effect of GHG is considered in the damage modelling. However, LIME only focuses on crops (rice, wheat and corn), while EPS also takes into account fruits, vegetables, meat and fish. ReCiPe does not include any damages on social assets that are identified in IPCC.

Water circulation will be changed via shrinking glaciers, which affects runoff, water resources, and permafrost degradation. Together with altered precipitation patterns caused by climate change, this will change the accessible water resources for human society (Figure 2). The accessibility of water resources is captured only in EPS. Due to lack of detailed descriptions, it is unclear, however, if all related pathways mentioned in IPCC are covered. As climate related natural disasters may cause migration, EPS also considers migration costs in human health damages. It is assessed as the costs of mitigation action against the vulnerability to climate change in certain areas. It can be the results of damages via many pathways, including flooding, loss of land, reduced agricultural productivity, and coastal erosion, etc. This may well overlap with the natural disaster related human health damage in EPS.

An important concern is the lack of climate related socio-economic damages in the LCIA damage modelling. For example, social property loss such as infrastructures due to extreme climate related events is not assessed in any of the LCIA methods. Relevant damages are only taken into consideration under the prism of human mortality. LIME, for instance, calculates the monetary value of damage only on the basis of the number of deaths and thus integrates this category only in the AoP of human health, without further assessing the property lost under its social assets. IPCC points out other socio-economic damages as well, including urban areas (poor population living in slums are vulnerable to climate events), human security (costs of the future climate-related violent conflicts) and livelihoods and poverty (climate-related hazards affect deeply vulnerable populations through impacts on livelihood, reduction in crop yields, and destruction of homes). They are not integrated in any of the three LCIA methods. It is likely due to the reason that traditional environmental LCA does not cover economic damages as an AoP. However, when estimating the climate related damages in monetary terms, the exclusion of economic damage in social assets may result in misleading conclusions.

In sum, among the three LCIA methods, EPS has the most extensive coverage of GHG emission related damages. LIME lacks ecosystem damages while ReCiPe does not consider the damages on social assets. Human health is by far the best covered category in all studied LCIA methods. Ecosystem quality, on the other hand, is the AoP with the poorest description of damages pathways, suffering from a lack of evidently sound damage estimations. Due to the scope limitation of the traditional environmental LCA, socio-economic damages are not covered in any of the investigated LCIA methods, thus not reflected in the GHG monetary values.



407

408 Figure 2. The damage pathways of GHG emissions on different areas of protection, adapted from (IPCC, 2014a)

4. Evaluation of monetized LCIA climate change damages

In this section we first discuss the uncertainty associated with the damage monetary values for one unit CO_2-eq emissions as applied in the LCIA methods. We further evaluate the CO_2-eq costs in comparison with other literature resources such as SCC. We also look into the decision contexts where the LCA CO_2-eq monetary values could be applied to understand if the level of uncertainty would lead to the wrong decisions. Finally, we discuss the limitations and future perspectives of monetizing climate change related impacts in LCIA.

4.1 Uncertainty associated with the CO_2-eq costs derived from LCIA methods

Uncertainty comes from both missing and poorly understood damage pathways, and from the monetary valuation approaches used to convert damages into monetary value.

4.1.1 Uncertainty in the damage coverage

Section 3 provides an overview of the known damage pathways which are missing in the three LCIA methods. We have investigated three sources of uncertainty in the resulting monetary value of damages in the LCIA methods: the mechanism describing natural disasters, the consideration of damages on human health and socio-economic assets, and estimating human health effects attributable to GHG emissions. For emission scenario we use the assumptions in EPS, which corresponds to the RCP 6.0 in IPCC with an accumulated emission of 3885 Gton CO_2-eq between 2012 and 2100. The estimated monetary value of damages will be divided with this emission amount to derive monetary values associated with damages per emitted tonne of CO_2-eq.

Natural disasters

Increased frequency and severity of flooding is predicted to be one of the major natural disasters that will be caused by climate change. In the world's major port cities, a total value of 3,000 billion US$ is estimated to be exposed to coastal flood event that happens once in 100 years (Hanson et al., 2011). This estimation is in line with another study where the annual global value lost due to flooding is estimated to be 6 billion US$ per year today, increasing to 52 billion US$ per year in 2050 and to 1000 billion US$ per year in 2100 (Hallegatte et al., 2013). Kousky (2014) looked into a broader range of weather-related extreme events including floods, and derived an average annual cost between 94 billion and 130 billion US$. Those studies indicate that within a 100 years span, an estimation of 3000 billion US$ property loss due to climate change is reasonable. If attributed to 3885 Gton CO_2-eq, this results in the monetary value of 0.8 US$/t$CO_2$-eq damage from flood. Pycroft et al. (2014) shows that a higher sea level rise due to extreme event icesheet collapse will cost 10-14 US$/t$CO_2$-eq extra. Considering the low probability and frequency of the extreme natural disasters, it is not surprise to see the low contribution (below 10%) to the monetary value of CO_2-eq, comparing with the other impacts that happens on daily basis such as disease and crop loss.

Note that these are estimations on the events that we understand using current knowledge. There are severe catastrophic events may cause irreversible damages that are beyond our understanding. Examples are release of massive methane from permafrost melting, and ocean circulation pattern change, which may lead to a sharp drop in seawater (Tol, 2009). What are the extra cost for those disasters, and the even unknown disasters remains unclear.

Human health and socio-economic damages

One of the worst socio-economic damages are wars to fight for accessible land and food. Taking the Second World War as the ultimate example, 77 million people died, in addition to a direct economic costs of 11 trillion US$ (Thompson, 2014). If a similar war were to happen again as a consequence of climate change, this would account for 61 $US\$_{2017}/tCO_2$-eq. The calculation is based on a similar assumption of direct economic cost and number of people died, using an average loss of 30 DALY per person died with a price of $74000€_{2003}$/DALY, attributed to 3885 Gton CO_2-eq. Considering the subsequential economic loss due to the war, this number can even be doubled or tripled. Needless to say, this damage is not included in LCIA methods, but it indicates the potential error by not representing the possible social-economic costs of climate change.

Dose-response function for human health damages

The results are sensitive to the data source and models used. For example, two orders of magnitude difference is observed for damages on human health (DALY/kg CO_2-eq) due to heat stress and diarrhea between two different LCIA methods. The estimated damages on ecosystem in EPS uses the affected fraction of birds to represent the affected fraction of red-listed species, while ReCiPe relies on expert prediction of species extinction rate due to temperature rise. These emphasize a lack of clearly interpretable dose-response function between climate change and related damages, as also stated in IPCC (IPCC, 2014a).

4.1.2 Uncertainty in the monetary value per unit damage

Different monetary valuation methods follow different principles. Some methods measure intrinsic, non-use values such as stated preferences methods, while other methods measure use values, such as the damage cost and abatement cost methods. These differences led to varying monetary values per unit damage as function of the method applied. Human health damages are the main contributor to the monetary value of CO_2-eq in all three LCIA methods. Therefore, the monetary value of the human health damage metrics DALY or YOLL is essential when assessing the monetary value of human health damages. We have looked into the estimated valuation of DALY in other studies (table 2). Avoided costs refer to valuation per unit of averted DALY. It is calculated from more than 3000 control costs of different diseases in different regions (Neumann et al., 2016). The "stated preference" and "value of a statistical life" are taken from Ryen and Svensson (2015), based on a review of 24 Willingness to pay (WTP) studies from EU, USA, China, Thailand, Japan, Australia, Republic of Korea, Taiwan and UK. Treatment costs in The Netherlands and USA are taken from Mangen *et al.* (2015) and Hoffmann et al. (2012), respectively. These are retrieved from costs of illness including the medical treatment costs, non-healthcare costs such as work days lost, and other potential indirect costs. Despite the large variation in avoided costs across the large number of datasets, the arithmetic means of avoided costs per DALY from the investigated studies is in the same order of magnitude as that estimated in Weidema (2009), LIME and EPS (table 2). However, the analysis results also indicate that the monetized DALY valuation may deviate from the mean value by at least 1-2 orders of magnitude, especially considering the averted-DALY costs due to the different situations in different countries. A similar range of variation will be translated into the uncertainty of the monetary value of per unit of CO_2-eq.

Table 2 Monetary evaluation for human health damages in other literatures (converted from original values to US$$_{2017}$/DALY)

Reference	Mean	Standard deviation
Avoid cost (Neumann et al., 2016)	1.75E+04	2.08E+05
WTP-stated preference (Ryen and Svensson, 2015)	1.46E+05	3.20E+04
WTP-value of statistical life (Ryen and Svensson, 2015)	3.63E+05	5.36E+04
Treatment Cost_Netherland (Mangen et al., 2015)	5.93E+04	3.99E+04
Treatment Cost_US (Hoffmann et al., 2012)	2.90E+05	1.51E+05
LIME (Itsubo et al., 2012)	1.33E+05	
EPS (Steen, 2016)	5.99E+04*	
Weidema (2009)	1.09E+05	

*The value is expressed in US$$_{2017}$/YOLL, which is similar to US$$_{2017}$/DALY as discussed in section 2.2.1.

Damages on ecosystems contribute 28% to the monetary value of CO_2-eq in ReCiPe, largely due to the monetary values of the potential species loss. Hence, we looked into the values of species loss in the literature. The ExternE project series (European Commision, 2005) derive a value between 63 and 350€$_{2005}$ per ha.year of ecosystems protected. The method used was revealed preferences, based on political negotiations. Assuming that the species density is 1.48×10^{-8} species.m^{-2} (Huijbregts et al., 2016), therefore 1.48×10^{-4} species per ha, we obtain a value per species between 6.0×10^{5} and 3.3×10^{6} US$$_{2017}$/species.year protected. Itsubo et al. (2012) obtained a monetized value of 1.42×10^{13} JPY$_{2012}$ (1.28×10^{11} US$$_{2017}$) per extinct species by a choice modelling method (stated preferences). Using the conversation factors 4.5×10^{-8} species-extinction/BAHY (Weidema, 2009) and species density above, we derive a monetary value of 3.9×10^{7} US$$_{2017}$/species.year. We observe that there are various monetary valuation approaches of ecosystems. The costs vary up to two orders of magnitude, comparing to the monetary value of 1.4×10^{7} US$_{2017}$/species.year derived by Weidema (2009). However, comparing with studies of human health damages, there are much fewer studies exploring the monetary value of ecosystems. It is a likely possibility that this variation is underestimated.

The monetary value of a unit damage on ecosystems has an uncertainty of 1-2 orders of magnitude, based on the current knowledge. The uncertainty caused by missing or unclear damage coverage is difficult to quantify, but likely to be within one order of magnitude.

4.2 Decision contexts for the application of CO_2-eq monetary values in LCIA

Uncertainty is associated with the CO_2-eq monetary values derived from LCIA. It does not mean that we cannot use those monetary values. The suitability of their application depends on the decision contexts. LCA aims at comparing the environmental impacts arising from different options such as products, services or systems, or identify hotspots along their life cycles. There, similar ranges of uncertainty will be associated with the different options, since the methods for quantifying damage and for monetary valuation are similar across the compared alternatives. Recently, LCA is being used for quantifying GHG emissions of policy or company actions, where the costs of CO_2-eq is sometimes used together with the GHG inventory estimations to incorporate them into CBA for decision support. If the estimated monetized GHG reduction is to be compared with an investment, the minimum 1-2 orders of magnitude uncertainty of CO_2-eq monetary value is in most decision contexts not negligible and may lead to wrong conclusions.

When using LCA derived CO_2-eq costs in CBA, another concern is that the system boundaries and scope of the CBA may not correspond to the assumptions used to quantify the CO_2-eq monetary value in LCIA. In LCIA, the damages related to emissions of GHGs (expressed in CO_2-eq) is usually put into a global perspective. Once emitted to the air, GHGs will contribute to global climate change impacts for a long time period, which leads to damages in the vulnerable places regardless of the emission location. In contrast, CBA always considers impacts in a certain area within a certain time period. The monetary value of CO_2-eq delivered by LCA will, however, not be able to reflect this temporal and geographical scope (Manzo and Dong, 2018), unless only allocate the relevant damages occur within the specific geographical and temporal boundary.

When looking at climate change, sometimes a precautionary principle is applied, especially for policy making purposes. In those cases, extreme impacts such as natural disasters and wars need to be included. In contrast, LCA aims at providing “best estimate” impacts caused by marginal emissions associated with the assessed system. This explains why there is limited coverage of extreme event damages in the damage modelling. This is also reflected in the associated CO_2-eq monetary values.

Note that LCIA assesses environmental impacts over an integrated time, where discounting of impacts are rarely considered. This means that the monetary values of CO_2-eq in the assessed three LCIA methods contain the integrated damages over the defined time period. As stated in Hellweg et al. (2003), discounting of environmental impacts is not encouraged due to ethic values. The reason is that the LCA assesses environmental impacts in a sustainability context where current and future generations are equally weighted. Hence, discounting is against these principles and would add more emphasis on current generations. However, if temporal differentiation is essential when using the monetary value of CO_2-eq in combination with dynamic emission inventory, discounting can be used with caution (Hellweg et al., 2003; Yuan et al., 2015).

4.3 Comparison of CO_2-eq monetary values from different sources

The price per unit CO_2-eq has been used in different decision contexts. For example, SCC calculates the monetary value of CO_2-eq that capture the potential impacts on the social wealth. It is often estimated using models such as FUND, DICE or PAGE. It is broadly used by US and Canadian governments for policy decision analysis. We have summarized few SCC values, and the monetary value of CO_2-eq used in other research field such as transport and waste landfill projects in table 3. Note that the models used for deriving these monetary value have different purposes. For example, SCC models are economic oriented, while LCA are environmental damage oriented. Thus the underlying model set ups such as coverage of impacts, model structure and discounting vary in those values.

Table 3 summary of CO_2-eq monetary values estimated in literatures (converted to $US\$_{2017}/tCO_2$-eq)

Mean value ($US\$_{2017}/tCO_2$-eq)	**Uncertainty range ($US\$_{2017}/tCO_2$-eq)**	**Considerations**	**Reference**
31	2 – 177	Value used as external economic cost/benefit in landfill projects from 19 studies	(Eshet et al., 2006)
31	-1 - 70	SCC estimated assuming “the global economic impact of climate change is a parabolic function of the global mean surface air temperature”.	(Tol, 2012)
121		SCC, damage cost on the society estimated under business as usual emission scenario	(Stern, 2006)
82-235		SCC estimated using PAGE09 with different climate sensitivity and damage exponents	(Pycroft et al., 2014)
126		SCC estimated by PAGE09 under business as usual emission scenario	(Hope, 2011b)
169	<21 - 2415	SCC value range derived from 232 published SCC studies reviewed in the reference	(Tol, 2009)
138 - 521		SCC estimated under a combination of “high climate sensitivity, high damages, and low discount rate”	(Ackerman and Stanton, 2012)
129		Best guess SCC estimated lower bound	(van den Bergh and Botzen, 2014)

172	-53 - 4575	Value used in transport project cost benefit analysis	(VTPI, 2017)
388	5 - 2084	Business-as-usual emissions (IPCC AC2)	(Dietz, 2011)

Based on the above information, we conclude that the monetary value of CO_2-eq comes with considerable uncertainty, regardless of the estimation method and application contexts. It seems that the values estimate by the LCIA methods, 160 and 140 US$_{2017}$/tCO_2-eq in EPS and ReCiPe, respectively (Table 1), are close to the mean values derived in most studies (Hope, 2011b; Stern, 2006; Tol, 2009; van den Bergh and Botzen, 2014; VTPI, 2017), while the uncertainty of at least 1-2 orders of magnitude is also within the similar range from the other studies. Therefore, whenever monetary estimates of consequences between different decisions vary within the uncertainty bound, related models and data should be refined before any decision can be taken about the preference for any decisions.

5. Conclusion and future perspectives

In the present study, we have looked into the monetary valuation of CO_2-eq estimated in three LCIA methods, LIME, EPS and ReCiPe+Wediema (2009). Human health damages contribute 70-97% to the monetary value of CO_2-eq, thus GHG in all three LCIA methods, largely because this is the most studied and known damage caused by climate change. The climate change impact pathways in EPS have a fairly good representativeness of the damages, covering human health, social assets and ecosystems. In comparison, ReCiPe lacks estimation of social assets damages, while LIME lacks estimation of ecosystem damages. The estimation of ecosystem damages in both EPS and ReCiPe is based on single studies, where the impact pathways are not sufficiently clear. Comparing to the environmental impact pathway presented by IPCC, none of the three LCIA methods has a comprehensive and robust modelling of ecosystem damages. Further research is needed there.

Due to the scope of conventional environmental LCA, socio-economic consequences are not well included in the LCIA methods, if at all. Due to the principle that LCA estimates average impacts from marginal emissions, only a small range of damages from the extreme events that are foreseen as possible by IPCC are covered in LCIA. This should be taken into account when using LCIA-based CO_2-eq monetary values in other decision contexts, especially policy decisions with precautionary intensions, since they may be underestimated. Comparing to the CO_2-eq monetary values presented in other studies, such as the lower bound SCC of 129 US$_{2017}$/tCO_2-eq in van den Bergh and Botzen (2014), the monetary values delivered by EPS (160 US$_{2017}$/tCO_2-eq) and ReCiPe+Weidema2009 (140 US$_{2017}$/tCO_2-eq) seem reasonable, while the value delivered by LIME lies one order of magnitude lower (16.2 US$_{2017}$/tCO_2-eq). We estimate the uncertainty range of the CO_2-eq monetary values to be at least 1-2 orders of magnitude, which is also in accordance with the range estimated in other studies.

Our study suggests that the CO_2-eq monetary values, thus also GHG monetary values, estimated in the three LCIA method are reasonable for use in decision context where LCA is often applied. Future research is needed to get a better estimation of damages on ecosystems and extreme events, and reduce the uncertainty to a level that is far better than the current range.

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Appendices Climate changes scenarios used in the three chosen LCIA method

Methods	LIME (Itsubo and Inaba, 2012a)	EPS(Steen, 2016)	ReCiPe (Huijbregts et al., 2016)
Scenarios	The difference between base scenario in 2000 and a future scenario in 2063 are used for calculating the marginal temperature rising, assuming that CO_2 concentration in the atmosphere becomes double during this period. Emission scenario in 2000 is fixed and the emission in 2063 is calculated by MAGICC (Wigley, 2008) using the median (P50) of the SRES scenario (IPCC, 2000).	Base scenario is in 2012 and future scenario is in 2100. Scenario RCP 6 in IPCCs Fifth Assessment report is used (IPCC, 2014a). It forecasts that emission will not be stabilized before 2100, reaching 670 ppm of CO_2 concentration by 2100 and a global rise of temperature of 2.2 °C at the end of the century. According to this scenario, the accumulated emission of CO_2 between 2012 and 2100 is 3885 Gton. The contribution of CO_2 to global warming is up to 88%.	Time span is 20 years for the individualist, 100 years for the hierarchist and 1000 years for the egalitarian. Model used is (F Joos et al., 2013)