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Choosing a monetary value of greenhouse gases in assessment tools

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Abstract

There is a societal need for using monetary estimates of social impacts of CO_2 and other greenhouse gases in different assessment tools, such as cost-benefit analysis and life-cycle assessment. A number of estimates are available in the literature. Since these differ by several orders of magnitude, there is ambiguity and confusion about which to use. This review aims to give some guidance on this issue. The variation in carbon value estimates depends on several uncertain aspects - which will remain uncertain - including climate sensitivity, assumptions about future emissions, and decision makers' ethical standpoints. Hence, there is no single correct monetary value for CO_2: it will depend on the ethical standpoint of the user. Due to this, estimates of social costs of CO_2 emissions cannot be used for calculating an optimal emission level, although they can inform such assessments. It is suggested that marginal abatement cost values are used for emissions capped by binding targets in short-term assessments, and that social cost of carbon values should be used for all other emissions. Benchmark principles for choosing a monetary carbon value are suggested along with associated estimates. Depending on the choices made with regard to ethical standpoints and assumptions about future emissions and climate sensitivity, estimates can be significantly higher than the ones typically used in assessment tools today. The estimates need continuous updating, and there is need for better understanding and communication around the limitations and uncertainties involved.

1. Introduction

In policy and business project appraisal, comprehensive interpretations of the climate impact of different policy and production alternatives are often used or needed. When deciding upon political ambition, policy measures or business projects, or when introducing specific regulatory instruments for incentivising change towards objectives already in place, descriptions on the direct and indirect emissions of CO_2 and other greenhouse gases and their associated costs and benefits to society as a whole are increasingly becoming mandatory (e.g. Directive 2012/27/EU). The usual procedure within policy is to express climate related impacts in monetary terms and apply these values in impact assessments and decision support tools, such as cost-benefit analyses (CBA) (OECD, 2014). Although less common, monetisation is also used for weighting different emissions and resource flows in life cycle assessment (LCA) for environmental management within different business sectors (Johnsen et al., 2013; Pizzol et al., 2015)[1]. Monetisation is sometimes used for weighting of different environmental impacts also in other environmental assessment tools, such as Environmental Impact Assessment, Life Cycle Costing and Strategic Environmental Assessment (Ahlroth et al., 2011) as well as in indicators of resource use and resource availability (e.g. Goedkoop et al., 2013 and Isacs et al., 2015).

Since there exist hundreds of different monetary value estimates of CO_2 and climate impacts in the scientific literature and in policy guidelines, it might be tricky to know which estimate to pick, what the difference between existing estimates actually signify, and what it implicates to use a specific estimate in impact assessments. In fact, these are commonly expressed concerns both within policy and business sectors wishing to make decision-making more robust and transparent (Ahlroth, 2014; Ahlroth et al., 2011; NIER, 2012; OECD, 2014). The objective of this paper is to give some guidance to practitioners who wants to – or must – apply a monetary value of CO_2 and other greenhouse gases in tools such as CBA and LCA on which estimates to pick and what the difference between different estimates signify and implicate.

A literature review was made based on literature searches and contacts with experts, selecting scientific publications and grey literature mainly from the years 2006-2015. Section 2 presents a number of applications of assessment tools in policy and in business where monetary carbon values are used or could be used. In section 3 we describe the theoretical and methodological basis of the two dominant approaches based in economics for monetising impacts of CO_2 emissions – the damage cost approach (SCC) and the marginal cost approach (MAC) – in order to clarify differences between them when used in decision support tools, within both policy and business. We also explain when and why different approaches are applicable and not under different circumstances, which factors are the most important determinants of the levels of SCC and MAC estimates, and which uncertainties are the most significant. Section 4 presents examples of existing carbon value estimates that are used and could be used in impact assessment tools within policy and business, and in Section 5 a selection of these are applied in a simple case study to illustrate how the choice of estimate impacts the assessment outcome. Based on this, we discuss and make some recommendations concerning benchmark principles for choosing a monetary carbon value in different applications and suggest future research needs (Section 6). The final section concludes.

A key aspect of our methodology was the close cooperation with stakeholders from industries, governmental agencies and researchers from different fields. Workshops, meetings and interviews were organised in order to identify key practical problems, important methodological aspects and relevant literature. The case study was based on data from two major international companies. Recommendations are partially based on previous studies, partially on discussions within the project group and with stakeholders.

2. Uses of monetary values

In both policy and business, there are different types of assessments where monetary values of environmental impacts are used or may be used. In the two sections below some of these are described.

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[1] We use the terms “monetary value” or “monetary estimate” when referring to values measured in money metrics, and hence “monetisation” for the “putting a monetary value on” something. The term “economic”, which is often used interchangeably with “monetary”, is a much broader concept, which comprise wider societal activities, like e.g. social interactions concerning consumption and production patterns of different kinds (not only marketed ones) and allocation relating to resource use and trade-offs between different values in general. Likewise, the term “value” is easily misled as denoting merely monetary value (see e.g. Baggethun et al. (2014, p.6), while its actual meaning rather relates to “importance” and, consequently, “valuation” to an “estimation of the worth, meaning, or importance of something” (Ibid). Nevertheless, we use the term “value” and “estimate” interchangeably when referring to measurements or metrics as in indicators, both in monetary terms and in broader value terms.

2.1 Different types of impact assessments in policy

Based on Watkiss and Downing (2008), UK Department of Energy and Climate Change (DECC) (2009) and OECD (2014), we identify four main types of policy appraisals where monetary estimates of the costs of CO_2 and other greenhouse gases are applied:

1. *Efficiency CBA* (target setting impact assessment): calculating the costs and benefits of different ambition levels in climate policy, e.g. an emission concentration level or an emission reduction level, assessing if targets are set optimally (as in whether estimated costs to reach the target equal the benefits of reaching the target).
2. *Policy CBA* (regulatory impact assessment): calculating and comparing the costs and benefits of emission savings resulting from governmental regulations where one of the primary purposes is to reduce emissions, e.g. quantitative restrictions or obligations like laws and quotas.
3. *Assessments of economic instruments*: determining the efficient rate of emission taxes, charges and subsidies or when adjusting such rates.
4. *Project CBA* (project appraisal): calculating and comparing costs and benefits of specific measures, e.g. implementations of or changes to transportation systems or energy investment programs, assessing whether the benefits of the project exceed (or at least equal) the costs.

As stressed by DECC (2009), however, costs of CO_2 may be relevant to assess in whatever policy or project being appraised, providing there is some material impact on emissions.

All four types of appraisals above can be performed both *ex ante,* supporting or informing on upcoming policy choices, and *ex post*, in the form of evaluations of, for instance, whether climate targets or tax rates have been imposed in line with overall ambitions.

2.2 Different types of impact assessments in business

Monetary estimates of impacts from CO_2 and other greenhouse gas emission can be used in a number of different decision situations within business. If the social costs of greenhouse gases to some extent have been internalised, for example through a CO_2 tax or tradable emission permits, these will be included in the regular business practices. In addition to these costs, it may be of interest to businesses to also consider social costs not yet internalised. The list below describes some situations where this might apply.

1. In *environmental management* there is a need to recognise the environmental aspects of an organisation and its activities and to identify those aspects that have or can have significant impact(s) on the environment (ISO, 2004). Monetary valuation of the impacts can be used for this identification (Ahlroth et al., 2011).

2. In LCA, a cut-off criterion for defining *which flows, unit processes and impact categories to include in an LCA* is sometimes needed (JRC-IES, 2010). The results from a preliminary weighting made with monetary metrics can be used to define such a cut-off criterion.

3. *Choices of product alternatives*, e.g. in procurement, often require making trade-offs through weighting (Byggeth and Hochschorner, 2006). An advantage with weighting through monetisation is that environmental costs may be compared to the value created by the product.

4. *Go/No Go decision in product development*: In product development the Gate Model is often used (Tingström et al., 2006), which implies checkpoints at certain steps in the development process where certain performance criteria have to be met. Environmental performance criteria may be formulated in physical terms or by estimating the impacts in monetary terms.

5. In *a permit application review* (for deciding upon e.g. emission allowances), terms and conditions can be influenced by monetisation of impacts. A guiding principle in setting permits is that the company must accept abatement measures that are economically and environmentally reasonable (Directive 2010/75/EU). Information about impact and abatement costs is thus crucial.

6. A yearly *reporting* of environmental costs of a company together with its economic performance is a way of showing to investors and other stakeholders that risks are known and monitored.

7. *Investments*: Monetary values of environmental impacts can be seen as measures of financial risks involved in an investment.

3. Valuation of greenhouse gases in economics

Although there exist several ways to estimate the cost of emissions driving climate change, finding monetary estimates for greenhouse gas emissions is more challenging compared to externalities that are relatively more limited in time and space. This is one of the reasons why model-based scenario approaches are common, rather than for example direct scenario approaches based on individuals' willingness to pay to avoid climate change.

Two main approaches currently stand out as most common in the literature on monetary valuation of climate impacts (e.g. Watkiss and Downing, 2008; Mandell, 2011; Bateman et al., 2014; OECD, 2014). Both have their basis in economic theory and practice. One of them tries to estimate the *damage cost* to society due to impacts from climate change. The other approach is based on estimating the cost of CO_2 or other greenhouse gas *emission reduction*. When expressed as a marginal value (an incremental change), the first is usually referred to as *the social cost of carbon* (SCC), the latter *the marginal abatement cost* (MAC).

An SCC estimate is defined as the value of the damage from climate change impacts associated with an additional ton of CO_2 emitted into the atmosphere (Pearce, 2003). Since the counterpart of the damage cost of that ton is the benefit of avoiding it, SCC can be used to measure both the damage cost of actions causing increased emissions and the benefit of measures avoiding emissions (Anthoff et al., 2009a). A MAC estimate is instead an estimate derived from the marginal cost to reach a certain emission reduction target. The cost at the target level is a measure of the price per ton CO_2 that society at least needs to pay to reach the target (Kesicki, 2013a).

Theoretically, estimates of SCC and MAC could be equal: since a MAC value represents society's cost to avoid climate change damages, it is, under perfect circumstances, a mirror of the benefit of avoiding those damages, just like the SCC value. If an emission target is set optimally, MAC at the target level should coincide with SCC at the target level.

Figure 1 shows a schematic illustration of MAC and SCC for different emission levels. A common result in the literature, which is also illustrated in Figure 1, is that damages are expected to rise more than proportionally to the atmospheric concentration or temperature (Pearce, 2003; Hope and Newbery, 2008). This is because an SCC estimate is a function of both the total emission level and the temperature increase, and costs related to one ton of CO_2 therefore depend on the timing of the emissions. As for the MAC curve, the more abatement is made (leading to less emissions) the more the abatement cost increases at the margin. This is explained by the fact that the market is expected to allocate abatement efforts in a least cost manner, realising low-cost measures before more expensive ones.

The point where MAC equals SCC can be interpreted as the optimum level of emissions. If we reduce emissions less than this, the cost of reduction is lower than the damage cost and it would therefore be worthwhile to reduce the emissions further. On the other hand, if we reduce emissions more than the optimum level, the cost of reducing the emissions is higher than the benefits from the avoided damages. Principally, this is the appropriate carbon value.

Thus, if perfect circumstances apply, either of the two approaches – valuation with SCC or MAC – is applicable to greenhouse gas emissions in a CBA and in other types of tools where climate change impacts are to be valued monetarily (DECC, 2009). This is the basis of carbon valuation based in economics. However, the fact that perfect circumstances do not apply means that no "true" estimate of damages costs is accessible; targets are also set more or less ambiguously, and, consequently, SCC and MAC estimates differ. The two approaches are therefore, to some extent, two independent exercises.

3.1 How are SCC estimates calculated?

An SCC estimates is a representation of the current understanding of the magnitude of quantifiable impacts of incremental greenhouse gas emissions, measured in monetary terms (DECC, 2009). SCC estimates are calculated in integrated assessment models (IAM), which combine modules of climate system dynamics and economic impacts of climate change. The most usually applied IAMs are PAGE (Hope, 2006; 2011), DICE (Nordhaus and Boyer, 2000), FUND (Tol, 1997) and RICE (Nordhaus and Yang, 1996). Tol (2008; 2013) shows that almost 90 per cent of the peer-reviewed SCC estimates are based on any of these four models. An IAM simulates the cost of the expected incremental damage along an emission pathway due to a small increase in CO_2 emissions (e.g. a ton) emitted at a certain point in time (Pearce, 2003). The SCC is then estimated as the sum of the differences in total damage cost between the reference case (i.e. business as usual) and the case with the extra ton.

Thus, the damage cost depends on what we assume about both the adjusted emission scenario and the original (reference) emission scenario, which in turn depend on current projections of the economic growth, carbon intensity and costs of mitigation. In turn, important determinants are the assumptions made about climate sensitivity, direct and indirect economic impact resulting from higher temperatures, society's adaptation and vulnerability as well as the monetary valuation of different impacts (e.g. Tol, 2012; Pindyck, 2013).

Parts of an emitted ton of CO_2 stay in the atmosphere for centuries. The impacts may linger even longer and be irreversible. SCC estimates should therefore include the value of the damages caused by the extra ton during its entire lifetime. The fact that most of the damage happens generations from the act of emitting therefore implies that any cost of reduction today of policies or other abatement actions must be justified by the benefits of impacts avoided in the far future (Anthoff et al., 2009a). Like in most economic assessments, such intertemporal weighing in IAMs is handled through the use of a discount factor describing the relative value of consumption over time in the eyes of current consumers, which can be thought of as an indicator of intergenerational concern. The typical discount rate used builds upon the so-called Ramsey formula (Ramsey, 1928), $r = \rho + \eta g$, where r is the social discount rate, ρ is the pure rate of time preference, η is the elasticity of marginal utility of consumption and g the growth in consumption per capita. The higher the rate of time preference, the lower the present value of costs of climate change incurred in the future, and a low rate of time preference therefore means a greater concern about climate change (Tol, 2013). Most economists support a rate of time preference higher than zero (Anthoff et al., 2009b, p.844); the common assumption is an average rate of 3% (Tol, 2013, p.913). As for the elasticity of marginal utility of consumption, it plays several roles partly working in opposite directions (Anthoff et al., 2009a). *Diminishing* marginal utility is a reason for placing a lower value on future generations' welfare if they are forecasted to be richer, because the utility received from extra consumption declines with higher levels of consumption; but it also implies risk aversion, meaning disliking uncertainty and negative surprises, which in turn increases the willingness to pay to mitigate climate change if climate change makes future consumption prospects uncertain. Moreover, it is a reason to place greater weight on climate impacts on poor, since the same monetary damage causes a greater utility loss to a poor person than to a rich (Ibid; Anthoff et al., 2009b) (a fact that means consumption sacrifices for emission reduction is relatively more expensive in poor countries than in rich, as highlighted by Dasgupta, 2007; 2008). Intra-generational distributional issues are mainly treated through so-called equity weighting. When an estimate is equity weighted, damage per monetary unit is assigned a higher weight in a relatively poor country than in a relatively rich country (Anthoff et al., 2009b). So, while most SCC estimates are presented as global aggregates, they should, according to Tol (2013), ideally be regionally adjusted with equity weights to take account of distributional effects due to different countries' economic development and vulnerability, also because poorer countries in general are more severely hit by climate impacts. The choice of equity weight thus drives differences in SCC estimates, as noted by Anthoff et al. (2009b, p.847):

> "… equity weighting explicitly assumes a social planner […]. The chosen perspective is crucially important. Different national decision makers would have different perspectives and choose different equity-weights. Equity-weights therefore do not overcome distributional concerns, or reconcile different positions— equity-weights merely make such concerns explicit."

In summary, taking into account diminishing marginal utility of consumption and growth in per capita consumption usually decreases damage estimates, while considering risk aversion and equity weighting increases them (Ibid; Pindyck, 2013). The fact that "the discount rate" in the SCC literature often refers to the rate of time preference alone indicates that its influence on estimates is substantial, although depending on the risk and equity preferences of decision-makers the combined effect of all parameters in the Ramsey formula is in fact ambiguous.

3.2 Important uncertainties of SCC estimates

In theory, thus, an SCC estimate should comprise all kinds of climate change impacts world-wide on different determinants of human welfare (Pierce, 2003) – from agricultural productivity changes to human health risks, loss of biodiversity and costs of extreme weathers, to pick but a few. In practice, however, the story is different, and the literature on the uncertainties of the SCC approach is extensive (see e.g. Stern, 2013; Pindyck, 2013; van den Bergh and Botzen, 2015). Marten et al. (2013) summarise a number of limitations associated with SCC estimates in general, among which some of the most prominent are the incomplete treatment of damages (including potential catastrophic impacts due to e.g. extreme weathers), the uncertainty regarding the extrapolation of damage functions to high temperatures (most studies treat damages below 2.5 or 3°C warming), and the poor treatment of adaptation and technological change. On the two first of these issues, Weitzman (2012) suggests that damages should be modelled at around 50 per cent of economic output at 6°C, and at 99 per cent at 12°C, to reflect the current understanding of climate risks. To our knowledge, few studies have incorporated the updates of the most recent IPCC scenarios from 2013-2014, where estimates of temperature change in 2100 (without further climate mitigation) range from 3.7°C to 4.8°C, or 2.5°C to 7.8°C when including climate uncertainty, with further temperature increases after that (IPPC, 2014). The risks associated with temperatures at or above a 4°C warming include substantial species extinction, global and regional food insecurity, consequential constraints on common human activities, and limited potential for adaptation (IPPC, 2014). Many of these impacts are lacking in published SCC estimates.

Other important issues concern how best to model long-term socio-economic pathways and emissions (O'Neill, 2010), the oversimplified physical climate and carbon cycle modelling within the IAMs (van Vuuren et al., 2011), and the inconsistency between non-constant economic growth scenarios and constant discount rates (Kopp and Mignone, 2012). Additional critical challenges of IAM modelling are the development of sectorial and regional disaggregation (Interagency Working Group on Social Cost of Carbon, 2013). Moreover, non-marketed effects are poorly reflected, if at all (e.g. Stern, 2013).

As pointed out above, the choice of discount rate has a significant effect on SCC estimates. As an example, the mean SCC for studies that choose a 3 per cent rate of time preference is approximately \$7/ton CO_2, while it is \$80/ton CO_2 for studies with a zero per cent rate (Tol, 2013). The time preference and the equity weighting are some of the main parameters of dispute in the discounting debate, as well as the risk premium society should be willing to pay to avoid catastrophe (Anthoff and Tol, 2013).

The discount rate is usually set either based on data from market rates, assuming long term interest rates accurately describe people's revealed preferences for consumption tomorrow versus consumption today, or on ethical principles or political decisions reflecting considerations of what stance society should take concerning intra- and intergenerational equity and risk (Arrow et al., 2012). There are controversies around which approach is the correct. Both can be considered normative, since market rates are far from perfect empirical descriptions of society's preferences on long-term societal issues, in particular environmental issues such as climate change (Baum, 2009). Arrow et al. (2012) note that the use of financial market data is likely to reflect intra-generational rather than intergenerational preferences. Ackerman and Stanton (2012) argue that either way arguments can be made for a low discount rate (below 3 per cent): long-term average risk-free discount rates are often estimated to be lower than 2.7 per cent, and, as shown by DeLong and Magin (2009), real returns on (US) Treasury bills and government bonds have averaged 1.4 and 1.1 per cent respectively since the World War II.

According to Arrow et al. (2012), there are compelling theoretical arguments for a declining discount rate, which would reflect the fact that we know less about the far future. Likewise, they argue, the assumed expected growth rate of per capita consumption represented in the discount rate should fall with time, in order to reflect the uncertainty about future growth possibilities. This is supported by recent IPCC findings (2014), where climate change is expected to have impacts on economic growth, especially in poorer countries. The fact that climate change has no effect, or only a very weak effect, on GDP growth in the IAMs most often used (Moore and Diaz, 2015) confirms this further.

The climate sensitivity is the parameter describing the long-run temperature increase expected from a doubling of the concentration of CO_2 in the atmosphere; higher climate sensitivity makes higher temperatures and increased risks of catastrophe occur sooner (Ackerman and Stanton, 2012). In a decomposition analysis of the SCC using the FUND model, Anthoff and Tol (2013) identify climate sensitivity to be the most important contributor to variation in SCC estimates irrespective of discount rate level. The likely range of the climate sensitivity is between 1.5 and 4.5°C (IPCC, 2014) indicating the uncertainty. Higher climate sensitivity leads to higher temperature increases and thus larger impacts for a given increase in CO_2. If the climate sensitivity is overestimated, the opposite will occur. The other top ten most important parameters all concern agriculture, cooling energy demand and migration.

Thus, the uncertainties around SCC estimations are immense, and existing SCC estimates do not comply with the theoretical ideals described in Section 3.1. Some of the uncertainties are related to the scientific understanding of the climate system. Other uncertainties relate to the choices society will make in the future, for example concerning mitigation efforts. These two groups may be seen as uncertainties in the analysis of the impacts (sometimes called the impact pathway analysis). Yet another group of uncertainties comprise fundamental ethical and ideological issues, such as the choice of discount rate, the degree of equity weighting and risk society should accept, and what aspects to include in the concern for environment and society, all of which belong to the actual valuation step of the impacts. For some of these issues, certain ambiguities can be reduced with more research, and they can be described statistically. For other issues, the uncertainties will persist. In particular, the ethical issues depend on highly subjective standpoints on the part of the decision-maker. Put simply, no "right" answers to the moral questions surrounding climate change exist. In Section 6, the implications of these uncertainties are discussed further.

3.3 How are MAC estimates calculated?

Ideally, a MAC estimate would include all costs related to the reduction of a unit of greenhouse gas emissions to achieve a given climate target. If markets work perfectly, such an estimate would describe the cost of avoided climate related damages, determined by the emission level (politically) set by the target. Since this type of "shadow price of emissions" is rarely observable in an economy, MAC values are mostly estimated in models. MAC models combine data on past experiences and future projections of the interaction between different components in the economy and, just like IAMs, calculate reduction costs in relation to a reference scenario with no emission reduction (Söderholm, 2012). The result of such simulations, so-called MAC curves, demonstrates the cost of emission abatement available across an economy or for specific sectors, as well as projected reduction potential. It is a standard tool in environmental economics research used to assess various policy issues, but it is also readily used by decision-makers due to the fairly easy concept of showing important information in one graph (Kesicki, 2013b).

MAC curves are static and display a single point in time, often a future year situation when a given reduction target is supposed to be reached (Kesicki, 2013a). A MAC estimate is thus typically derived from the marginal cost associated with the last reduced unit of emission in the target year, which also equals the carbon price needed to meet the target (that is, the preferred carbon tax).

There are mainly two types of models, bottom-up and top-down, which broadly result in somewhat competing cost estimates. Bottom-up models are based on individual assessments of different abatement techniques, where the resulting MAC curve portrays a ranking of these techniques' reduction cost per emission unit from lowest to highest (Kesicki, 2013a). Top-down models are macro-economic general equilibrium or energy models, which, by the use of elasticities describing how actors respond both directly and indirectly to changes in market incentives, generally create the MAC curves by altering the price of carbon in the economy (for example a carbon tax) to record the corresponding aggregate emission reduction achieved up to a specific target (Kesicki and Ekins, 2011). While bottom-up estimations allow for great technological detail and reflect different substitution possibilities in the energy system (Kesicki, 2011), top-down estimations are often highly aggregated and best suited for analyses of sectors with relatively few firms and homogenous production and abatement technologies (Moran et al., 2011). However, in reviewing the literature, Kesicki (2013b) finds no consistent picture of the influence of model type on final MAC estimates.

Like mentioned above, in line with standard assumptions in economic theory about the marginal cost increasing with increased reduction efforts, long-term MAC are typically assumed to be higher than short-term MAC. Actual (realised) MAC levels are, however, ambiguous and depend on both past actions and expectations about future policies (Kesicki, 2013a). Much as with SCC, significant determinants are model assumptions made about the reference emission scenario, policy design and inclusion of non-marketed costs and benefits, but the most important factors concern the availability of abatement measures (Kesicki, 2013b), the development of their costs and efficacy (Söderholm, 2012) as well as the lifetime of technologies (Kesicki and Ekins, 2011).

Dietz and Frankhauser (2010) show that even though the variation in models and methodologies used for MAC estimations are much larger than for those of SCC, the spread in MAC estimates is ten times smaller than for SCC estimates. Like SCC estimates, MAC estimates are discounted in order to illustrate how abatement costs occurring further into the future are valued in relation to investment costs today, but since the time scale is mostly shorter than in SCC estimations, the problems associated with discounting are less pronounced with MAC estimates (Tol, 2012). In assessing several key parameters shaping MAC curves for the United Kingdom, Kesicki (2013b) shows however that the choice of discount rate is one of the factors influencing MAC estimate levels the most.

Estimates based on reduction costs derived from implemented climate policy instruments, like a CO_2 tax or an emission trading system, are sometimes treated as a separate approach for carbon valuation (see e.g. Mandell, 2013). We view such policy-derived estimates as a subcategory of the MAC approach, since they tend to be tied to regional, national or international policy regimes with binding or semi-binding targets. When in place, these can under certain circumstances function as MAC estimates. We return to this below.

3.4 Important uncertainties of MAC estimates

Like for SCC, many of the factors determining a MAC value are highly uncertain. According to Kesicki and Strachan (2011), uncertainty and inter-temporal issues are treated in a limited manner in MAC estimations, market failures and barriers are disregarded, and they lack transparency concerning basic assumptions in general. The choice of the discount rate is an important source of uncertainty here too (Kesicki, 2013b). In principle, in analyses where both types of estimates are applied, the same discount rate should be used for SCC and MAC for a given period in time. Since existing estimates may be discounted differently, an issue is therefore that comparisons at specific points in time are principally inadequate.

Different bottom-up and top-down models have their specific weaknesses (Söderholm, 2012; Kesicki, 2013b; 2011). Common to both types approaches is their sensitivity to assumptions made on key input drivers, like the emission levels of the reference scenario (Kesicki, 2011). A specific aspect concerning top-down models is that the elasticities used are based on historical data on market adjustments to previous changes in the economy, which creates a built-in conservative bias with respect to the possibilities of predicting behavioural change (Jaccard et al., 2011). Indeed, some of the most important uncertainties of MAC curves concern their dependency on forecasts about technological development; technical progress and efficiency gains are, for example, often found to shift MAC curves downwards, but they can also increase the cost of abatement by making the reference emission level less expensive (e.g. Kesicki, 2013b; Golosov et al., 2014). The same goes for the influence of policy: although, for example, the possibility of emission trading usually reduces abatement costs (e.g. Klepper and Peterson, 2006), the strength of past polices and the timing of the policy introduction can influence MAC estimates substantially in different directions (e.g. van Vuuren et al., 2004).

3.5 Social costs of CO_2 under a binding target

When choosing a monetary estimate for the social cost of CO_2 emissions, the existence of a binding policy target is a determinant factor. The reason is that when there is a fixed quantitative target for aggregate CO_2 or greenhouse gas emissions in a certain area, the aggregate climate-related damage from that area will, at least in principle, be fixed too. As long as the target is in effect, a project leading to a marginal increase in emissions still leaves overall emissions unchanged since a reduction of emissions is needed somewhere else in the targeted area with an equal amount in order to stick to the target. The unit cost for society of increased carbon emissions under such circumstances is therefore the cost of having to reduce emissions elsewhere in the economy (DECC, 2009). In efficient markets, this cost is typically the current marginal abatement cost in the economy as a whole (or in a sector if there is a sector-specific target): clearly a MAC value. If there is a well-functioning target-consistent policy instrument implemented setting a price on carbon emissions, the appropriate cost estimate to use for emissions occurring in the targeted area should therefore be based on the current marginal cost associated with that policy (Mandell, 2013; OECD, 2014). Then, as a measure of social value, a MAC estimate mirrors the opportunity cost for society of both marginal increases and decreases of emissions (c.f. DECC, 2009)

An important issue is thereby whether the emissions to be valued occur under a binding target or not. This is not always clear-cut, since both targets and target-related policies may be more or less rigid and can change. It seems reasonable, for instance, to argue that in the EU there is a binding target until 2020 for those sectors that are included in the European emissions trading system (EU ETS), whereas the 2020 targets for the remaining (non-trading) EU sectors are more uncertain (Mandell, 2013) and targets beyond 2020 are – at least this far – only intentional. Another example is the UK, which has a regulatory framework with a 2050 target set in law (DECC, 2009), which at least principally binds total UK emissions. The latter partly explains why, in 2009, UK changed its guidance for carbon valuation in policy appraisal from an SCC approach to a MAC approach.

Since different sectors often face different quantitative targets, MAC values deviate considerably at a given point in time, even within a single country. This is the case in UK and

Sweden, for example, where one part of the economy is capped under the EU ETS target and another by country-specific EU targets up to 2020. In Sweden, emissions of the non-trading sector are mainly controlled by a tax on CO_2, while UK has implemented a Carbon Price Floor from 2013 applicable to fossil fuels used for electricity generation. Both the permit price and a homogenous emissions tax (or similar cost-effective incentives) are principally appropriate estimates of the marginal abatement cost in the sectors to which they apply (Mandell, 2013). This is because profit maximising actors have incentives to reduce emissions as long as their marginal reduction cost is lower than the permit price (or tax). When the reduction cost is higher than the permit price, it will be cheaper to buy permits than to reduce. With increasing marginal costs of reduction it can therefore be assumed that aggregate emissions will be abated up to the level at which all actors' marginal cost equal the prevalent permit price (or tax level) at market.

Using taxes as MAC estimates is not straightforward though, since the actual abatement resulting from an emission tax is unlikely to correspond perfectly to a given target; to achieve that, the policymaker would have to have perfect information about the properties of the aggregate marginal cost of reduction at the market. Moreover, CO_2 taxes often have more motives than to reduce CO_2 emissions, such as fiscal or distributional motives (Mandell, 2013), which means that a tax-based MAC value could result in an overestimation (would the actual "CO_2 share" of the tax be correct) or an underestimate (if the policy makers can not introduce a high enough tax due to political or distributional reasons) of actual CO_2 costs. Most importantly, both emissions permit prices and CO_2 taxes rely on political decisions: using these values as decision support creates a circular bias (c.f. Clarkson and Deyes, 2002, as highlighted by Mandell, 2011).

Thus, the MAC approach seems to be relevant when a given binding emission target is in place, since it captures the actual social cost of emissions, determined by the value of the reduction reallocations in the economy. Although not optimal from an efficiency point of view, several MAC estimates may be valid simultaneously for different sectors, as described above, but in the long run the standard assumption is that MAC values will converge globally. This is further discussed below. It should be noted that MAC values develop with time, since both targets and technology can change. Consequently, the MAC approach implies that it is essential to stay updated regarding reassessments of both targets and related estimates. Should, for example, the emission targets become more stringent than those currently given by the EU, MAC values would increase (DECC, 2009). Here, the relation between SCC and MAC is relevant. Reassessments of targets naturally come as a result of political negotiations informed by economic and scientific evidence, SCC estimates included. As expressed by DECC (2009), "if realised abatement costs are higher or lower than expected, then this would feed into the modeling for IAMs and other such exercises, possibly leading to a reassessment of targets. Equally, new information on damage costs would feed into any reassessments of targets." (p.35).

4. Examples of estimates

Based on our review of scientific publications and grey literature from the years 2006-2015, as well as contacts with experts and practitioners, a selection of estimates is given in Table 1 to illustrate the broad range of possible carbon value estimates that could be used in impact assessment tools within policy and business. Being snapshots of existing SCC and MAC values in the literature, their applicability in practice should be treated with caution, but the estimates can be considered representative for the two types of approaches, and as under- rather than overestimates. Except for the EU ETS prices, which in line with Section 3.5 are given by current market prices, selection motives for each estimate respectively are given below.

Values are given for two points in time, for emissions in 2015 and in 2050, and for lower and higher values in each category. The MAC estimates apply to EU. In line with the discussion in the former sections, there are two different categories of MAC estimates: one for emissions that are capped under the EU ETS, and one for the EU emissions outside EU

ETS. The Swedish CO_2 tax is chosen as an example of a country-specific MAC estimate for non-traded emissions in short-term analyses. The SCC estimates are global.

Table 1. Examples of carbon value estimates in the literature, EUR/ton CO_2, 2015 price level.

Approach & sector relevance		**2015**		**2050**	
		Lower	*Higher*	*Lower*	*Higher*
MAC	*EU traded emissions*	Current low EU ETS price[a] EUR 6.5	Current high Futures EU ETS price[a] EUR 7.3	Projected low global market price[c] EUR 133	Projected high global market price[c] EUR 398
	Non-traded EU emissions	Min current Swedish CO_2 tax rate[b] EUR 72	Max current Swedish CO_2 tax rate[b] EUR 120		
SCC	*Emissions without binding target*	Mean global 2015 estimate of Tol 2013[d] EUR 6.1	Ackerman & Stanton highest[e] EUR 724	Mean global 2050 estimate of Tol 2013[d] EUR 13.4	Ackerman & Stanton highest[e] EUR 1214

Sources: All estimates are converted from original values (presented below) to a 2015 EUR level using deflators and exchange rates from official statistics, respectively, when so needed.

[a] European Energy Exchange (2015): corresponding to EU ETS market values of EUAs in 2015 EUR/ton CO_2 as of 2015-02-11.

[b] Swedish Tax Agency (2015a; 2015b): original values in 2015 SEK (660 and 1100/ton CO_2, respectively).

[c] DECC (2013): original values in 2013 GBP (110 and 329/ton CO_2e, respectively), based on forecasted long-run prices from the GLOCAF model (see DECC, 2009).

[d] Tol (2013): our 2015 estimate origins from Tol's value in 2010 USD (25/ton C, which was converted to CO_2 by dividing it with 3.67). The 2050 estimate is calculated using the 2010-value and its annual growth rate, 2.3%, as presented in Tol (2013) (see also Bateman et al., 2014, where Tol's value is used for calculating long-term SCCs in the same manner).

[e] Ackerman and Stanton (2012): original values in 2007 USD (892 and 1,496/ton CO_2, respectively).

The lower short-term MAC estimate for emissions covered by the EU ETS cap, EUR 6.5/t CO_2, is the current (February 2015) market price of European Emission Allowances (EUAs), while the higher estimate in the same category, EUR 7.3, is the observed maximum market price of EUA Futures in 2015 at the same point in time (European Energy Exchange, 2015).

Other studies have presented considerably higher upper levels of short-term EU ETS prices (e.g. DECC, 2013; Tol, 2012). Observed market prices for futures up to the year 2017 (European Energy Exchange, 2015) and several policy analyses (see e.g. Zetterberg et al., 2013) do, however, indicate that the EU ETS price will stay at current levels until year 2020. Given that the only currently binding target for EU ETS is that of 2020, it is reasonable to pick a level consistent with that policy.

As stated above, the Swedish tax on carbon emissions can be used as a MAC value for the non-trading Swedish sectors, such as transport and housing. The minimum level of the Swedish tax on CO_2 in 2015 is EUR 72/ton CO_2, which represents 60 per cent of the full tax rate of EUR 120/ton CO_2 in 2015 (Swedish Tax Agency, 2015a; 2015b). The lower level applies to part of the manufacturing industry subject to international competition.

In comparison, in a report for the European Commission, Korzhenevych et al. (2014) present a short-term central value of EUR 90/ton CO_2 (in 2005 prices) for use in impact assessments of transport policy based on recalculations of a meta-study of MAC estimates by Kuik et al. (2009). The estimate is said to represent "the avoidance costs" of efforts required to meet the 2°C target, and the authors argue that using MAC instead of SCC values is relevant "if the emission reduction targets adequately reflect the preferences of society" (Korzhenevych et al., 2014, p.55). The value, which is of the same magnitude as the Swedish carbon tax, could serve as a short-term MAC estimate for non-traded EU emissions.

The 2050 MAC estimates, EUR 133 and 398/ton CO_2, represent the sensitivity interval of the global carbon values in 2050 projected by DECC (2013; 2009), that is, -/+50 per cent of a central value estimated by the use of UK's MAC model Global Carbon Finance. The value is said to equal the global carbon price expected to be consistent with the 2°C target (equalling a stabilisation level of 475-500 ppm). According to DECC (2009), the sensitivity range is based on most of the available 2050 model estimates of global abatement costs for relevant emissions trajectories by the time of the study, excepting studies with unreasonable assumptions regarding, for example, target-consistency and outdated business-as-usual assumptions. As seen, the EU ETS and non-ETS long-term MAC estimates picked in Table 1 are the same. This is in line with most studies of long-term marginal abatement costs, which assume a global carbon market is in place by 2050, resulting in converged prices between the EU ETS trading and non-trading sectors (DECC, 2009). Evidence suggests that costs may be significantly higher without full international trading, and the 2050 estimates may therefore be underestimates (Ibid).

The SCC estimates in Table 1 are picked from two studies assessing global damage costs from which we could derive both 2015 and 2050 estimates. The lower estimates, EUR 6.1 and 13.4 per ton CO_2 respectively, are taken from a meta-analysis made by Tol (2013), covering 588 damage cost estimates. They represent the mean SCC value in 2010 of studies using a 3 per cent rate of time preference, which is assumed to grow at a constant growth rate of 2.3 per cent yearly (see also Balmford et al., 2014). Despite being mean values, and although even lower figures exist, these are here regarded as low SCC estimates. The reasons are several: the meta-analysis include studies based on old data, conservative assumptions about climate sensitivity and incomplete damage functions, where uncertainty about climate change itself, future emissions and concentrations are disregarded, as are possible changes in vulnerability of society to climate change. Furthermore, since the original studies only assess scenarios up to 3.0°C warming, SCC for greater warming is based on highly uncertain extrapolation. The (standard but) relatively high discount rate, no equity weighting and/or risk premium imply the figures may be underestimated considerably with regard to possible catastrophic climate change (c.f. van den Bergh and Botzen, 2014). Short-term SCC estimates at EUR 6.1 to 13.4/ton CO_2 are also in line with average lower-end estimates of other studies (e.g. Anthoff and Tol, 2013), as well as with the lowest SCC estimate for 2015 in the recently updated US guidelines for policy appraisal (Interagency Working Group on Social Cost of Carbon, 2013).

The higher SCC estimates for both 2015 and 2050 are from Ackerman and Stanton (2012), who explores the effects of adjusting the DICE model for four major uncertainties affecting SCC calculations: the climate sensitivity, the level of damages expected at low and at high temperatures (the damage function), and the discount rate. The estimates picked here, EUR 724 and 1214/ton CO_2 for 2010 and 2050 respectively, result from combining a low discount rate (a pure rate-of-time preference of 0.1 per cent), high climate sensitivity, and damage estimations taking catastrophic climate change into account. Results obtained by the US' Interagency Working Group on Social Cost of Carbon (2010) indicate that Ackerman and Stantons' model adjustments would have generated higher estimates if they had been applied to a model with a less conservative treatment of potential catastrophic climate change than that of the DICE model (and, conversely, lower estimates if applied to an even more conservative model) (Ackerman and Stanton, 2012). Thus, the high SCC estimates of Table 1 may be viewed as intermediate when considering model design. On the other hand, although the estimates from Ackerman and Stanton here serve as examples of high SCC estimates, there are higher estimates still: the maximum value included in the above-mentioned meta-study by Tol (2013), for example, far exceeds the estimate of Ackerman and Stanton reported here, and Anthoff et al. (2009a) present global SCC as high as EUR 30,000/ton CO_2 (in 2005 prices).

It can be noted that in general the range between low and high values for a given time period is larger for SCC estimates than for MAC estimates. This is not surprising given the large uncertainties of SCC estimates related to long-term impacts of climate change and ethical considerations.

5. Case study

To illustrate the influence of different levels of monetary estimates of CO_2 in practice, we performed a simple case study. Based on environmental and financial reports from two global businesses, ABB and the Volvo Group, the costs of their contribution to climate change were calculated and compared to their financial results (ABB, 2013, 2014; Volvo Group, 2014).

ABB is a company in the power and automation business with over 300 manufacturing sites located in more than 100 countries (ABB, 2014). The Volvo Group is one of the world's leading manufacturers of trucks, buses, and construction equipment and drive systems for marine and industrial applications, with production in 19 countries and sales of products and services in more than 190 markets.

The monetary values of Table 1 were applied to the emissions emanating from both production and operational activities of the two companies, including emissions from production of electricity and heat. The resulting total CO_2 costs were compared to their respective annual earnings before interest, taxes, depreciation and amortisation (EBITDA). The results are presented in Table 2. Depending on the valuation approach and estimate used, the cost for emissions spans from non-significant to highly significant. The results indicate that the monetary value of their respective CO_2 emissions can be significant, compared to the earnings of the companies. Hence, if external CO_2 costs were to become internalised, this could have a substantial impact on the long-term performance of the companies.

A comparison of the costs of the two companies shows that the location of manufacturing sites, and associated energy mixes, has a high impact on the total cost of emissions for the companies. This results in substantial differences in CO_2 emissions per EBITDA (Table 2), and indicates that countries with low emission energy mixes and investments in renewables and low carbon energy, such as Sweden, will become more attractive for manufacturing, provided that CO_2 emissions from transport do not increase more than the CO_2 reduction achieved by changing the location of the production site.

Table 2. Costs of CO_2 in 2015 and 2050 of the two companies for different types and levels of estimates, in % of annual earnings measured in EBITDA.

		MAC				SCC	
		EU ETS		Swedish non-ETS			
		Low	High	Low	High	Low	High
2015	ABB	0.23	0.26	2.6	4.3	0.22	26
	Volvo	0.11	0.13	1.2	2.1	0.10	12
2050	ABB	4.7	14	4.7	14	0.48	43
	Volvo	2.3	6.8	2.3	6.8	0.23	21

Sources: Data from the 2013 Annual Reports and Sustainability Reports of ABB and Volvo Group, respectively, published in 2014. Unpublished data of total EBITDA of the Volvo Group and updates of the Volvo Group emission data, accessed through personal communication, are added ex post.

6. Discussion and recommendations

From the review presented in this paper, it is clear that there are important uncertainties related to estimations of the monetary value of social impacts of CO_2. These uncertainties are related to ethical issues, but also to climate sensitivity and future emissions of CO_2 and other greenhouse gases. The two latter determine the future temperature increase to which the value of CO_2 is sensitive. The fact that monetary values depend on ethical positions, to which there are no objective answers, means that there is no single correct monetary value for CO_2; it will depend on the ethical standpoint of the users.

6.1 Monetary carbon values in policy-making

The uncertainties and limitations of MAC and SCC estimates at any given temperature level imply, according to IPCC (2014), that they cannot be used for evaluating the costs and benefits of climate mitigation. It is therefore outside the scope of science to identify a single best climate change target and climate policy (Ibid). In Section 2 of this paper, a number of applications were presented where monetary values of carbon emissions may be relevant in assessments of policies. Although calculations of the social cost of climate change can inform target setting (c.f. DECC, 2009), akin to an efficiency CBA, they cannot replace the political process where a broader spectrum of issues can be contained. The other types of CBAs described in Section 2.1 are, however, performed more or less routinely, in some contexts they are even required by law, and the question therefore remains what values to use in these situations.

As discussed above, there is a significant difference between situations where there are binding targets or not. Where there are binding targets, MAC values for the geographical area in question may be used for many decisions, since, as long as the target remains binding, a MAC value describe the social cost associated with marginal changes in carbon emissions in that area. It may not always be clear-cut if existing targets are binding or not, though. There may, for example, be targets for which it is unclear to what extent they actually limit overall emissions. Specifically, due to the uncertainties surrounding both technological development and long-term policies, the accuracy of a MAC estimate diminishes the further in time we are from the target (and this applies no matter how binding the target currently seems). It may therefore be questioned whether MAC estimates are at all relevant in long-term assessments. In such cases, it is suggested that sensitivity analyses are made using both higher and lower values of MAC and SCC, respectively.

For emissions not covered by binding targets, SCC values should be used. There is still the question, however, of which SCC estimate to pick. We make two suggestions:

1. The choice of monetary estimate should reflect the values that the decision-maker wants to be revealed in the decision.
2. Sensitivity analyses should be made using alternative estimates.

Related to the first recommendation, it may in practice be difficult to interpret what the different SCC estimates presently at hand imply. In such cases, we suggest three sets of benchmark principles to use when choosing an SCC value, varying with the main uncertainty aspects highlighted in this paper:

A. Estimates based on assumptions of low climate sensitivity, less importance of future generations compared to current (suggesting a higher discount rate), and less risk concern. The lower SCC values in Table 1 could be consistent with these values (EUR 6.1/ton CO_2 for short-term assessments and EUR 13.4/ton CO_2 for long-term (year 2050)).

B. Estimates based on assumptions of high climate sensitivity, an equally important weight put on future generations as that of the current (suggesting a lower discount rate), and the inclusion of possible catastrophic climate change. The higher SCC values in Table 1 could be consistent with these values (EUR 724/ton CO_2 for short-term assessments and EUR 1214/ton CO_2 for long-term (year 2050)).

C. An intermediate between the two previous sets; this would suggest an SCC estimate equal to the average of sets A and B (i.e. EUR 365/ton CO_2 for short-term assessments and EUR 614/ton CO_2 for long-term).

Set C may be used if no consensus can de reached on arguments for any of the others. This might seem contradictory, given the message of this paper: why advocate a figure when no estimate is said to be truer than the other? The suggestion to use an average between the estimates in sets A and B is motivated by the notion that the values on which the estimates are built, are all equally relevant – including the ethical aspects. A more sophisticated statistical distribution for the ethical values is not meaningful, as there is – at least to date – no satisfying empirical data for such a distribution. An average based on all existing estimates presented in the literature would also suffer from selection bias, since, when a majority of the calculations are run using a similar set of assumptions this has a substantial influence on the results. With regard to the ethical aspects, it is a well-known fact that many of the estimates published in the literature consistently discount the value of future generations, and does so on a comparatively weak basis considering the circumstances. The mean value of a majority of the existing SCC estimates, as presented in Tol (2013), is therefore not far-fetched as a benchmark for the values in our set A. The set A estimates can also be considered conservative due to their dependence on older data concerning the impacts of climate change; indeed, van der Bergh and Botzen (2014) argue that values corresponding to set A "represent severe underestimates" (p.256).

It should be noted that the estimates presented in Table 1 are examples from the literature. The background of these is presented in Section 4. Short-term MAC values are based on current market data. This is in line with guidelines in the UK approach (DECC, 2009), which is among the most comprehensive and transparent assessments of carbon valuation. From UK's approach are also the long-term MAC values chosen. Since it is assumed that European MAC values will converge – a common assumption in several analyses – they can be viewed as relevant also for other parts of Europe (although, as highlighted above, all long term MAC estimates should be treated with caution). In relation to the SCC estimates it can be noted that both higher and lower values are available in the literature than the ones given in Table 1. The set A estimates are for example significantly higher than the USD 125/ton CO_2 described by van der Bergh and Botzen (2014) as a conservative lower bound to SCC. Our figures should therefore not be considered as extremes, but rather as examples of low and high values. As noted above, the lower values from Tol (2013) illustrate estimates typical for assessments based on assumptions leading to relatively low SCC estimates. The higher SCC estimates of Ackerman and Stanton (2012) exemplify a study where different assumptions were tested in a systematic way, not only one by one but also combined, to illustrate their aggregate effect on SCC. It can also be noted that although the uncertainty is large, this is not uncommon for impact assessment data in general. For example, the precision of characterisation factors for human toxicity data is considered to be up to three orders of magnitude (Rosenbaum et al., 2008).

The suggestion to base valuation on different sets of archetype values, and to carry out sensitivity analyses is similar to the approach used in some Life Cycle Impact Assessment methods, in particular the Ecoindicator and the ReCiPe (Goedkoop et al., 1998; 2013) where a cultural perspective is used (Hofstetter et al, 2000). In their words, our set A corresponds to the so-called "Individualist perspective", set B to the "Egalitarian perspective", and set C to the "Hierarchist perspective" where these perspectives influence not only the weighting step, but also other parts of the assessment which should be consistent with the chosen values.

6.2 Monetary values in business applications

As discussed in Section 2.2, there may be different applications in business where the social costs of CO_2 and other greenhouse gas emissions are of relevance. Three different types of uses can be identified, where SCC and MAC values are suitable under different circumstances:

- Situations where the monetary estimates are used as measures of the environmental impacts and the different impacts need to be compared to each other: two examples are environmental management and life cycle assessment where emissions of CO_2 and other greenhouse gases are compared to emissions of other pollutants. In such situations, it is reasonable to use the SCC values as a best approximation of the significance of CO_2, also in situations where there are binding targets. The reason is that SCC is a more adequate measure of potential damage costs, which can be compared to the damage costs of other pollutants.

- Situations where the social costs of greenhouse gas emissions are to be compared to other costs: this could for example be the case in procurement, product development or in permit applications. These situations are similar to a cost-benefit analysis and the same recommendations as for policy are relevant; that is, to use MAC values in cases where there are binding targets and SCC values when there are no binding targets. It is also important to consider to what extent the external cost have already been internalised in order to avoid double-counting.

- Situations where the social cost is considered as a possible financial risk. If there are high possible social costs associated with, for example, an investment or a product that has not yet been internalised, there is a risk associated with this investment or product. If regulations to internalise the social costs are implemented, previous economic assessments may change and the profitability of the investment or product may decrease. In this case, it is the SCC minus the already internalised cost of CO_2 or other greenhouse gases that is a measure of the possible consequence. Focusing on risk, the higher values represented by set B above should be of interest.

As suggested above, in some situations MAC values would be most relevant. As a consequence, companies working on international markets may need to use several different cost estimates for CO_2. This may seem inconsistent with general principles of cost-effectiveness, but is, as described in Section 3.6 above, related to the geographical and sectorial dependence of the MAC values and the fact that different countries face different climate targets. The energy mixes in different countries already influence the location of new facilities in some sectors, such as server halls (Facebook) now located in the north of Sweden in order to profit both from the climate and the energy mix of that area. The different MAC values in different countries could also be relevant when different locations are compared. In the long run, it is, however, expected that reduction costs in different countries and sectors, and consequently MAC values, will converge along with converging product markets and linking of policy regimes.

A MAC value represents the actual payment per unit of CO_2 emission that companies are facing if there is a policy instrument connected to a binding target. Although the same does not apply to the SCC, the SCC value is relevant from a risk perspective. Significant social costs of carbon associated with a product, a service or other types of business activities may entail future risks that decision-makers within business should be aware of and, possibly, avoid. Risk indicators are regularly demanded by banks and insurance companies. Monetary estimates of carbon emissions may serve as such and benefit actors who are able to show that their emission costs are decreasing.

As noted in the case study above, the choice of value can have a significant influence on the results. The higher values result in significant costs compared to annual earnings. Reducing emissions would be a way of reducing such risks. Monetisation of CO_2 emissions can also motivate investments in renewable energy generation and increase the need for new technologies in this area. Besides identifying risks, monetisation can also be used to identify possibilities and needs for new products and technologies. In such applications, the choice of different values can also influence the ranking of different alternatives.

To decrease the total CO_2 emissions of the globalised economy, a homogeneous approach for the implementation of monetisation is needed in order to avoid sub-optimisation. Businesses today tend to move manufacturing sites to low-cost areas in order to optimise revenues. If systems of monetisation are designed badly, they can lead to unwanted side effects that increase both CO_2 emissions and total social costs of abatement. The MAC values that companies are facing should therefore not be too low or too high compared to the SCC value, why it is important to regularly assess the two iteratively.

6.3 Future research needs

Although some of the limitations and uncertainties involved in calculations of social costs of climate change are inherent and will remain, it is important that research is continued in this area. This is because decision-makers both within policy and business demand monetary estimates of CO_2 and other greenhouse gases. It is therefore vital both that the limitations that can be reduced are so done, and that those that cannot be reduced are clearly described and understood.

Some of the uncertainties are related to the scientific understanding of climate change and, as science evolves, it is important that it gets integrated in the models with minimum time lags. The models and estimates currently used are typically not based on the latest climate change science. Since it is clear that without the introduction of ambitious mitigation measures, the temperature increases can be significantly larger than those for which most estimates are calculated, it is essential to develop models and estimates also for higher temperature changes.

The estimates depend on values concerning the importance of future generations' welfare compared to that of current generations and the risk society is willing to take. In the calculations made, these values are normally based on assumptions made by scientists or on market observations. It would, however, be interesting to study the values that different groups of people actually hold and how these influence final carbon estimates. Moxnes (2014) showed that people are able to choose among policies by inspecting time graphs of policy consequences. In this way, discount rates could be deduced and used in future calculations. Also, Itsubo et al. (2015) used questionnaires where people in different countries choose between different policy packages to deduce weighting factors for LCA.

As mentioned, the suggestion to use benchmark sets of values coheres with ideas used for impact assessment methods within life-cycle assessment (e.g. Goedkoop et al., 2013). This could be further developed if estimates are calculated for explicitly stated sets of values. Another approach would be to systematically gather published estimates and sort them in relation to key uncertainties and assumptions regarding critical ethical standpoints. In this way estimates matched to different sets of values and standpoints could be better deduced.

The estimates and applications discussed here have mainly concerned CBA, LCA and assessment within environmental management and reporting. The applicability in other tools, such as environmental impact assessment, strategic environmental assessment and life cycle costing, are also of interest, however, and should be further investigated.

7. Conclusions

There are a number of monetary carbon values available, which differ by several orders of magnitude. The estimates depend on several uncertain aspects, including climate sensitivity, assumptions on future emissions and subjective ethical standpoints. We conclude that there is no single correct monetary value for CO_2 to be used in impact assessments tools; it will depend on the ethical standpoint of the user. The carbon values are likely to increase in the future, because impacts are expected to increase with increasing temperature. Thus, depending on the choices made on ethical standpoints and assumptions about future emissions and climate sensitivity, estimates can be significantly higher than the CO_2 values typically used today. Due to this, SCC estimates cannot be used for calculating an optimal emission level, although they can inform target-setting processes. It is suggested that MAC values are used for assessing emissions under binding targets in short-term assessments, and that SCC values are used in all other situations. The SCC value used should reflect the ethical standpoints of the decision-maker. We suggest three sets of benchmark principles with associated SCC estimates to guide decision-makers' choice of a monetary value in impact assessments. The estimates need continuous updating and there is need for better understanding and communication around the limitations and uncertainties involved for an improved interpretation of the results by different stakeholders.

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Figure caption

Figure 1. A comparison of SCC and MAC and their relation to an optimal carbon value and its associated climate target.