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The social cost of methane

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Abstract

A rapid and sustained reduction of methane emissions has been proposed recently as a key strategy to meet the climate targets of the Paris Agreement. The social cost of methane (SCM), which expresses the climate damage cost associated with an additional metric ton of methane emitted, is a metric that can be used to design policies to reduce the emissions of this gas. Here, we extend the DICE-2016R2 model so that it includes an improved carbon cycle and energy balance model as well as methane emissions, methane abatement cost, and an atmospheric methane cycle explicitly to be able to provide consistent estimations of the SCM. We estimate the SCM to lie in the range 880–8100 USD/tCH$_4$ in 2020, with a base case estimate of 4000 USD/tCH$_4$. We find our base case estimate to be larger than the average SCM presented in other studies mainly due to the revised damage function we use. We also estimate the social cost of carbon (SCC) and find that SCM estimates are less sensitive to variations in the social discount rate than the SCC due to the relatively short lifetime of methane. Changes in the parameterization of the damage function have similar relative impacts on both SCM and SCC. Furthermore, we evaluate the ratio of SCM to SCC as an alternative metric to GWP-100 of CH$_4$ to facilitate tradeoffs between these two gases. We find this ratio to lie in the range 7–33 in 2020, with a base case estimate of 21, based on an extensive sensitivity analysis with respect to the discount rate, damage cost, and underlying emission scenarios. We also show that the global warming potential (GWP) and the SCM to SCC ratio are almost the same if the inverse of the effective discounting (in the social cost calculations) is equal to the time horizon used to evaluate the GWP. For comparison, the most widely used GWP, i.e., with a time horizon of 100 years, equals 27, hence in the upper range of the ratio we find using the SCM to SCC ratio.

Keywords Social cost of methane · Social cost of carbon · GWP · Metrics · Methane abatement

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1 Introduction

Traditionally, climate change mitigation has been predominantly focused on CO_2 abatement, since this gas is the key driver behind past and expected future global warming (Masson-Delmotte et al. 2021). However, some studies contend that rapid and sustained reductions in anthropogenic methane emissions are both cost-effective and necessary to limit global warming to 1.5 to 2 °C above pre-industrial levels (see e.g., United Nations Environment Programme and Climate and Clean Air Coallition 2021). Policymakers have accepted this idea, as the recent joint pledge of the US and the EU to cut methane emissions by 30% before 2030 exemplifies (Harvey 2021). It is important now to develop and refine reliable metrics such as the social cost of methane to better understand and characterize its relative importance.

The social cost of greenhouse gas emissions (GHGs), which expresses the marginal damage cost associated with an additional unit emitted of each respective gas, has become one of the most frequently used metrics in climate change economics, and several governments are producing their own estimates (Interagency Working Group on Social Cost of Greenhouse Gases 2016; Interagency Working Group on Social Cost of Greenhouse Gases (IWG) 2021; Environment and Climate Change Canada 2016, US EPA 2022). This metric is commonly estimated using climate-economic Integrated Assessment Models (IAMs). These models provide optimal temperature and emissions trajectories by balancing the climate damages caused by the emissions and the costs of emission reductions. The social cost of GHGs estimated with these models can then be used to design policies to reduce these emissions. However, there are problems of monitoring and accounting since many methane sources are so-called non-point source pollutants, which makes pricing methane emission more difficult than taxing CO_2 from fossil fuels.

The Dynamic Integrated Climate-Economy (DICE) (Nordhaus 1992) model is one of the most widely used IAMs for social cost of GHGs estimates (Barrage 2019; Paul et al. 2017). In its original structure, as well as its most recent version 2016R2, DICE only allows the user to estimate the social cost of carbon dioxide (SCC). Similarly, it only provides an optimal path for carbon emissions. The radiative forcing pathways of other gases such as methane are entered exogenously. The social cost of non-CO_2 greenhouse gases is not calculated in DICE but is often estimated as the product of the SCC and the global warming potential (GWP) of a specific gas. Typically, a 100-year time horizon is used when estimating GWPs. The concept of global warming potential and the relative contribution of different gases to the greenhouse effect was first introduced by (Lashof & Ahuja 1990) and (Rodhe 1990) to provide a basis for comparing different GHG emissions considering their relative radiative forcing and time-dependence of atmospheric concentrations. These are defined to ensure equivalence in time-integrated radiative forcing of emissions over a specific time horizon. However, the choice of using GWPs for GHGs comparison has been criticized by both climate economists and scientists mainly because the equivalence expressed by the GWP metric does not apply if other measures than (integrated) radiative forcing are used. The equivalency measures will be different if economic costs are taken into account, or, for example, if one studies sea level rise or temperature changes in a particular year (Johansson 2011).

Several studies have shown that estimating the social cost of non-CO_2 GHGs as the product of GWPs and SCC is not correct (Reilly & Richards 1993; Hoel & Isaksen 1995; Hammitt et al 1996; Schmalensee 1993; Kandlikar 1996, Johansson et al. 2006; Aaheim et al. 2006; Boucher 2012, Marten & Newbold 2012; Rautiainen & Lintunen 2017,

and Lintunen & Rautiainen 2021). The reason for this is that the social cost measure is an integration of the net present value of future marginal damages (which depends on the discount rate and the damage function), whereas the GWP measure is an integrated measure of future changes in radiative forcing (which depends on the time horizon chosen). The time horizon in the GWP measure plays a role that is similar to the (inverse of the) "effective" discount rate (i.e., the discount rate minus the consumption per capita growth rate) in the social cost measure. In addition, in the social cost measure, future background temperature and concentration are allowed to vary, whereas the background concentration of greenhouse gases is held constant in the GWP calculation.

With this said, there are still strong conceptual similarities between the ratio of the social cost of a non-CO_2 GHG to SCC and GWP, and the metrics are relatively similar given certain assumptions (Tol et al. 2012; Azar & Johansson 2012b; Sarofim & Giordano 2018; Mallapragada & Mignone 2020; Lintunen & Rautiainen 2021see also the Appendix).

Methane is second to carbon dioxide the most important anthropogenic greenhouse gas. Currently, the contribution to global mean surface temperature rise since pre-industrial time from methane emissions is about 0.5 °C, while that of CO_2 emissions is 0.8 °C (Masson-Delmotte et al. 2021). Emissions of methane also lead to local pollution through ozone formation and hundreds of thousands of deaths (United Nations Environment Programme and Climate and Clean Air Coallition 2021, Sarofim et al. 2017; Shindell et al 2017). In this paper, we strive to endogenize not only carbon but also methane (and nitrous oxide) emissions, but we only focus on the climate-related damages associated with methane emissions and do not consider co-benefits of methane abatement. We draw the system boundary analogously for non-climate impacts of CO_2, for example, the impact of increased atmospheric CO_2 on yields through CO_2 fertilization and the ocean acidification caused by the CO_2 uptake by the oceans are not considered.

We extend the available studies (Hope 2006; Marten & Newbold 2012; Marten et al. 2014; Shindell et al 2017; Errickson et al. 2021) on the social cost of methane in several ways. To start with, we use an updated version of DICE-2016R2 (Nordhaus 2018a, b) to provide consistent estimations of the social cost of carbon dioxide and methane. With this approach, we generate cost-efficient pathways for both CO_2 and CH_4 using recent findings and expert assessments of the social discount rate, damage functions and the dynamics of the carbon and methane cycles (including both concentration and climate feedbacks on both gas cycles) and on the temperature change. We also estimate the ratio of the social cost of methane (SCM) to SCC as an alternative to GWP. In addition, we run our model using Nordhaus' parametrization of the damage function and the discount rate and perform a series of sensitivity analyses on underlying emission scenarios, damage cost, discount rate, and the availability of negative emissions technologies.

2 Methodology

The modeling approach is based on the DICE model (Nordhaus 1992) which is an integrated Ramsey-Koopmans-Cass model of optimal economic growth hard-linked to a climate model. DICE models CO_2 emissions, their abatement cost and impact on the carbon cycle, global mean surface temperature, and damages to the economy. The model seeks the optimal balance between abatement costs and climate damages by maximizing the net present value utility of consumption (over the time period 2015–2515).

DICE is a highly influential and prominent climate economy model and used widely in environmental-related policy-making discussions (Interagency Working Group on Social Cost of Greenhouse Gases 2016; Environment and Climate Change Canada 2016). It is also Nordhaus's work on DICE, now extending some 3 decades, that was the key motivation for the decision to award him the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel (Barrage 2019). However, it has also been criticized on various grounds, see, for example, (Hänsel et al. 2020; Pindyck 2013).

Regarding the climate module, the main critique has been directed towards the use of a carbon cycle and an energy balance model that are not in line with the most recent scientific knowledge (Azar & Johansson 2021; Joos et al. 1999; Glotter et al. 2014; National Academy of Sciences, Engineering, and Medicine 2017; Dietz et al 2021; Rennert et al 2022). The DICE model used in this paper is the DICE-2016R2 version but we have updated the carbon cycle model and the energy balance model using FaIR 2.0 (Leach et al. 2021, see below for details). In the 2016R2 version of DICE, the carbon cycle module was parameterized in a way that gave too low an uptake of carbon into natural sinks for atmospheric concentration and temperature increases of < 3 °C and it did not consider the fact that the uptake is concentration and temperature dependent, so that higher concentrations and temperatures lead to a lower uptake. This is now endogenously modeled (as explained below, see the climate model equations in the supplementary material, S1).

With respect to the economic module, Nordhaus' damage function has been criticized for being based on a meta-analysis that gives too much weight to the estimates of a small group of authors (Howard & Sterner 2017), not properly considering the uncertainty of catastrophic damages (Azar & Lindgren 2003; Weitzman 2012), the treatment of non-market damages (Sterner & Persson 2008), and the effect of temperature increase in human mortality (Bresser 2021). The choice of social discount rate parameters has also been extensively discussed; see, for example, (Azar & Sterner 1996; Stern 2006; Nordhaus 2007; Arrow et al. 2013 and Newell et al. 2022).

In addition, we implement atmospheric gas cycles for CH_4 and N_2O in DICE-2016R2 using the modeling approach in FaIR 2.0.0 (Leach et al. 2021), and by incorporating marginal abatement cost (MAC) curves for CH_4 and N_2O.

2.1 Updates to the climate module

We update the climate module by introducing the latest version of the carbon, methane, and nitrous oxide cycle modules of the simple climate model Finite Amplitude Impulse Response (FaIR v2.0.0) (Leach et al. 2021). To calibrate the model and set the initial values, we use historical emissions and concentrations of CO_2, CH_4, and N_2O from the Reduced Complexity Model Intercomparison Project (RCMIP) database (Nicholls & Lewis 2021). The energy balance model we use is based on (Geoffroy et al. 2013). The energy balance model is calibrated using the radiative forcing value from the RCMIP database (Nicholls & Lewis 2021).

The baseline assumptions for the anthropogenic emissions of CH_4 and N_2O are based on the shared socioeconomic pathway SSP2 of SSP Public database (Riahi et al. 2017), assuming that baseline emissions remain constant after 2100. Hence, these baseline scenarios are not tied to GDP in the same way as baseljne CO_2 emissions are in DICE, but still, the CH_4 and N_2O emissions can be abated at a cost determined by a marginal abatement cost (MAC) function. Finally, we update the exogenous radiative forcing for

GHGs other than CO_2, CH_4, and N_2O using scenario SSP1-26 from RCMIP database (Nicholls & Lewis 2021).

2.2 Updates to the economic module and base case parameter values

We base the MAC function for CH_4 and N_2O, respectively, on the work presented in (Harmsen et al. 2019), who based their work on (Lucas et al. 2007), see S2 in the Supplementary Material (SM) for details.

The social discount rate is determined by the "Ramsey rule" (see S3 in the SM), i.e.,

$$r = \eta \cdot g + \delta \tag{1}$$

where r is the discount rate, η the elasticity of marginal utility of consumption, g the annual growth rate of per capita consumption and δ the pure rate of time preference.

We set $\eta = 1$ and $\delta = 0.5\%$. These values correspond to the median values found in a survey of 173 experts in (Drupp et al. 2018). In DICE-2016R2, $\eta = 1.45$ and $\delta = 1.5\%$/year.

The damage function expresses the magnitude of economic damages as a share of GDP caused by the temperature increase. In DICE-2016R2 (Nordhaus 2018a, b) it is defined as

$$D(t) = \varphi \cdot T(t)^2 \tag{2}$$

where T is the increase in temperature and φ is the proportionality constant in the damage function. In DICE-2016R2, $\varphi = 0.00236$ (which means that the damage becomes equal to 0.94% of global GDP for a global average temperature increase of two degrees). Uncertainties are very large for the magnitude of these damages. Here, we set $\varphi = 0.007438$ based on (Howard & Sterner 2017). Howard and Sterner (2017) provide several estimates depending on such factors as the treatment of catastrophic damages. We opt for using their preferred model without catastrophic damages. This approach was also used in Hänsel et al. (2020).

We first run our model using these damage costs and discounting parameters, and we refer to this as our base case. Then, we run our model under Nordhaus' parametrization of the damage function and choice for the discount rate (Nordhaus 2018a, b), and finally we perform an extensive series of sensitivity analyses. For further information about constraints on the maximum rate of abatement and maximum abatement level see the SM.

3 Results

When our revised version of DICE-2016R2 model is run for our base case, we find that it is optimal to limit the global average surface temperature increase to 1.5 °C above the average 1850–1900 by 2100 after peaking at almost 1.7 °C in 2070. In the optimal solution, CO_2 emissions are reduced by 63% relative to baseline emissions in 2030 and they become negative from 2065 onwards, reaching a maximum reduction level (constraint in the model) in 2085. Methane emissions are reduced at maximum rate until 2035. From 2035 onwards, methane emissions roughly stabilize due to a large increase in the marginal abatement costs beyond 65 to 70% abatement; see Harmsen et al. (2019) for further details. By the year 2100, methane emissions are reduced by 75% relative to the baseline.

In Fig. 2, we present our estimates for the SCM and SCC in our base case. We find that the SCM is estimated at 3,997 USD/tCH_4 and the SCC is estimated at 192 USD/tCO_2 in
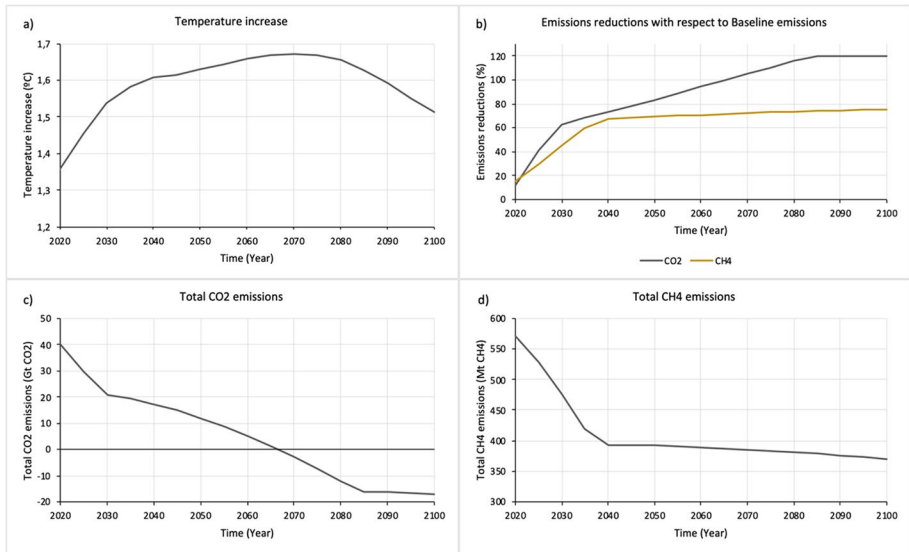
Fig. 1 Base case results: temperature increase since 1900, emissions reductions, total CO_2 emissions, total CH_4 emissions
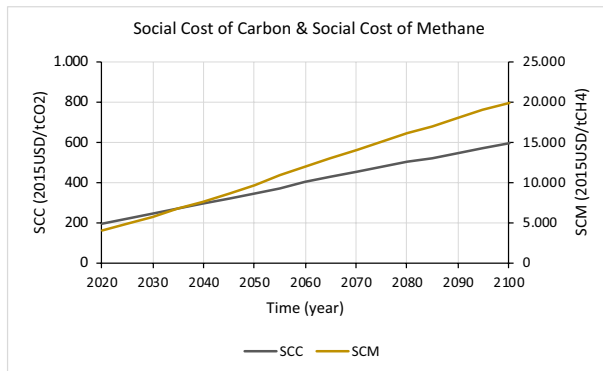

Fig. 2 Social cost of carbon and social cost of methane

the year 2020.[1] It can also be seen in Fig. 2 that both SCC and SCM grow roughly linearly over the time interval shown (twenty-first century).

In Eq. 2, we see that as the temperature level increases, marginal damages increase and so do the social cost of carbon and methane (marginal damages are proportional to the temperature level when the damage function is quadratic in the temperature change (T in Eq. 2). In our base case, $T(t)$ does not vary so much over the twenty-first century (see Fig. 1) and $\Delta T_X(t)$ does not change much neither for CO_2 nor CH_4 when the concentration

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[1] With ton we mean metric ton, i.e. 1000 kg. We use this definition throughout the paper.
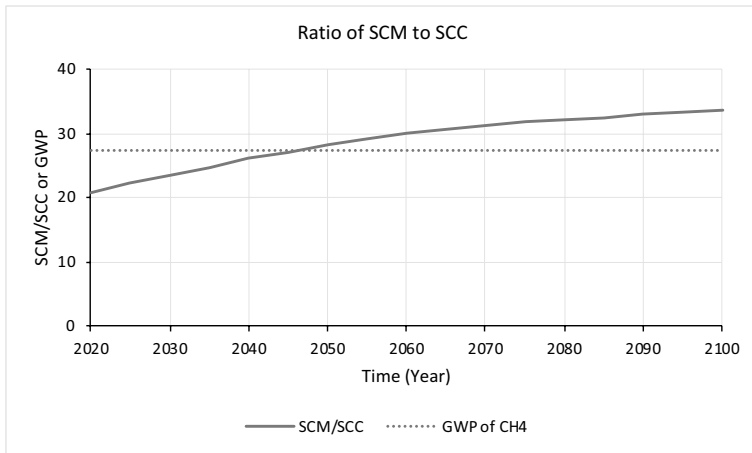
Fig. 3 Results: ratio of SCM to SCC and GWP-100 of CH$_4$

levels are relatively close to the present values, so the main reason why social costs increase over time is fundamentally that global GDP increases over time.

As SCC and SCM increase (Fig. 2), their ratio SCM/SCC also grows over time (see Fig. 3). The increase in the SCM/SCC ratio is driven by a drop in the relative growth rate of the background temperature, and more specifically in this case a leveling off and a subsequent fall in the background temperature. Reductions in the long-term temperature response (all else equal) reduce SCC more than SCM (because of the shorter lifetime of methane). Hence, this causes the ratio of SCM to SCC to increase over time. The result that the ratio increases over time can also be observed in Marten & Newbold 2012, Marten et al. 2014 Rautiainen & Lintunen (2017) & US EPA (2022).

Figure 3 also includes the GWP-100 value for methane given in IPCC AR6 (Masson-Delmotte et al. 2021). The GWP-100 value for methane and the SCM/SCC values are rather similar (see Appendix for an analytical derivation of why this is the case). The ratio of SCM to SCC is smaller than the GWP-100 until 2050 and then it becomes larger. This means that, if the SCM were indirectly estimated by multiplying the SCC with the GWP-100 as estimated by IPCC AR6, it would be somewhat overestimated until 2050 and underestimated afterwards.
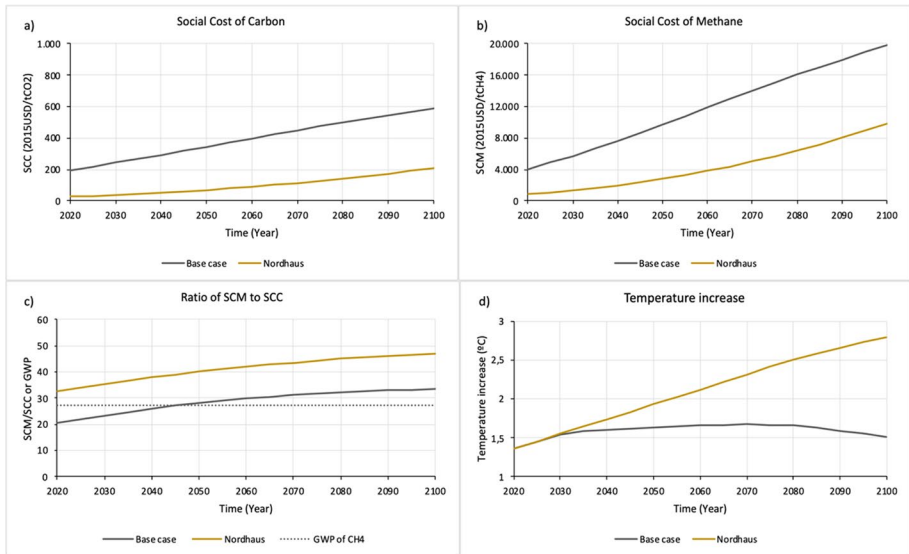
4 Sensitivity analyses

In this section, we analyze the sensitivity of the results with respect to some critical changes in the assumptions. A summary table (Table S1) can be found in the SM.

4.1 Nordhaus' damage cost and discounting parameters

We here present an alternative case with the damage function and discount rate parameters that Nordhaus uses (Nordhaus 2018a, b).

As shown in Fig. 4, both SCC and SCM are significantly smaller with Nordhaus' parametrization due both to the lower damage cost and the higher discount rate. The SCC
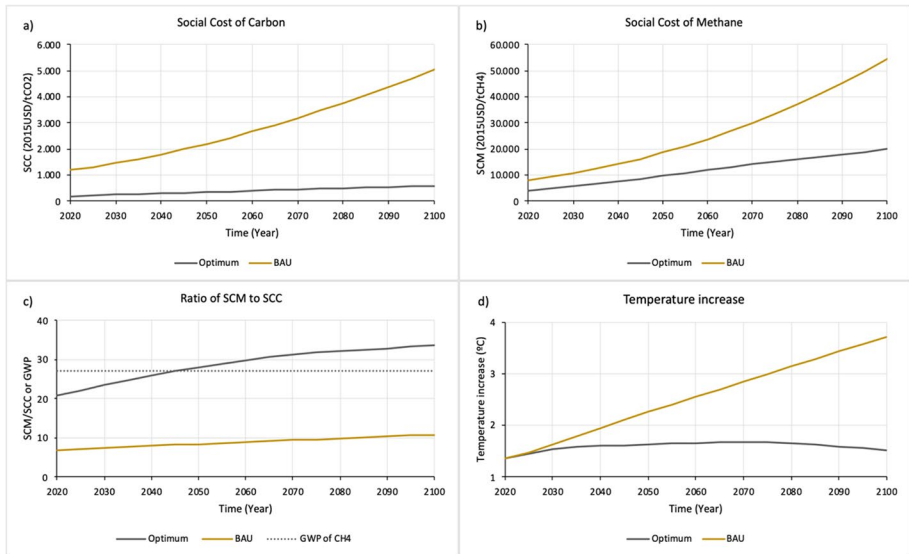
Fig. 4 Sensitivity analysis—base case parametrization versus Nordhaus's parametrization: social cost of carbon, social cost of methane, ratio of SCM to SCC, temperature increase since 1900

is seven times lower in 2020 while the SCM is 4.6 times lower in 2020. The difference in the SCM is smaller than the difference for SCC because SCM estimates are less affected by variations in the discount rate due to the short lifetime of methane, while the SCC is highly affected by these variations. As a consequence, the ratio SCM/SCC becomes higher under Nordhaus's higher discount rate. The reason for this is that CO_2 has more long-run impacts (is more long-lived) than methane but these long-run impacts matter less with a high discount rate. This is also essentially the same reason why the GWP for methane is higher under shorter time horizons (see the Appendix below, as well as Sarofim & Giordano (2018) and Mallapragada & Mignone 2020).

4.2 Social cost estimates under a business-as-usual scenario

The main results presented in this study correspond to a case where the social cost of carbon and methane is evaluated along the optimal temperature path, so the social cost estimates and their ratio reflect a case where the optimal emission trajectories are followed. However, it is far from certain that the world will succeed in reducing GHG emissions in line with what may be considered optimal. It is therefore also of interest to study scenarios that do not follow the optimal emissions trajectory. To analyze these, we run our model under a so-called business-as-usual scenario (BaU) in which no emissions reductions take place at all. The BaU scenario is generated when running DICE without any climate policy/carbon taxes; hence, emissions follow the baseline assumption, which leads to substantially larger temperature changes (see Fig. 5).

Fig. 5 shows that both the SCC and SCM are higher under the BaU scenario, but the impact on these two metrics is not symmetrical: the SCC increases much more than the

Fig. 5 Sensitivity analysis—optimum solution (base case parameter assumptions) versus BaU conditions: social cost of carbon, social cost of methane, ratio of SCM to SCC, temperature increase since 1900

SCM as we move from the optimal to the BaU scenario. Hence, the ratio of SCM to SCC is lower under the BaU scenario.

Both SCC and SCM increase because marginal damages are proportional to the temperature increase, so higher temperature means higher marginal damages and therefore higher social cost estimates. Consider an emission pulse in the year 2020. For methane, the social cost is mostly determined by what happens during the next few decades when the business-as-usual temperature and the optimal temperature are rather similar. However, for carbon dioxide, where the temperature impact of a pulse emission lingers for centuries, the difference between the BaU temperature and the optimal temperature towards the end of the century and beyond will matter (in particular with lower discount rates). Hence, under these conditions the SCC will increase more than SCM under the BaU scenario, which explains why the ratio SCM/SCC drops.

4.3 No NETs

Negative Emission Technologies (NETs) are a key element of most IPCC emission pathways that stay below 2 °C or 1.5 °C (Edenhofer et al. 2014; Masson-Delmotte et al. 2018), although they are also criticized for being uncertain (Minx et al. 2018; Fuss et al. 2018). Therefore, we also explore results if no NETs were available.

As observed in Fig. 6, the SCC is significantly higher when no NETs are considered compared to our base case, 318 USD/tCO$_2$ versus 192 USD/tCO$_2$ in 2020, a finding consistent with (Hänsel et al. 2020). On the other hand, the SCM is approximately the same in both cases until 2055 and then it becomes higher in the no NETs case. Consequently, the ratio of SCM to SCC is much lower than in our base case.
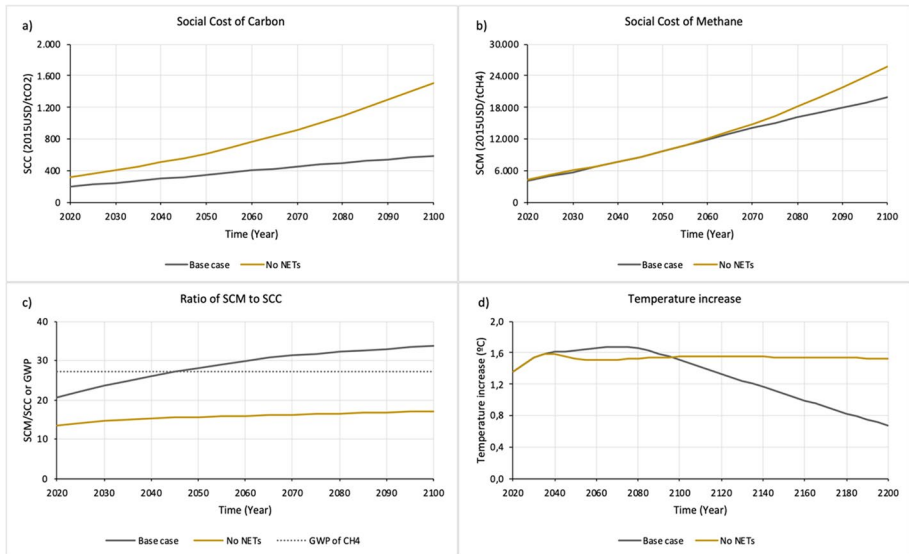
Fig. 6 Sensitivity analysis—base case versus no NETs: social cost of carbon, social cost of methane, ratio of SCM to SCC, temperature increase since 1900

This is explained by the difference in temperature increase from 2095 onwards. As seen in Fig. 6d, the temperature increase during the twenty-first century is relatively similar, but it starts to deviate towards the end of the century and during the twenty-second century it drops a lot in the base case but stays roughly constant at approximately 1.6 °C in the case without NETs. Due to its long lifetime, the temperature impact of a pulse emission of CO_2 lingers for centuries, so the SCC in 2020 is affected by the difference in temperature pathways in the twenty-second century between these two cases. However, the SCM is not affected by the difference in temperature until the end of the twenty-first century because of the relatively short lifetime of methane.

4.4 Variations in the damage function

The quantification of damages caused by a specific temperature increase is highly uncertain. In order to explore the impact of different values on SCM and SCC we carry out a sensitivity analysis on the proportionality coefficient φ so that damages caused by a 2 °C temperature increase are varied in the range 1 to 5% of global GDP (3% corresponds to the proportionality coefficient that we use in our base case).

As observed in Fig. 7, the ratio of SCM to SCC is larger the larger the damage coefficient. A larger damage coefficient would increase equally both SCM and SCC if the temperature path were not affected, but this is not the case in an optimisation model with endogenous abatement. A higher damage coefficient means that emissions will be abated more and hence the optimal temperature pathway will be lower. This will cause both SCC and SCM to drop in comparison to a case where the temperature paths were unaffected by changes in the damage coefficient. However, this drop in the optimal temperature will affect SCC more than SCM due to the much longer lifetime of CO_2 than CH_4. Hence, the

Fig. 7 Sensitivity analysis—the ratio of SCM to SCC for different values of the proportionality constant, i.e., the percentage damage level at a warming of 2 °C, of the damage function, and over time
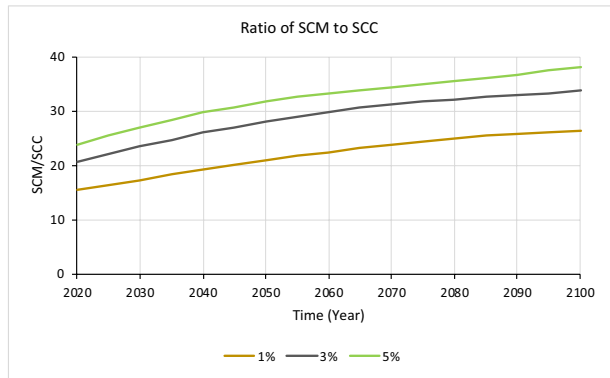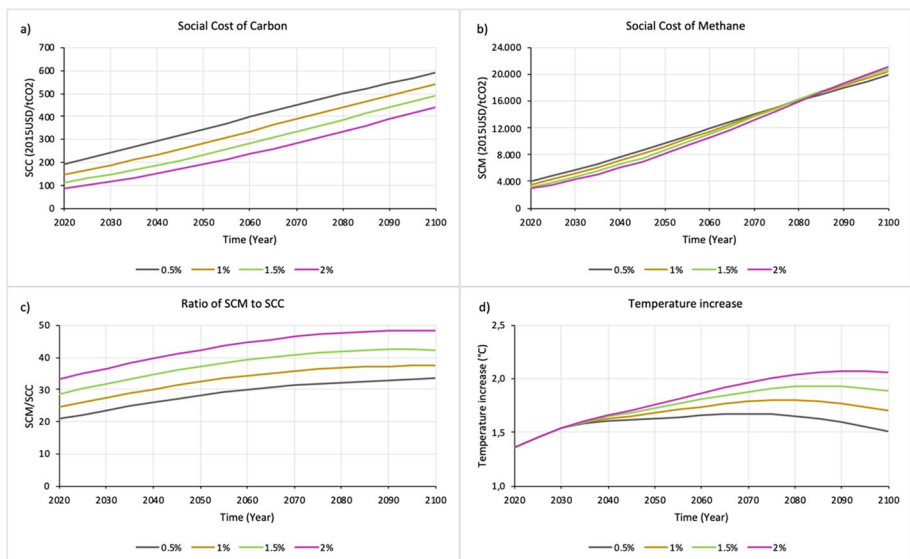

ratio of SCM to SCC increases with an increasing damage cost coefficient (as can be seen in the figure).

4.5 Variations in the social discount rate

To test how sensitive our results are to the social discount rate (SDR), we explore the effect of different values for δ while holding η constant at 1. The δ values tested here are 0.5, 1, 1.5, and 2%/year.

Figure 8 shows that the SCC is higher the lower the discount rate. The same holds for the SCM but only until around 2080 (given that the optimal paths for each δ is followed). If we stretch beyond 2100 also, at some point in the future, lower values of the discount

Fig. 8 Sensitivity analysis—pure rate of time preference: social cost of carbon, social cost of methane, ratio of SCM to SCC, temperature increase since 1900

rate will also give lower values of SCC. This happens because there are two countervailing mechanisms acting here: on the one hand, the SCC and SCM are reduced with a higher discount rate because the value of future damages matters less. On the other hand, a high discount rate will also imply that emissions will be abated less, and therefore the temperature will become higher in the future. Given that marginal damages are proportional to the temperature increase when the damage function is quadratic, higher temperature in the future will imply higher marginal damages and therefore higher social cost estimates.

One can also observe in Fig. 8 that the SCC is relatively more sensitive to variations in the discount rate than the SCM. This is due to the much longer lifetime of CO_2 compared to CH_4 (see Sect. 4.1 for a more detailed explanation).

We also tested a case where the pure rate of time preference is set to 0.1%/year as in Stern 2006. Under this assumption the 2020 value for SCM becomes equal to 4481 USD/tCH_4, SCC is estimated at 245 USD/tCO_2 and the ratio is equal to 18. The impact of a lower value for the pure rate of time preference on the SCM is rather low since the half time of methane is "only" around a decade.

5 Discussion

In this study, we have estimated the social cost of methane, the social cost of carbon and the ratio between the two. We do this by updating a version of DICE-2016R2 (Nordhaus 2018a, b). The version used here includes explicit methane and nitrous oxide cycles and a carbon cycle based on FaIR 2.0.0 (Leach et al. 2021). Parameters in the energy balance module as well as the damage cost function have also been updated.

We estimate SCM (for the year 2020) to lie in the range 880–8100 USD/tCH_4, depending on model assumptions. The lowest value is obtained with Nordhaus' parametrization of the discount rate and the damage function (Nordhaus 2018a, b) (with lower damage cost and higher discount rates). The highest value corresponds to the BaU case without any abatement and with our updated parameters for the damage cost and discount rates. Our base case estimate of the SCM is 4000 USD/tCH_4 and a case without NETs gives a value of 4300 USD/tCH_4.

Note that the estimated SCM varies significantly with changes in the damage cost parameter φ and the scenario with no abatement overall (i.e., the BaU scenario), but less with the discount rate parameters and the scenario without NETs.

Fig. 9 shows SCM estimates presented in different studies conducted in the last decade. It can be observed that our base case (as well as the BaU and no NETs scenarios) estimate is above other existing SCM estimates. This can be explained by our use of the relatively high damage estimate by (Howard and Sterner 2017) and—to a minor extent—the use of the relatively low discount rate obtained by using a parameterization based on the expert survey presented in (Drupp et al. 2018). When using the parameterization from Nordhaus (2018a, b), a SCM value in line with previous estimates are obtained.

In addition, we have estimated the SCC, and find the year 2020 values to lie in the range 27–1200 USD/tCO_2. The lowest value is obtained with Nordhaus' parametrization (of the damages and discount rate), and the highest with the BaU scenario (i.e. no abatement and using our base case assumptions for the damage cost and the discount rate). The SCC values in 2020 in our base case and the no NETs case are 192 USD/tCO_2 and 318 USD/tCO_2, respectively.
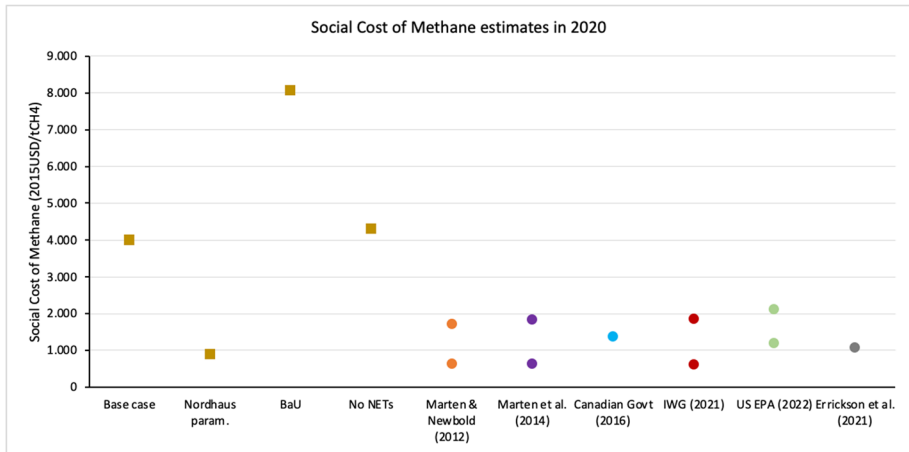
Fig. 9 Social cost of methane estimates in 2020: base case, our model under Nordhaus' parametrization, our model under the BaU scenario, our model without NETs, (Marten & Newbold 2012), (Marten et al. 2014), (Environment and Climate Change Canada 2016), (IWG 2021), (US EPA (2022), (Errickson et al. 2021)

The BaU estimate for the SCC is almost six times larger than the SCC estimated in our base case (in both scenarios we use the same parametrization of the damage cost and the discount rate) which shows that estimates of the SCC where it is assumed that the world will follow an optimal low carbon emission path may severely be underestimated. We observe that the SCC varies a lot with changes in the damage function, and the discount rate parameters, as well as under the BaU and no NETs scenarios.

Furthermore, we have estimated the ratio of SCM to SCC (see Fig. 10). This ratio can be seen as a key metric relevant for guiding tradeoffs between methane and carbon dioxide abatement. We find that this ratio lies in the range 7–32 in 2020, the lowest value corresponding to the BaU scenario and the highest to Nordhaus' case. The base case and no NETs scenario estimates are 21 and 13, respectively.

In the BAU scenario, we have a high temperature path which gives higher SCC, which in turn means that the SCM/SCC ratio is rather low for our BaU scenario compared to our base case scenario (SCC increases significantly more than SCM). This is also the case in our no NET case since the temperature path is higher in this case than in our base-case scenario, but the difference is not as big as for the BaU case.

Changes in the discount rate, damage cost and underlying scenarios affect both social cost estimates in the same direction, but still have consequences for the SCM to SCC ratio. Changes in the discount rate have a strong impact on the ratio (the higher the discount rate, the larger the ratio) because it affects the SCC much more than the SCM due to the much longer atmospheric residence time of CO_2. It is also clear that changes in the damage cost coefficient affect both SCC and SCM in a similar direction. The ratio SCM/SCC increases with higher values for the damage coefficient, but not by very much when this parameter is changed (as is explained more fully in Sect. 4.4). This is particularly true when the discount rate is large, since damages occurring in the future are highly discounted (see Figs. 7 and S1).

Fig. 10 also shows our estimate of the ratio of SCM to SCC compared to a range of other recent studies. It can be observed that our estimate of SCM/SCC in our base case, as
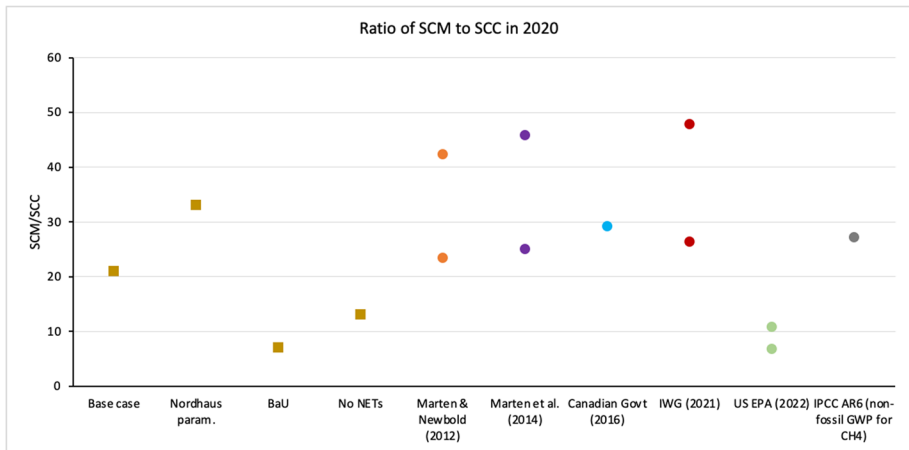
Fig. 10 Ratio of social cost of methane to social cost of carbon dioxide in 2020: base case, our model under Nordhaus' parametrization, our model under the BaU scenario, our model without NETs, (Marten & Newbold 2012), (Marten, et al. 2014), (Environment and Climate Change Canada 2016), (IWG 2021), US EPA (20,220), IPCC AR6

well as in the BaU and the no NETs scenarios, is lower than in many other studies, in particular their high-end values. The main explanation for this is the use of the relatively low discount rate obtained by using a parameterization based on the expert survey presented in (Drupp et al. 2018), but it also depends on the background temperature path as explained above. When using the parameterization from Nordhaus (2018a, b), values for the SCM/SCC ratio are found to be in line with previous estimates.

It can also be seen that our base case estimate for the SCM/SCC ratio is rather similar to the lower range values reported in the studies by Marten & Newbold (2012), Marten, et al. (2014), and the IWG (2021). This is likely due to the fact that the low-range SCM/SCC values in these studies are based on discount rates similar to that used in our base case. However, one should also be aware of that there are differences in modeling approaches. Marten & Newbold (2012), Marten et al (2014) and IWG (2021) use exogenous, rather than optimized, pathways, account for uncertainty in equiblibrium climate sensitivity and estimate the average SCM and SCC over many different runs using a Monte Carlo approach. Their modeling uses different climate models than what we do. Hence, our approaches are not directly comparable. Also, Hope (2006) finds a SCM/SCC ratio equal to 21 when using the mean values for SCC and SCM.

In the study by the US EPA (2022), they find an SCM equal to 1600 USD/ton CH_4 and an SCC equal to 190 USD/ton CO_2 (for the year 2020 and a discount rate of 2%/year, see table ES1). Their SCC is essentially the same as our base case estimate (192 USD/tCO_2). However, their SCM is less than half of our estimate of 4000 USD/ton CH_4. The reasons for this are, we believe, two-fold. First, our damage cost for a certain level of temperature change is higher, which (everything else equal) leads to higher social cost of emissions. Second, the US EPA has on average significantly higher background temperatures in the long run (a temperature increase in the range 2–3 °C, see their Fig. 2.2.2, whereas we peak at around 1.7 °C, see our Fig. 1) which (everything else equal) gives a higher marginal damage (the marginal damage is proportional to the background temperature, see Eq. 3). Hence, the reason why our SCC and that of the EPA is roughly equal is because the effects

of our higher damage coefficient and our lower background temperature path roughly cancel out. But for methane, which is short lived, the impact of the long-term background temperature path is less pronounced, and the impact of the higher damage coefficient dominates, and hence we get a higher SCM than EPA. This also explains why the EPA SCM/ SCC ratio (using the social cost estimates mentioned here) is significantly lower than our estimate. There are other factors at stake here, like differences in modeling approaches, the discount rate and their Monte Carlo analysis, but we believe that these are the most important ones.

Furthermore, the SCC estimate by Rennert et al. (2022) is 185 USD/ton CO_2 which is very close to our estimate of 192 USD/ton CO_2. In the Rennert et al. paper, they do not estimate any values for the social cost of methane. However, in a webbased platform (https:// www.rff.org/publications/data-tools/scc-explorer/), consistent with the Rennert et al. paper, such estimates are provided. The SCM estimated by using this platform is 1939 USD/tCH_4 which can be compared to the EPA estimate of 1600 USD/tCH_4 and our SCM estimate of 4000 USD/tCH_4. The reason why we get roughly twice as a high a value for the SCM but roughly the same SCC is the same as the reasons given above for the similarities and differences compared to the EPA estimate. The estimates by EPA and Rennert et al. (2022) are based on strongly related methodologies.

6 Conclusion

In this paper, we provide consistent estimations of the social cost of methane and carbon dioxide based on recent findings and expert assessments of the social discount rate, damage functions and the dynamics of the carbon and methane cycles (including both concentration and climate feedbacks on both gas cycles) and on the resulting temperature change. We find that the SCM (for the year 2020) for the cases tested lies in the range 880–8100 USD/tCH_4, with a base case estimate of the SCM at 4000 USD/tCH_4.

This can, for example, be compared to latest official estimates from the US EPA (2022), which lie in the range 1300 and 2300 USD/tCH_4, where the range depends on the discount rate (their range is 1.5–2.5%/year). The reason why our base case value is higher than the estimates obtained by the EPA (2022) is largely due to our use of a higher damage function.

For the ratio of SCM to SCC, which can be used as an alternative metric to the standard GWP metric, we find a range between 7 and 32 in 2020, with 21 as our base case estimate. GWP-100 in IPCC AR6 (Masson-Delmotte et al. 2021) is 27. This difference largely has to do with the fact that our discount parameters correspond roughly to a 200-year time horizon. (The GWP-200 value[2] is about 16.) Furthermore, the estimated ratio grows over time and becomes higher than the standard GWP-100 value around the year 2050.

This changing ratio implies that, until 2050, the relative focus in the model is slightly less on methane abatement than what would be suggested by a simple application of the GWP-100 rule. It might sound like a contradiction since we found rather high SCMs but our SCC is also higher (Fig. 9)—in fact more so, and thus the SCM/SCC ratio is somewhat lower.

We hope the modelers and policy makers will find this an interesting and valuable finding. For many practical policy purposes, the differences are still modest and considering

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[2] Estimated using the simple climate model presented at doi.org/10.5281/zenodo.5957222.

the many uncertainties, we might also conclude by saying that the GWP-100 approximation is still quite reasonable for many practical policy applications.[3]

Appendix

Theoretical framework for the ratio of social cost of different greenhouse gases

The relationship between SCC and SCM can be understood by analyzing the following simple analytical expressions.

The social cost of gas X (SCX) can be approximated as

$$SCX = \int_0^\infty Y(t)e^{-rt}\varphi\Big(\big(T(t) + \Delta T_X(t)\big)^2 - T(t)^2\Big)dt \approx \int_0^\infty Y(t)e^{-rt}2\varphi T(t)\Delta T_X(t)dt \tag{3}$$

where SCX is the Net Present Value (NPV) climate change damages of one additional ton of gas X for a damage function that is quadratic in the temperature change, T. Here $Y(t)$ is equal to global GDP, and r is the discount rate according to the Ramsey rule, φ is the damage proportionality constant, $T(t)$ is the global average background temperature increase (i.e., the change from pre-industrial times) in the year t and $\Delta T_X(t)$ is the temperature response at time t as a result of an emission pulse of gas X. The term $Y(t)2\varphi T(t)\Delta T_X(t)$ refers to the marginal damage in each year in the future caused by a unit emission pulse of gas X in year 0 (the start year).

For the sake of simplicity and clarity we assume a fixed global population and a fixed savings rate. Using the Ramsey rule (see Eq. 1), we get:

$$SCX \approx \int_0^\infty Y_0 e^{gt} e^{-(\eta \cdot g + \delta) \cdot t} 2\varphi T(t)\Delta T_X(t)dt = \int_0^\infty Y_0 e^{g \cdot t \cdot (1-\eta) - \delta \cdot t} 2\varphi T(t)\Delta T_X(t)dt \tag{4}$$

where Y_0 is global GDP at time $t=0$.

If $\eta = 1$ (as in our base case), or if the per capita consumption growth rate is zero, i.e., g=0, we get:

$$SCX \approx \int_0^\infty Y_0 e^{-\delta t} 2\varphi T(t)\Delta T_X(t)dt \tag{5}$$

The ratio of SCM to SCC is then obtained as

$$\frac{SCM}{SCC} \approx \frac{\int_0^\infty Y_0 e^{-\delta t} 2\varphi T(t)\Delta T_{CH_4}(t)dt}{\int_0^\infty Y_0 e^{-\delta t} 2\varphi T(t)\Delta T_{CO_2}(t)dt} = \frac{\int_0^\infty e^{-\delta t} T(t)\Delta T_{CH_4}(t)dt}{\int_0^\infty e^{-\delta t} T(t)\Delta T_{CO_2}(t)dt} \tag{6}$$

Hence the ratio is, under these simplifying assumptions, independent of the damage coefficient φ and the size of the economy (Y) and only dependent on the pure rate of time preference, the background temperature path (T) and the temperature impacts of the emission impulses of methane (ΔT_{CH_4}) and carbon dioxide (ΔT_{CO_2}), respectively. (It should be noted that in an optimization model as in DICE, the damage coefficient has an

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[3] Estimated using the simple climate model presented at doi.org/10.5281/zenodo.5957222 which is based on chapter IPCC AR6 WG1 (Forster et al., 2021).

impact on the optimal temperature, so changes in the damage coefficient may nevertheless have an impact on this ratio – a feature we analyze in the sensitivity analysis.)

If we assume a fixed background atmosphere and constant temperature (as done when calculating the GWP) we get:

$$\frac{SCM}{SCC} \approx \frac{\int_0^\infty e^{-\delta t}\Delta T_{CH_4}(t)dt}{\int_0^\infty e^{-\delta t}\Delta T_{CO_2}(t)dt} \tag{7}$$

This is the time integrated discounted temperature response of an emissions pulse of methane, where the discount rate equals the pure rate of time preference, divided by the corresponding estimate for an emissions pulse of carbon dioxide.

Now we can make the following observation about the numerator. The temperature response of a pulse emission of CH_4 follows a pattern that is similar to the atmospheric stock response of CH_4 emissions, but with a lag due to the thermal inertia of the climate system, see Fig. 11 in the Appendix. This means (a) that the SCM is rather insensitive to the time horizon used in the integration of damages (as long as it is longer than half a century irrespective of the discount rate applied) and (b) that SCM is rather insensitive to the value δ as long as it is low compared to β, the inverse of the perturbation lifetime. The perturbation lifetime time is 12 years (and hence beta = 0.083) while values for the pure rate of time preference in our base case is 0.5% per year hence $\beta \gg \delta$: Let us now assume, as an approximation, that

$$\Delta T_{CH_4}(t) \approx \Delta T^0_{CH_4} e^{-\beta t} \tag{8}$$

We can then rewrite SCM as

$$SCM \approx 2\varphi Y_0 T_0 \Delta T^0_{CH_4} \int_0^\infty e^{-\delta t}e^{-\beta t}dt \approx 2\varphi Y_0 T_0 \Delta T^0_{CH_4} \int_0^H e^{-\delta t}e^{-\beta t}dt$$

$$= 2\varphi Y_0 T_0 \Delta T^0_{CH_4} \int_0^H e^{-\beta(1+\frac{\delta}{\beta})t}dt \approx 2\varphi Y_0 T_0 \Delta T^0_{CH_4} \int_0^H e^{-\beta t}dt \approx 2\varphi Y_0 T_0 \int_0^H \Delta T_{CH_4}(t)dt \tag{9}$$

In the second step, we just integrate to H because beyond a certain time horizon, the remaining value of the integral is very small; hence, H is assumed to be sufficiently large. In the third to fourth step we take advantage of the assumption that $(\delta \ll \beta)$ and as an approximation the discounting term can be neglected. This approximation holds rather well if $H = 1/\delta$ is several times large than the perturbation lifetime of the gas in question.
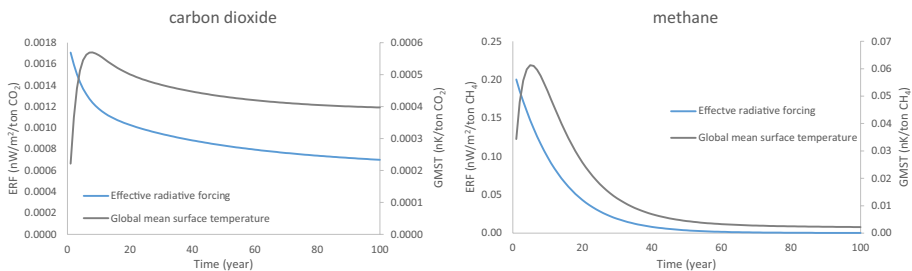
Fig. 11 The impulse response for effective radiative forcing and global mean surface temperature for emissions of one ton of carbon dioxide and one ton of methane, respectively. The figure is based on the assumptions used when calculating metrics in chapter IPCC AR6 WG1

For the denominator the approximation is somewhat easier. Observe here that ΔT_{CO_2} is roughly constant over time (Fig. 11). This means that instead of integrating the relatively constant temperature response multiplied by $e^{-\delta t}$ to infinity, one may integrate the temperature response from zero to an endpoint t = H, since $\int_0^\infty e^{-\delta t} dt = \frac{1}{\delta} = H = \int_0^H dt$ where $H = 1/\delta$.

Given these approximations, expression (7) can be approximated as

$$\frac{SCM}{SCC} \approx \frac{\int_0^\infty e^{-\delta t} \Delta T_{CH_4}(t) dt}{\int_0^\infty e^{-\delta t} \Delta T_{CO_2}(t) dt} \approx \frac{\int_0^H \Delta T_{CH_4}(t) dt}{\int_0^H \Delta T_{CO_2}(t) dt} \tag{10}$$

It may now be observed that last expression is the definition of the integrated Global Temperature change Potential (iGTP) with time horizon H (*i.e., the integrated value of the temperature response from a pulse emission of methane divided with the corresponding value for a pulse emission of CO₂*).

We know from Peters et al. (2011) and Azar & Johansson (2012a) that iGTP (H) is approximately equal to the global warming potential, i.e.,

$$GWP(H) \approx iGTP(H) = \frac{\int_0^H \Delta T_{CH_4}(t) dt}{\int_0^H \Delta T_{CO_2}(t) dt} \tag{11}$$

Hence, with the assumptions stated above we have

$$\frac{SCM(\delta)}{SCC(\delta)} \approx GWP(H) \tag{12}$$

given that
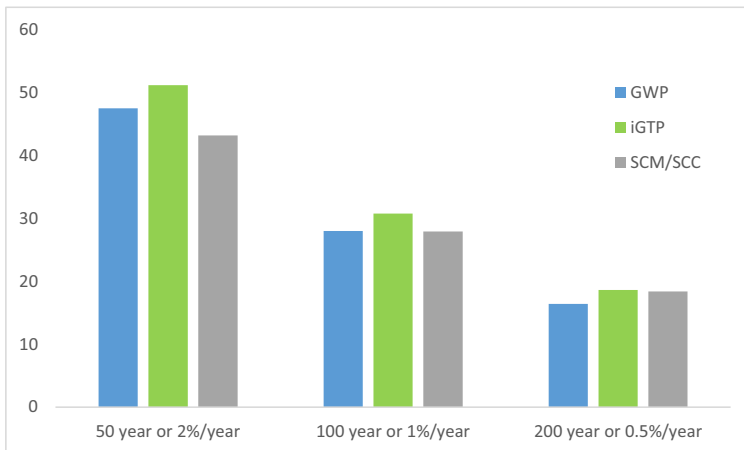
Fig. 12 The estimated ratio of social cost of methane to social cost of carbon dioxide using Eq. 7 with the pure rate of time preference stated in the figure and compared with the global warming potential and the integrated temperature change potential values for methane with the different time horizons stated in the figure. The values presented in the figure are not based on methane and carbon dioxide cycles and energy balance model used in our revised version of DICE, but the ones used in IPCC AR6 (2021)

$$\delta = 1/H \tag{13}$$

Similar lines of reasoning have been presented in Azar & Johansson (2012b), Sarofim and Giordano (2018) Mallapragda & Mignone (2020) and Lintunen & Rautiainen (2021).

The numerical values for GWP, iGTP and SCM/SCC when $\delta = 1/H$ are shown in Fig. 12 for different time horizons. As can be seen, the numerical value for the metrics is strikingly similar when consistent assumptions on δ and H are used[4].

Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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[4] Estimated using the simple climate model presented at doi.org/10.5281/zenodo.5957222 which is based on chapter IPCC AR6 WG1 (Forster et al., 2021). GWP and iGTP values are estimated as the integral under the effective radiative forcing response and temperature response curves, respectively, while the SCM to SCC ratio is estimated based on the time integrated temperature response with discounting over a 1000 year time horizon.

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