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A lower bound to the social cost of CO_2 emissions

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Many studies have estimated the social cost of carbon (SCC). We critically evaluate SCC estimates, focusing on omitted cost categories, discounting, uncertainties about damage costs and risk aversion. This allows for the calculation of a lower bound to the SCC. Dominant SCC values turn out to be gross underestimates, notably, but not only, for a low discount rate. The validity of this lower bound is supported by a precautionary approach to reflect risk aversion against extreme climate change. The results justify a more stringent climate policy than is suggested by most influential past studies.

Climate change has been called "the biggest market failure the world has seen"[1] and "the mother of all externalities"[2]. Many studies have been performed to try and estimate its economic costs. The most condensed outcome of this is the social cost of carbon (SCC), that is, the societal cost of emitting an additional tonne of greenhouse gases (GHGs) in the atmosphere. This is calculated as the net present value of the economic costs of an additional tonne of CO_2 emissions. Because of the difficulty in estimating the SCC, fierce debate has been waged over its true value. The existence of a wide range of SCC values in the literature impedes straightforward translation to policy. This study provides a critical evaluation of reported SCC estimates and their underlying key assumptions, which then allows for improved meta-estimations of the SCC. We show that mainstream estimates of the SCC should be treated with great care in the design of climate policy as they tend to be based on assumptions that lead to considerable underestimates.

The policy relevance of the SCC is huge as it defines the break-even point of socially optimal investments in the reduction of GHG emissions, such as in energy efficiency improvements and renewable energy. In other words, optimal policies to reduce greenhouse gas emissions can be determined with the SCC. A higher SCC value means that such investments have a higher return in terms of future economic damage avoided. The SCC also provides the basis for pricing or setting a tax on GHG emissions, which will steer production and consumption away from carbon-intensive goods and services[3]. Here we offer insight into the wide range of SCC estimates and underlying assumptions. In addition, we present a conservative lower bound to the true SCC.

SCC values are calculated using so-called policy-optimizing integrated assessment models (IAMs) of climate–economy interactions[4]. The three most influential are DICE, FUND and PAGE[5]. These models have estimated the global effects of GHG emissions on production, consumption and welfare over a period of 100 years or longer. While such IAMs have produced the clearest policy advice, several of their assumptions have been heavily criticized[6–23].

More than 300 estimates of the SCC are now available[24]. They have been derived under a large variety of assumptions about relevant categories of climate impacts, the social discount rate, uncertainty and risk aversion. The range of SCC values reported in the literature is very dispersed, as is illustrated by a meta-analysis[2] of 232 SCC estimates, which uses a weighting procedure that results in an average of US$41, a median of US$24 and a 95th percentile of US$146 per tonne of CO_2 (tCO_2). All these estimates should be treated with care as they are based on many studies that have various shortcomings, as will be discussed below. The PAGE model tends to result in higher SCC values than DICE[25] and FUND[26]. A US$85 SCC was reported by the Stern Review[1] using the PAGE model, which is considerably higher than earlier estimates of PAGE[27] and estimates of the other two models due to using different assumptions, notably a lower social discount rate, distributional weights to capture income differences between countries affected by climate change and a more complete treatment of uncertainty about climate change impacts. Each model has generated a broad range of values, associated with variation in assumptions (discount rates, extreme damages, uncertainty, distributional weights), model extension or versions (sectors, damage categories, explicit treatment of sea-level rise, technological progress, heating requirements) and updates of data and parameter values (temperature response to CO_2 concentration, carbon cycle, abrupt damages). DICE values more than doubled to US$6 per tCO2 in the 2007 version of the model compared with the 1999 version[25]. FUND values remain roughly the same according to Waldhoff *et al.*, who propose[28] a base estimate of US$8 per tCO2, which is in line with earlier FUND estimates[26]. This value is argued to be low because of the positive effects of carbon dioxide fertilization on agriculture[23,26]. On the other hand, Anthoff *et al.* show[26] that the SCC value of FUND is above US$25 per tCO2 if average income differences are taken into account. For PAGE, a central estimate of US$100 was recently proposed using a new version (1.7) of the model[29].

In 2010 an expert group in the US Environmental Protection Agency (EPA) proposed three average SCC estimates for 2010 based on runs of FUND, PAGE and DICE, for use in regulatory analyses. The estimates were US$5, US$21 and US$35 (in 2007 dollars), associated with the 5%, 3% and 2.5% discount rates, respectively. A fourth value of US$65 was included to represent the higher-than-expected impacts, using the average SCC value for the 95th percentile at a 3% discount rate[5]. This study was updated in 2013 leading to a set of equivalent SCC values (also for 2010) of US$11, US$33, US$52 and US$90, respectively[30]. These estimates, notably the average SCC for 3% discounting, have played a crucial role in preparing the US climate policy[31], having been discussed in a subcommittee of the Senate.

This illustrates the relevance of offering a clear insight into the adequate range of SCC values, which is the purpose of this article.

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Table 1 | Categories of climate change effects that are not, or only partly, included in current estimates of the SCC.

Category of climate change effects	Effect on the SCC
Large biodiversity losses	+
Impact on long-term economic growth	+
Political instability and violent conflicts	+
Large migration flows	+
Faster generation of renewable energy	-
Shipping at the poles	-
Oil exploration at the poles	+-
Effects of warmer weather on clothes, food and traffic congestion	-
More extreme weather and natural disasters	+
Extreme and irreversible climate change	+

Partly based on Ackerman *et al.*[20] and Tol[2,24]. + = expected increase in the SCC, +- = positive or negative effect on the SCC and – = expected decrease in the SCC.

Whereas the EPA study used the three dominant models to calculate average SCC values, we estimate a lower bound to the SCC by going beyond these models and explicitly considering their shortcomings. The EPA study also mentions some of their shortcomings, but does not attempt to translate these into a lower bound.

It should be noted that the costs of non-CO_2 gas emissions can differ substantially from the SCC. For example, using the baseline model run of DICE adopted by the EPA expert group, Marten and Newbold[32] estimate the social costs of CH_4 and N_2O emissions to be US$810 and US$13,000 per tonne, respectively. These are considerably higher than the SCC due to the much higher radiative forcing of the respective gases compared with that of CO_2.

The remainder of this Perspective discusses the omitted categories of climate change damage costs, the discounting of future climate impacts, uncertainties about climate change damage and dealing with risk aversion. A lower bound to the SCC is then derived on the basis of information about each of these issues.

We conclude that quantifying the true SCC value is complicated because of various difficult-to-quantify damage cost categories and the interaction of discounting, uncertainty, large damages and risk aversion. The best that can be offered is a lower bound. Accounting for risk aversion to uncertain large climate damages in the future only translates to a correct SCC value if a fair intertemporal, social discount weight is assigned to such damages. Based on the inspection of the most important arguments for and against a high discount rate value, we will conclude that adopting a low social discount rate is the most defensible choice. This means that low-probability/high-impact climate scenarios are critical to the SCC. We derive a lower bound to the SCC value by applying the average of surcharges for uncertainty and risk aversion found in the literature, and derive that dominant SCC values in the literature represent a serious underestimate. Our lower-bound SCC estimate should be considered conservative for three reasons: it comes from a conservative meta-estimate that aggregates studies using high and low discount rates, it does not account for various climate change damages owing to a lack of reliable information, and it does not consider a minimax regret argument addressing damages associated with extreme climate change.

Omitted categories of climate change damage costs

A first problem is that the empirical basis for the SCC is narrow as values are derived from only 14 estimates of total climate change costs[24]. Many cost data are based on extrapolations of earlier studies, mostly for the USA[33]. Moreover, damage costs for developing countries, where climate change impacts are projected to be large, are generally low quality[10,33,34]. Climate change effects that are partially or entirely quantified in the SCC are associated with agriculture, forestry, water supply, coastal zones, energy use, air quality and human health and mortality[24]. Some studies also include the consequences of extreme weather, like storms and difficult-to-value impacts on ecosystems and migration. Based on a review of the literature, Table 1 lists some of the most important effects of climate change that have not been well quantified. Obviously, listing all unquantified potential effects is infeasible. Nevertheless, our summary of the main effects provides a clear insight, namely that unquantified negative effects of climate change tend to dominate unquantified positive effects. The negative effects comprise large biodiversity losses, political instability, violent conflicts, large-scale migration, extreme weather events, natural disasters and the effect on long-term economic growth. Accounting for the latter is likely to increase the SCC because large impacts of climate change are expected to reduce the rate of GDP growth, partly because of negative effects on labour and capital productivity[35].

Discounting of future climate impacts

IAMs make assumptions about the social discount rate to evaluate the societal impacts of public projects over time. A higher social discount rate means that the further in the future damages due to GHG emissions are, the smaller weight they receive. A higher discount rate generally results in a lower SCC value because climate change damages occur predominantly in the future. The social discount rate (r) is often defined as the sum of two elements: the pure time-preference (δ) and the average growth-rate of consumption per capita (g) multiplied by the elasticity of marginal utility-of-consumption (η). This results in the 'Ramsey formula': $r = \delta + \eta g$. The last two parameters signify that a lower value is placed on the consumption of wealthier future generations, because the utility they receive from an extra dollar of consumption declines as their level of consumption is higher. The sensitivity of the SCC to the discount parameters is illustrated by a meta-analysis[2]: setting δ equal to 0%, 1% or 2% results in an average (uncertainty weighted) SCC of US$40, US$33 and US$13 per tCO_2, respectively.

A wide range of social discount rate values (r) have been used to estimate climate change costs, ranging from 1.5% (ref. 36) to 5.5% (ref. 25). The appropriate discount rate for climate–economy studies has been strongly debated. The following main arguments have been used for the use of a high social discount rate: (1) society shows the same degree of impatience as individuals[37], (2) discount rates can be based on market returns on investment as these reflect the opportunity costs of capital outlays on climate policy — although low returns can be observed for certain investments, this argument has typically been used to support higher discount rates[38] and (3) a zero-discount rate implies a high level of savings by the current generation, which is not observed in practice[39].

The main arguments that have been used in favour of a low social discount rate are: (1) the degree of impatience or time-preference differs between individuals whose life ends at some point in time and societies that survive the individual as they consist of overlapping generations[40], (2) striving towards environmental sustainability turns the long-term duration of human society into an explicit goal that implies a low pure-social time-preference[22], (3) there is no unique value of the opportunity cost of capital because a large variation of interest rates and rates of return can be observed in real markets[41], (4) high market rates of return are partly determined by the failures of financial markets, such as imperfect information and behavioural anomalies[41], (5) high market interest rates do not reflect the long investment horizon that is consistent with climate policy[42], (6) high market rates of return are based on activities with a high productivity, which often pollute and greatly contribute to global warming[43], (7) the application of a high discount rate to future losses in ecosystems and biodiversity does not reflect that natural resources are being depleted and are quickly becoming scarce[44], (8) only an equal treatment of different generations through the use of a zero-discount rate is ethically justifiable[45], (9) 'social climate discounting' reflects normative judgments about how to weight the welfare of future generations, for which positive observations of market returns provide no guidance[46,47] and (10) if there is uncertainty about the discount rate (or about future consumption), long-term costs should be discounted at a lower rate than short-term costs (the certainly equivalent discount rate is less than the mean discount rate and it declines over time)[48].

Pro (high discount rate) argument 1 is not convincing as it really is an assumption. Pro argument 2 is effectively countered by contra (low discount rate) arguments 3–6 and 9, and pro argument 3 is countered by contra argument 9. Furthermore, contra arguments 4, 6 and 7 relate to the more general concern that economic growth may be lower in the future than in the past for various reasons — for example, satiation of consumption, diminishing returns to technology, rising energy prices, scarcer land and other natural resources, environmental pollution and ecosystem damage and ageing populations. This means that the growth component in the Ramsey formula will become small, suggesting a lower discount rate. In view of these qualifications, as well as the compelling contra arguments 1, 2 and 7–10, we conclude that the defence of a low discount rate is most persuasive.

Uncertainties about climate change damage

Large uncertainties surround climate change costs[49]. These relate to uncertainty about the climate system and cover different phases of the causal chain of climate–economy interactions: GHG emissions, the effect of emissions on atmospheric GHG concentrations, the effect of concentrations on temperature, consequences of temperature rises for regional climates, sea level and weather extremes and finally, the translation of these into welfare losses[50,51]. IAMs do not completely account for these uncertainties and tend to exclude low-probability/high-impact scenarios, or only implicitly address them through sensitivity analysis and probability distributions for uncertain model parameters. An exception is PAGE, which has included catastrophic outcomes since 2002[52]. These outcomes, though, often reflect subjective judgements and abstract scenarios rather than objective probabilities and concrete climate catastrophes[20]. A more accurate, but probably infeasible, approach would be to account for all the important extreme scenarios and the probabilities of their occurrence separately, rather than represent all scenarios by a single abstract probability distribution, as is common practice. In any case, such extreme scenarios should receive serious attention in IAMs, as has been argued by Weitzman[53–55]. Botzen and van den Bergh[56] show that incorporating his suggestions in the DICE model results in a considerably more stringent optimal path of greenhouse gas emission reductions.

Also using DICE, Tol[24] finds that uncertainty about the estimates of total economic costs translates into a 95% confidence interval for SCC of US\$–0.3 to US\$18 per tCO_2, with an average of US\$8. Pycroft *et al.* show[57] that, for PAGE, just considering uncertainty about the effect of the concentration of GHGs on temperature gives rise to an 85% higher SCC. Ceronsky *et al.* find[58] that low-probability/high-impact climate change scenarios increase the SCC by a factor of three. Using PAGE, Dietz shows[59] that Weitzman's suggestion to give more attention to uncertain consequences of high temperature increases ("fat-tailed risks") leads to an SCC value of US\$445 per tCO_2, using the low discount rate proposed by Stern[1], and US\$346 if a 1.5% discount rate is used. The first value is 420% higher than the standard SCC proposed by Stern[1]. Moreover, Dietz shows[59] that if a high discount rate is used, including low-probability/high-impact climate scenarios in IAMs has a small effect on the SCC. The reason is that very large future climate damages receive a very small weight in the SCC value. Ackerman and Stanton examine[60] the sensitivity of DICE to Weitzman's suggestion combined with a proposal by Hanemann that higher climate damages can result even at lower temperature increases[61]. Under a business-as-usual emissions scenario, this results in an average SCC value of US\$96 per tCO_2 if a discount rate of 3% is applied, and an average SCC value of US\$445 using a discount rate of 1.5% (with a 95th percentile SCC of US\$892). The latter average value is 277% higher than the SCC that Ackerman and Stanton obtain[60] using the standard DICE damage function.

Table 2 | Regret matrix for climate change scenarios.

Public choice	Climate change scenario		
	No climate change	Moderate climate change	Extreme climate change
Climate policy	*A*	0	0
No climate policy	0	*B*	*C*

C>>*A* and *C*>>*B*; and *A*, *B*, *C* >0. Furthermore, *A*>(<)*B* if climate policy is strict (weak).

Risk aversion

Current SCC estimates hardly, or imperfectly, account for individual attitudes regarding risk aversion to climate uncertainties, even though they can have important implications. Dealing well with risk aversion is complicated because of an incomplete treatment of uncertainty in IAMs[20,53] and a lack of good empirical estimates of the individual degree of risk aversion to particular climate change effects[62,63]. Some IAMs, like PAGE, model risk aversion using a coefficient of relative risk aversion, which is also used to capture attitudes to inequality, resulting in so-called equity weighting[64]. Nevertheless, Dietz *et al.* argue[65] that combining the representation of inequality and risk attitudes in a single parameter reflects a debatable simplification of the conventional model. This is because aversion to risk and aversion to inequality are distinct concepts[66,67]. Dietz *et al.* conclude that specifying models that disentangle these concepts is an area for further research.

Risk aversion can be expressed in the SCC in the form of a risk premium, which is the maximum willingness to pay for reducing the risk in addition to the component of the average climate damage included in the SCC. Empirical estimates of this risk premium are scarce[62]. A sensitivity analysis of the SCC of FUND using variations in the degree of risk aversion results in an SCC of US\$11 per tCO_2 without uncertainty about climate change damages, and an SCC of US\$32 per tCO_2 with uncertainty[63]. This implies a risk premium of 185%. Another study estimates that risk aversion can result in a 70% increase in the SCC[64]. This illustrates that assumptions about risk aversion can have a large impact on the SCC.

One could go a step further in dealing with risk aversion by adopting a precautionary approach. This is best formalized through a minimax regret function that focuses on avoiding very costly mistakes. Various authors confirm that minimax regret is the best approach in the case of deep uncertainty[65,66] that can be included in an IAM, as is shown by Anthoff and Tol[71]. Only a few similar studies are available, but none report — or even make a connection with — an SCC[71–73]. A minimax regret approach means that one compares, for each possible extreme scenario, the regret due to not adopting a safe policy and, thus, suffering from extreme climate change. The regret matrix can be derived from a so-called net payoff matrix. Table 2 conceptualizes this approach for two public choices (climate policy versus no climate policy) and three scenarios of climate change (none, moderate and extreme). Under the first scenario, the best choice would be no climate policy, while under the other two scenarios climate policy would be the best choice. The maximum regret for climate policy is *A*, associated with no climate change. The maximum regret for no climate policy is *C*, associated with extreme climate change. The minimax regret strategy is, therefore, associated with *A* as *A* << *C*, meaning that climate policy is the best strategy. For the SCC, the relevant reasoning is that the climate policy is driven by avoiding the extremely high cost *C*, even though this is associated with one particular, uncertain scenario. So, according to the minimax regret approach the SCC can be set in accordance with this extreme climate scenario associated with regret *C*, implying a very high value associated with extreme climate change. As the values in the table are variable, any extreme scenario can be accommodated. Furthermore, it is possible to add columns to the table with additional scenarios of extreme climate change. This will, however, not alter the argument and conclusion drawn.

Several studies have examined the pros and cons of adopting a precautionary approach in public risk management, including the design of climate policy[74–76]. It should be realized that adopting a non-probabilistic decision criterium, like a minimax regret function, can have the disadvantage that unlikely worst-case scenarios have too much influence on public decision making[77]. Others have argued that adopting a precautionary approach to climate policy is sensible given the importance of uncertain but potentially very harmful, irreversible and global surprises associated with changing climate conditions[78]. Our intention here is not to advocate a precautionary strategy but to examine its meaning for the SCC.

Table 3 | Summary of SCC values per tonne CO_2 reported here.

Source	SCC
SCC estimates from the main IAMs	
DICE, study by Nordhaus[25]	US$6
DICE, study by Tol[24], 95% confidence interval	US$−0.3 to US$18
FUND, study by Anthoff *et al.*[26]	US$8
FUND, Anthoff *et al.*[26] using different assumptions	US$25
PAGE, study by Hope[27]	US$5
PAGE, study by Stern[1]	US$85
PAGE, study by Hope[29]	US$100
DICE, FUND and PAGE, study by US Government[32]	US$36
Meta-analysis by Tol[2]	
Average	US$41
Median	US$24
95th percentile	US$146
Sensitivity to time preference parameter of the discount rate[2]	
Average for 0%	US$40
Average for 1%	US$33
Average for 3%	US$14
Observed surcharge (%) on the SCC	
Uncertainty about GHG concentrations[57]	85%
Inclusion of costs of large temperature rise[59]	420%
Allowing for overall higher climate damages[60]	277%
Low-probability/high-impact climate change risks[58]	200%
Risk aversion[68]	185%
Risk aversion[69]	70%

Deriving a lower bound to the SCC

Table 3 summarizes the main reported SCC estimates and surcharges. It illustrates the wide range of SCC estimates. Quantifying the true SCC is particularly difficult because of the intricate interplay of discounting, uncertainty, large damages and risk aversion. The following four main insights can be derived. First, the mentioned meta-analysis estimates suggest that the central SCC values from the main IAMs underestimates the true SCC, except for some recent estimates by the PAGE model. Even the average SCC from the meta-analysis is likely to be an underestimate, as it aggregates many studies that use high discount rates, ignores important cost categories and does not completely account for low-probability/high-impact climate change scenarios.

Second, it is widely accepted that the social discount rate has a large influence on the SCC. What is less recognized is that the effect of discounting is magnified by extreme climate outcomes and risk aversion. Accounting for risk aversion to uncertain large climate damages in the future only translates to a correct SCC value if such damages receive a fair intertemporal, social discount weight. For a high discount rate value we concluded, from inspecting the important pro and contra arguments, that adopting a low social discount rate value is the most defensible choice. This implies that future climate outcomes and low-probability/high-impact climate scenarios are important for the SCC.

Third, SCC values under US$125 are hard to defend if a low discount rate is used and low-probability/high-impact climate outcomes as well as risk aversion are taken seriously. To illustrate this, let us take the rather low average SCC of US$41 — obtained with a meta-analysis, as reported in Table 3 — as a starting point, and add to this the minimum and maximum surcharges. This gives SCC values of about US$70 and US$213. In addition, applying the average of the surcharges from Table 3 (equal to 206%) results in an SCC of roughly US$125 per tCO_2. Although these simple calculations do not arrive at the 'true SCC' value — which would be too ambitious given the previous discussion of the various shortcomings of the model — they do show that mainstream SCC values represent severe underestimates.

Fourth, the various unquantified climate change damages, as summarized in Table 1, result in a further underestimate of the SCC. In other words, the lower bound of US$125 is conservative. Future research should try to assess the impact of the unquantified damages on the lower bound to the SCC.

On the basis of the precautionary, minimax regret approach, one can arrive at considerably higher estimates of the SCC than US$125. The value associated with extreme climate change (and regret *C* in Table 2) might have an order of magnitude that corresponds to SCC values that have been estimated under uncertain large consequences of climate change, such as the SCC value of US$346 per tCO_2 reported by Dietz[59], or values between US$241 and US$445, reported by Ackerman and Stanton[60] (both for a low discount rate of 1.5%). This supports the validity of the US$125 lower bound derived above. Because many observers and commentators on climate change are of the opinion that a precautionary approach is needed, this idea of linking the SCC to a regret approach requires further research.

Finally, we would like to stress that the US$125 lower bound to the SCC, though higher than the dominant estimates, is obtained from a conservative meta-estimate that aggregates studies using high and low discount rates. The latter means that the lower bound is not simply the result of adopting a low discount rate. On the other hand, it should be noted that a low discount rate contributes to a high lower bound, in particular as it means giving more weight to any extreme damages from future climate change.

The lower bound to the SCC of US$125 per tCO_2 is far below various estimates found in the literature that attribute a high weight to potentially large climate change impacts. Therefore, the proposed lower bound can be considered a realistic and conservative value.

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Competing financial interests

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