Social Cost of Methane:

An estimation using an Integrated Assessment Model

Master's thesis in Sustainable Energy Systems

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Abstract

Methane is the second most important anthropogenic greenhouse gas and therefore one of the main contributors to the anthropogenic greenhouse gas effect, the main mechanism causing climate change. Due to its short lifetime and relatively strong forcing impact per unit of gas in the atmosphere, a reduction of methane emissions allows to rapidly reduce the temperature increase, so specific methane emissions reduction policies can be a key strategy for short-term global warming reduction. In addition, keeping methane emissions low in the future may help to also reduce long-term climate change.

This study provides an estimate of the social cost of methane that could be used as a reference metric for policymaking specifically targeted to reduce the impact of anthropogenic methane emissions. This is done by further developing the DICE model presented in Hänsel et al. including a methane cycle and a methane abatement cost function. The study evaluates the time evolution of the social cost of methane, social cost of carbon, and the ratio of SCM to SCC, and explores how sensitive these estimates are to changes in the discount rate, the damage function, and the marginal abatement cost curve of methane.

We find that the social cost of methane grows almost linearly over time, as the social cost of carbon, and is estimated to be 7,000 $/tCH_4$ in 2020 and 15,300 $/CH_4$ in 2050. The ratio of SCM to SCC also grows with time, being 32 in 2020 and 41 in 2050. The social cost of methane is less sensitive to variations in the discount rate than the social cost of carbon, but almost equally as sensitive to variations in the damage function. Finally, the cost of abating methane has a large impact on the pace at which this is abated, but it almost does not alter its social cost. However, it does have a significant impact on the social cost of carbon, which is lower when abating methane is cheaper.

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To my family: Mamá, Papá, Paula, thank you for your unconditional support. Knowing that you have my back no matter what gives me the freedom to pursue what I really want to do in my life. 'Gracias, siempre'.

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Abbreviations

CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CH_4	Methane
COP	Conference of Parties
CO_2	Carbon dioxide
DICE	Dynamic-Integrated Climate Economic model
ERF	Effective Radiative Forcing
ETS	Emissions Trading System
GDP	Gross Domestic Product
FAIR	Finite Amplitude Impulse Response
FUND	Climate Framework for Uncertainty, Negotiation and Distribution
LFT	Lifetime
GMST	Global Mean Surface Temperature
GHG	Greenhouse Gas
GWP	Global Warming Potential
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
MAC	Marginal Abatement Cost
NET	Negative Emission Technologies
NO_2	Nitrous oxide
REMIND	Regional Model of Investment and Development
RF	Radiative Forcing
SCAR	Social Cost of Atmospheric Release

SCC	Social Cost of Carbon
SCM	Social Cost of Methane
SPC	Shadow Price of Carbon
SPM	Shadow Price of Methane

1. Introduction

Climate change is probably the biggest collective threat that our society will be facing for several generations. The main mechanism causing climate change is the anthropogenic greenhouse effect, whose main driver is the anthropogenic emission of greenhouse gases (GHGs). Most of the consequences of the increase in greenhouse gases' concentrations are known (temperature change, sea level rise, precipitation change, ocean acidification etc.), but the extent to which these will occur and how large the consequences will be for a certain change in the concentrations is uncertain. This uncertainty, together with the complex physical dynamics that govern climate change, makes expected benefits of emission reductions significantly difficult to evaluate, and therefore contributes to making it hard to design a policy for it. Another added difficulty to the avoidance of climate change is the fact that it is a global externality, meaning that its costs are not captured in markets and its impacts are spread around the world. There are only weak incentives for states to reduce their emission on their own because they will only experience a small fraction of the benefits of such actions, so cooperative multinational policies are required to tackle climate change [1].

The United Nations Framework Convention on Climate Change adopted in 1992 constituted the first step for the development of a global strategy to reduce emissions and limit average global temperature increase. This convention was followed in 1995 by the first Conference of Parties (COP), which is the supreme decision-making body of the Convention where Parties review its implementation and any other legal instruments adopted in it [2], and has been celebrated since then 25 times[1]. A key agent in the international cooperation is The Intergovernmental Panel on Climate Change (IPCC), which was founded 1988 as a technical body of the United Nations to produce scientific assessments on climate change as well as assessment of the research on adaptation and mitigation options to help policymakers with scientific input in their decision-making process. Among many other things, the IPCC assesses Integrated Assessment Models (IAMs) and the results generated by them. IAMs typically combine economic, energy systems, land use and climate models. In some of them a damage function is included in order to carry out cost-benefit analyses

[1] COP25 was celebrated from 2nd to 3rd of December 2019.

and find the optimum level of abatement that maximizes a welfare function. Other IAMs that do not include a damage function are often set to meet a predefined climate target and minimize the cost of abatement to meet such a target, i.e., perform a cost-effectiveness analysis.

One of the most proliferous IAMs is the Dynamic Integrated Climate-Economic Model (DICE) developed by Nobel Prize laureate William Nordhaus. The model explores the optimal temperature and emission trajectories by balancing the damages caused by climate change (in economic terms) and the costs of emission reductions. The latest version of his model suggests a climate policy path that limits average temperature increase to 3.5ºC by 2100 [3], which is far from the 2ºC to 1.5ºC target agreed in the Paris Agreement. Hänsel et al. [4] introduces a series of updates to the last version of DICE to show that the UN climate targets may be economically optimal if the model is properly updated. These updates include a more sophisticated carbon cycle module from the Finite Amplitude Impulse Response (FAIR) climate model presented in Smith et al. [5], a re-calibration of the energy-balance model using the findings in Geoffroy et al. [6], the use of the damage function presented in Howard and Sterner [7] instead of Nordhaus', new values of the pure rate of time preference and elasticity of marginal utility that are in line with the most recent expert recommendations included in Drupp et al. [8], a pathway for non-CO_2 forcers estimated by the Regional Model of Investment and Development (REMIND) using the SSP2 baseline, and allowing for negative CO_2 emissions from 2050 onwards.

Cost-benefit analyses carried out with IAMs applied to climate science have traditionally calculated the social cost of carbon (SCC), which, in an optimized climate policy model, will equal the optimal carbon price or carbon tax [1], but often other GHGs have been included exogenously in these models. In a context where the concentrations of non-CO_2 GHGs are projected to increase substantially [9], especially methane and nitrogen oxide, it can be very useful for policymakers to have a measurement of the cost associated with the damages caused by the emission of these gases, which would allow to design efficient policy instruments to reduce them.

The exogeneity of non-CO_2 GHGs in most CBA studies only allows for an indirect estimate of the social cost of these gases through the use of global warming potentials (GWP), i.e., one uses GWP to calculate the CO_2 equivalent emissions and multiply this with the social cost of carbon in order to get an estimate on the social cost of the non-CO_2 GHG in question.

These indirect estimates have been proven to potentially lead to significant errors for the abatement benefits of individual GHGs [10]. It is therefore a significant line of investigation to make non-CO_2 GHGs endogenous to the model, so that a direct estimate of their social cost can be obtained to better design a policy pathway that reduces emissions efficiently. Further, the ratio of the social cost for a non-CO_2 GHG to the social cost of CO_2 can be used as an alternative metric to GWP to place different gases in a common scale, i.e., CO_2-equivalents.

1.1. Aim & Scope

The aim of this master's thesis is to provide an estimate of the social cost of methane that could be used as a basis for policymaking given that the global climate impact of methane is considered. This study makes methane emissions endogenous to the model by including a baseline emissions scenario for methane, a cost function for its abatement, and a representation of how methane affects climate. The thesis evaluates the estimates of social cost of methane, social cost of carbon, and their ratio and explores how critical parameters of the model, such as social discount rate determinants, damage function, and marginal abatement cost of methane, alter the results. A reflection about how these estimates can be used as a reference metric by both private and public sectors to internalize the externalities associated with the emissions of these gases is also included.

This study uses the updated DICE model presented in Hänsel et al. [4] as a base and then updates it even further by including a baseline emissions scenario for methane, a methane cycle and a methane abatement cost function. It seeks to provide relevant information about the social cost of methane based on the latest scientific evidence. Therefore, the following questions will be answered:

- What effect does methane endogeneity have on the optimal temperature increase found in the model?
- What is the optimal path of methane emissions reduction to achieve this temperature increase?
- What is the estimated social cost of methane and what is the ratio of social cost of methane to social cost of carbon?
    - How much does it differ to an indirect estimation of the social cost of methane through GWP?

- How are the social cost of carbon and methane affected by variations in social discount rate parameters, damage function, and methane abatement cost function?
  - Why are these estimates affected in such ways by variations in these parameters?
- What is the value for the shadow price of methane and shadow price of carbon obtained in a cost-effectiveness analysis in which the Paris Climate target is set to be met and how do these compare to the social cost estimates obtained in the cost-benefit analysis?
- How can social cost estimates help policymakers to design the best policies to tackle climate change?
  - Are these estimates being currently used? In what way?

1.2. Outline of the Thesis

The report is structured as follows:

- **Chapter 1 – Introduction:** The topic of the thesis is introduced and contextualized, the aim of the study is explained, and the specific research questions that are addressed are presented.
- **Chapter 2 – Background:** The theoretical concepts that are essential to understand the aim and development of the study are explained.
- **Chapter 3 – Literature review:** An overview of up-to-date scientific literature in this field is exposed.
- **Chapter 4 – Methodology:** A detailed description of the modifications introduced in the model presented in Hänsel et al. [4] and the data chosen are explained.
- **Chapter 5 – Results:** The results of the model are presented.
- **Chapter 6 – Discussion:** A discussion of the implication of the results obtained is carried out.
- **Chapter 7 – Conclusion:** A synthesis and final remarks of the study are presented.

2. Background

This chapter introduces the theoretical concepts that constitute the framework in which this master's thesis is contextualized, presents key concepts to understand the usefulness of the model developed, and explains how critical variables of this model relate.

2.1. Climate Change and Global Warming

According to the Intergovernmental Panel on Climate Change [11], climate change refers "to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer". Many consequences of climate change are well known, but there might also be others that are still not known. What is clearly uncertain is the extent to which they will occur. Although these consequences are global, the impacts are unevenly distributed across the world. For instance, the melting of land-based ice shields will cause a rise in the sea level which affects coastal and low-lying areas, and extreme weather events and shifting rainfall will affect developing countries the most because of their heavy dependence on their natural environment and smaller capability to adapt to changes [12].

Global warming is defined as "the estimated increase in global mean surface temperature (GMST) averaged over a 30-year period, or the 30-year period centered on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified" by the same institution [11], and is considered the main driver of climate change. The main drivers of global warming are anthropogenic GHGs emissions, which are the object of this study.

2.2. Greenhouse Gases, Radiative Forcing and Effective Radiative Forcing

Greenhouse gases are generally defined as gases that capture infrared radiation emitted from the Earth's surface causing a global (temporary) energy imbalance (more solar radiation is absorbed by the Earth system than the amount of infrared radiation that leaves it), which implies a warming of the planet, including the atmosphere. The main anthropogenic greenhouse gases are CO_2, CH_4 and NO_2. When comparing GHGs, two characteristics are particularly relevant: their radiative efficiency, which refers to their capacity to absorb and radiate energy; and their atmospheric lifetime, which indicates the time the gases will stay in the atmosphere before they are naturally removed. These two concepts are captured in the global warming potential, a measure of the amount of energy absorbed by the emission of one additional unit of a gas relative to that of one additional unit of a reference gas (usually CO_2) over a given time horizon, usually 100 years [13].

Radiative forcing (RF) is often referred as a measure of how much a change in the atmospheric concentration of a GHG contributes to global warming. The IPCC defines it in its 5th assessment report as "the change in net downward radiative flux at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding surface and tropospheric temperatures and state variables such as water vapor and cloud cover fixed at the unperturbed values". It provides a very useful information to compare different forcing agents based on their potential climate change effect, but it does not provide an accurate relation of the temperature response of all of them. While RF includes the effects of the forcing agent itself, effective radiative forcing (ERF) also accounts for rapid adjustments in the troposphere, which have been proved to be useful to better capture climate dynamics [14]. Therefore, the ERF can be considered a more sophisticated version of RF. For well mixed gases like CO_2, CH_4 and NO_2 RF and ERF are essentially the same.

2.2.1. Why should methane be made endogenous in integrated assessment modelling

Climate change mitigation strategies have been predominantly focused on CO_2 abatement and, indeed, it is the most emitted GHG by far and represents around two thirds of total radiative forcing [15]. But the main non-CO_2 GHGs, predominantly CH_4 and NO_2, already represent a large share of total radiative forcing and they are expected to represent an increasingly larger share of total GHG emissions if we are to meet climate targets in line with those expressed in the Paris agreement [16], so specific emissions reduction strategies for these gases appear to be crucial to achieve the 2º to 1.5ºC temperature increase target by 2100.

Methane is the second most important anthropogenic GHG and has contributed to approximately 23% of the additional radiative forcing in the lower atmosphere since 1750 [17]. This gas has a lifetime of about 9.1 years [18] and a GWP_{100} of 34 [19][2]. Due to its characteristics, a reduction of methane emissions implies a rapid decrease in its atmospheric concentration, which translates into a decrease in radiative forcing. As a consequence, the reduction of methane emissions can be a very interesting tool for short-term global warming reduction.

Traditionally, the social cost of non-CO_2 greenhouse gases has been indirectly estimated by converting non-CO_2 GHG emissions to CO_2-equivalents using GWP, but this approach has been proven to provide inaccurate estimations. The use of GWP does not to capture the interrelationships between the rate of decay of the gases considered, the discount rate and changes in marginal climate damages over time, which will further translate into misleading estimations of social cost of these gases [10].

By modelling methane explicitly in DICE, it is possible to directly estimate its social cost, which is a key metric to design an efficient policy for the reduction of its emissions.

2.3. Integrated Assessment Models

Assessing the impacts of climate change on physical capital, human lives, wildlife and ecosystems requires an understanding of the relationships within and between biochemical and socioeconomic components that constitute the Earth system. To evaluate them and the effect of public policies implementation, quantitative models, referred as Integrated Assessment Models, have been developed. These models have been extensively used to inform policymakers regarding climate impact consequences on the economy and possible mitigation strategies to overcome these. IAMs have evolved substantially and differ in their scope, structure and solution methods, but many of them share three core components: An economic model with a forward-looking representative agent, a climate model which models the effect of economic activity on future temperature, and in some cases a damage function that translates temperature changes into economic damages [20].

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[2] With inclusion of climate-carbon feedbacks.

Integrated assessment models can be generally classified into two main categories: Detailed process (DP) and cost-benefit (CB) IAMs. The former is a more disaggregated model that provides information of emissions abatement opportunities at the sectoral and regional levels and typically do not consider damage functions, while the latter typically aggregates climate change impacts over regions and sectors into a simplified fashion, includes a damage function, and has a simplified approach of assessing the cost of abatement. This study mainly focuses on cost-benefit IAMs.

2.3.1. Policy optimization vs Policy evaluation models

There are two main applications of integrated assessment models built for the climate change discussion: the computation of optimal GHG emissions trajectories and the price charged to these, and the evaluation of the costs and benefits associated with climate policy to reach a predefined target.

The first one refers to so-called policy optimization models. These models compute the optimal climate policy by balancing marginal costs of emissions against marginal damage costs to maximize welfare. The outcome of these models is typically the social cost of a GHG, the optimal abatement level and optimal change in global mean surface temperature. Optimal policy can be achieved by, for instance, imposing a tax on emissions of a gas that is equal to the social cost of that gas.

The second one refers to policy evaluation models. These models usually compare alternative policy scenarios where no damage caused by temperature increase is considered and a maximum temperature increase is imposed, e.g., 1.5ºC or 2ºC above pre-industrial level, and evaluate the cost associated with them [21]. The outcome of these models is the shadow price of the GHG and the emission trajectories towards the predefined target.

Traditionally, IAMs without damage function have been more extensively used in technical reports to assess policymakers. Perhaps the most obvious example of this is the IPCC report, in which the technology rich IAM without damage function used to perform a cost-effectiveness analysis takes much more space than the IAM that conducts a cost-benefit analysis and incorporates a damage function. But the social cost of greenhouse gases, particularly CO_2, are gradually attracting more attention and a variety of IAMs are being developed to produce more sophisticated and accurate estimates to be used by national and regional governments, like the US, Canada, or California [22].

The DICE model is originally designed to work as a policy optimization model but can also, with appropriate modifications be used as a policy evaluation model.

2.4. Social Cost and Shadow Price of Greenhouse gases

The social cost of a greenhouse gas represents the social value of avoided future damages caused by one more unit of that gas emitted. It is one of the main results of IAMs that conduct cost-benefit analyses and provides policymakers a monetary value of the damages caused by this additional emission of the gas studied, which can be used to design an efficient emissions reduction policy. In a more academic definition, the social cost of a GHG is the change in the discounted value of consumption expressed as current consumption per unit of an additional current emissions [1]. A general expression for the social cost of a gas X is:

$$SCX(t) = \int_{t}^{\infty} \frac{\partial C(\hat{t})e^{-r\hat{t}}}{\partial E_X(t)} d\hat{t} \tag{1}$$

The shadow price of a greenhouse gas represents how much society should be willing to pay per additional unit of GHG emitted to prevent a temperature increase above an agreed target. It is one of the main outcomes of IAMs that conduct cost-effectiveness analyses and can be used by policymakers to set the proper incentive to guide investments towards low-emission solutions. Mathematically, it is the value to the objective function obtained from relaxing the constraint on the variable that is investigated.

The main difference between these two metrics is the damage function. While social cost estimates are the result of balancing monetary damages caused by an additional unit of a GHG emitted with the cost of reducing its emission, shadow prices are the result of finding the optimum level of abatement to avoid an increase in temperature above a predefine target, minimizing the abatement costs.

These estimates are rather uncertain, and their value depends on critical parameter choices subjected, in some cases, to ethical criteria.

2.5. Carbon Pricing

There is a growing consensus that carbon pricing is the single most effective instrument to mitigate climate change. The World Bank Group [23] differentiates three concepts: carbon pricing, internal carbon pricing, and implicit carbon pricing.

Carbon pricing refers to initiatives that put and explicit price on greenhouse gas emissions expressed in monetary units per tCO_2-eq. This includes carbon taxes, emissions trading systems (ETSs), offset mechanisms, and results-based climate finance.

Internal carbon pricing refers to the practice of organizations assigning a monetary value to GHG emissions in their policy analysis and decision making.

Implicit carbon pricing refers to other policies that implicitly price GHG emissions, such as the removal of fossil fuel subsidies and fuel taxation.

3. Literature review

This chapter presents a review of the most recent and relevant publications related to methane emissions and concentration projections, its social cost estimates, and how these estimates are being used today when designing policy schemes to reduce the emission of this gas.

3.1. Methane emissions and concentration

Methane currently constitutes the second largest greenhouse gas emission, only surpassed by carbon dioxide. The main sources of natural emissions are wetlands, and the largest anthropogenic emissions come from agriculture, fossil fuel production and use, waste disposal, and alterations of methane fluxes due to increased concentrations of atmospheric carbon dioxide and climate change [9]. Figure 1 shows the geographical distribution of these emissions by source category in the 2008-2017 decade.

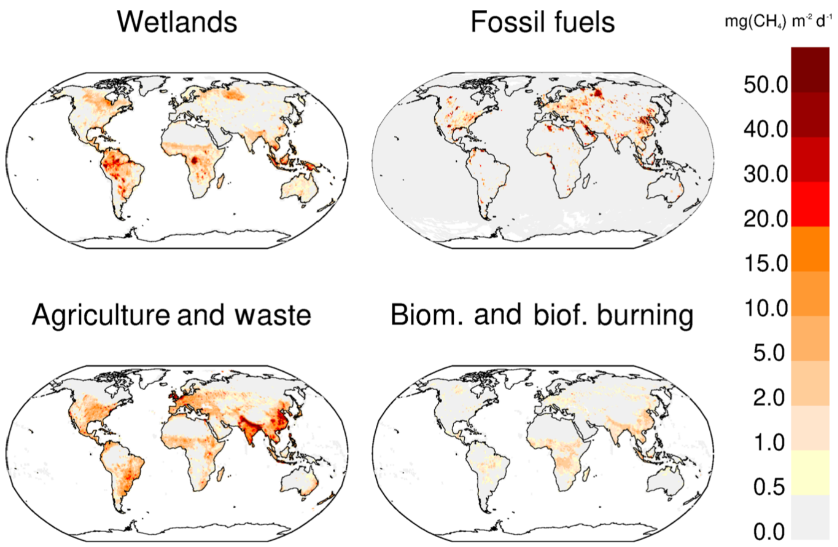

Figure 1: Methane emissions from main categories: natural wetlands (excluding lakes, ponds, and rivers), biomass and biofuels burning, agriculture and waste, and fossil fuels for the 2008-2017 decade [9].

According to the Shared Socioeconomic Pathways (SSP) database [24], the middle of the road (SSP2)[3] baseline scenario for anthropogenic methane emissions projects a steady increase of these until 2085, reaching a value of 530 Mt, when emissions start slowly declining until the end of the century, as observed in Figure 2.

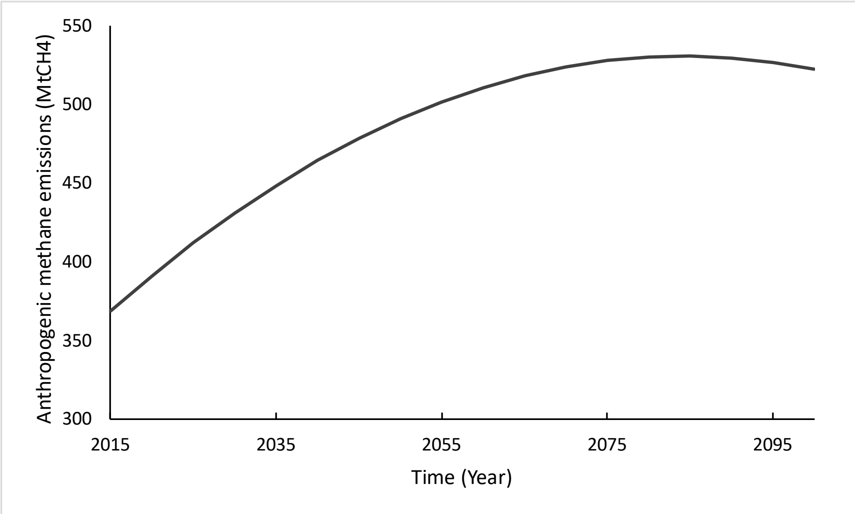

Figure 2: Anthropogenic methane emissions from 2015 to 2100.

The atmospheric concertation of methane is approximately 2.6 times larger than its atmospheric pre-industrial equilibrium value in 1750 [9]. To represent the historic evolution of methane concentration on the atmosphere, a simple model has been developed where parameters such as natural emissions and lifetimes have been balanced to obtain a coherent evolution. To build it, methane emissions from 1765 to 1990 are taken from RCP database [25] and emissions from 1990 to 2015 are taken from SSP database [24]. As observed in Figure 3, the calculated concentration from the model is in line with the measured methane concentrations in the ice cores, Cape Grim (Australia) and Mauna Loa (Hawaii), and follows an exponential path.

[3] Average of AIM/CGE, GCAM4, IMAGE, MESSAGE-GLOBIOM, REMIND-MAGPIE, WITCH-GLOBIOM models projections.

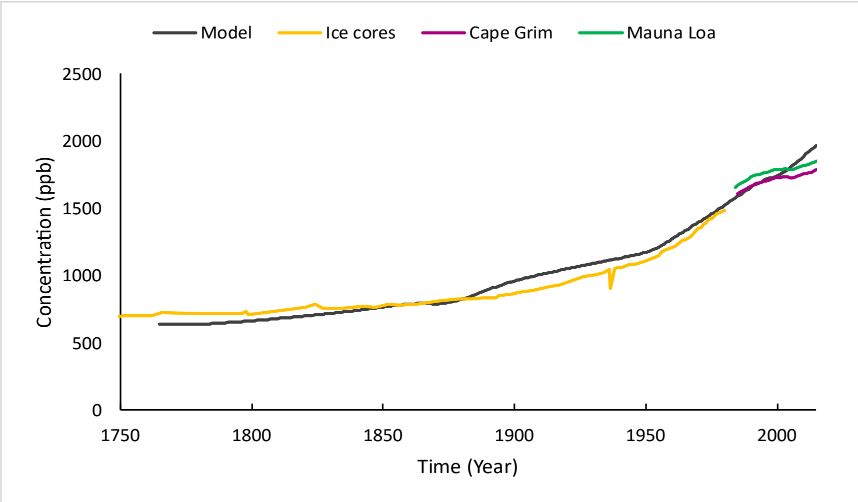

Figure 3: Methane concentration evolution since 1765: Model, Ice cores measurement, Cape Grim (Australia) measurement, Mauna Loa (Hawaii) measurement.

The methane concentration in the atmosphere is estimated to be 1,969 ppb in 2015, according to the model. This is the value that has been used as the initial methane concentration in the IAM developed for this study.

3.2. Social cost of methane estimates

The social cost of methane has traditionally been indirectly estimated by converting methane emissions to CO_2-equivalents through GWP, but this approach can underestimate the benefits of current methane abatement substantially [10]. In the last decade, a number of research groups have developed models that permit a direct estimation of the social cost of methane and have provided interesting initial insights about the costs that methane emissions will cause on society and nature.

Marten and Newbold [10] point out that the standard DICE version is a poor tool for examining non-CO_2 GHGs because they are only represented in a catch-all exogenous forcing variable, which does not allow for a representation of the individual particularities of each of these gases. As a solution, they replace the climate sub-model of DICE with the 5.3 version of MAGICC climate model, which includes gas-cycle models for methane and nitrous oxide, include a probability distribution over the equilibrium climate sensitivity parameter, and keep the components of the economic sub-model of DICE unchanged.

Marten et al. [26] present a series of updates that can be implemented to several IAMs, such as DICE and PAGE, to be able to obtain direct estimates of non-CO_2 GHG emissions. The updates presented are consistent with USG Social Cost of Carbon estimates presented in

2012 and 2013. DICE and PAGE were updated by including scenarios for methane and nitrous oxide emissions, a one-box gas cycle model with a constant decay rate for CH_4 and NO_2 to estimate their atmospheric concentrations based on their emissions path, and an updated exogenous radiative forcing projection that includes the additional radiative forcing associated with additional perturbations of non-CO_2 gas emissions. These updates allow the authors to estimate climate damages in the perturbated scenario that are then compared to baseline damages to determine the social cost of the non-CO_2 gas studied.

Waldhoff et al. [27] use the 3.9 version of Climate Framework for Uncertainty, Negotiation and Distribution (FUND) to calculate the ratio of marginal impacts of non-CO_2 GHGs to CO_2 to compare the value of GHGs in terms of their climate impacts, as an alternative to the classic approach of physical comparison through GWPs. This model includes exogenous assumption about emissions of CO_2, CH_4, NO_2, SF_6, and aerosols. The change in atmospheric concentration of CO_2 is represented by a linear impulse response function and feedback effects from climate is modelled as in Tol [28]. The radiative forcing of the gases studied is incorporated as done in the Forth Assessment Report of the IPCC. The social cost of GHGs is estimated by aggregating all regional SC estimates weighted by the ratio of average per capita consumption in the reference region to regional average per capita consumption raised to the power of equality aversion.

Sarofim et al. [29] calculate the monetized benefits of mitigating a ton of methane emissions in a given year that translates into the avoidance of respiratory mortality caused by ozone-related health impacts. The approach taken is consistent with the methodology used by the US Government for calculating the social cost of carbon. They assume a log-linear relationship between relative risk and ozone concentration, which is calculated by using a mean response of 13 ppt O_3 and considering that at steady state 1 Tg per year of methane is equivalent to 12 Tg of atmospheric methane loading. Ozone mortality impacts are calculated for daily exposure (short-term) and repeated exposure over a warm season (long-term), which correspond to the two values included in the table below.

Shindell [30] uses DICE 2007 to calculate the social cost of atmospheric release (SCAR), a multi-impact evaluation framework to extend the social cost of carbon for CO_2 to a wider range of pollutants, so that the economic damages associated with a marginal change in emissions of a pollutant are evaluated. In this study, the effects of both climate and air quality are accounted. Climate damages are assumed to be proportional to global mean surface temperature change and RF for most pollutants is based on the Fifth Assessment Report of the IPCC. Temperature responses to forcings are calculated with the time dependence impulse-response function from Boucher et al. (2009) [31].

Shindell et al. [32] extend the work presented in Shindell [30] by incorporating a more sophisticated climate response function and a carbon-cycle response to temperature, the impact of climate change to human health via air quality, pollutant-specific crop responses, the impact of ozone generated by methane on carbon uptake, and forestry and non-mortality impacts.

Environment and Climate Change Canada [33] adopted the US Environmental Protection Agency values of social cost of methane presented in 2015, only considering a discount rate of 3% as their central scenario and also considering 95th percentile to represent the lower probability, high-cost climate change impacts scenario.

Under the Biden Administration, the Interagency Working Group on Social Cost of Greenhouse Gases released a review of the social cost of carbon, methane and nitrous oxide [34] in February 2021 and presented interim estimations of these gases. These estimates rely on the previous work developed under the Obama Administration, in which three IAMs (DICE, FUND and PAGE) were employed to calculate four sets of social cost estimates to capture the uncertainty regarding the discount rate. The discount rates considered are 5%, 3%, 2.5%, and 3% 95th percentile, and average between the three models are provided.

Errickson at al. [35] use an ensemble of IAMs (MAGICC, Hector, FAIN, AND FUND) to provide improved social cost of methane estimates that account for the 25% upward revision of radiative forcing of this gas and previously neglected climate uncertainties. To do so, the original methane cycle component of each IAM is paired with the Simple Nonlinear Earth System model, and then coupled with the non-climate components of DICE and FUND.

Table 1 below gathers all social cost of methane estimates that are presented in the studies review, indicating the discount rate and Ramsey parameters used (if applicable), and the emissions year considered for the social cost estimate.

Table 1. Previous Social Cost of Methane direct estimates

Study	Discount rate	η	ρ	Emissions Year	Social Cost of Methane (2015USD/tCH4)
Marten & Newbold [10]	5%	0	0.05	2020	638
				2050	1,740
	3%	0	0.03	2020	1,276
				2050	3,364
	2.5%	0	0.025	2020	1,740
				2050	4,060
	4%	1.5	0.01	2020	766
				2050	2,320
Marten et al. [26]	5%	-	-	2020	638
				2050	1,624
	3%	-	-	2020	1,392
				2050	2,900
	2.5%	-	-	2020	1,856
				2050	3,596
Waldhoff et al. [27]	1%	0	0.01	2010	491
Sarofim et al. [29]	3%	-	-	2020	845[4]
				2020	1,899[5]
Shindell [30]	5%	-	-	2010	3,132
	3%	-	-	2010	5,336
	1.4%	-	-	2010	6,960
Shindell et al. [32]	10%	-	-	2010	1,618
	5%	-	-	2010	2,807

[4] It is related with their base estimate of the global avoided premature cardiovascular and pulmonary deaths to short-term peak ozone exposure.

[5] It is related with avoided premature global respiratory deaths among the population older than 30 due to long-term peak ozone exposure.

	4%	-	-	2010	3,329
	3%	-	-	2010	4,170
	2.5%	-	-	2010	4,831
	1.4%	-	-	2010	7,598
Canadian Govt. [33]	3%	-	-	2020	986
				2050	2,036
Biden Admin. [34]	5%	-	-	2020	615
				2050	1,560
	3%	-	-	2020	1,376
				2050	2,844
	2.5%	-	-	2020	1,835
				2050	3,486
Errickson at al. [35]	3%	-	-	2020	1,082

3.3. Application of the Social Cost of GHGs in policy making

The social cost of GHGs is a powerful metric that helps administrations to evaluate almost all energy regulations and environmental rules and actions. It can be used in rulemaking that addresses greenhouse gas emissions, electricity ratemaking and regulation, natural resource valuation and royalty setting, regulatory cost-benefit analysis for climate actions, environmental impact statements, and setting greenhouse gas emissions caps and taxes [22]. Perhaps the last two policy instruments cited, emissions caps and taxes, are the most extended policy mechanisms used by governmental institutions to internalize externalities.

In 2020, there were 61 carbon pricing initiatives implemented or scheduled worldwide, 31 ETS and 30 carbon taxes, covering 22% of global GHG emissions. The geographical distribution of these can be seen in Figure 4.

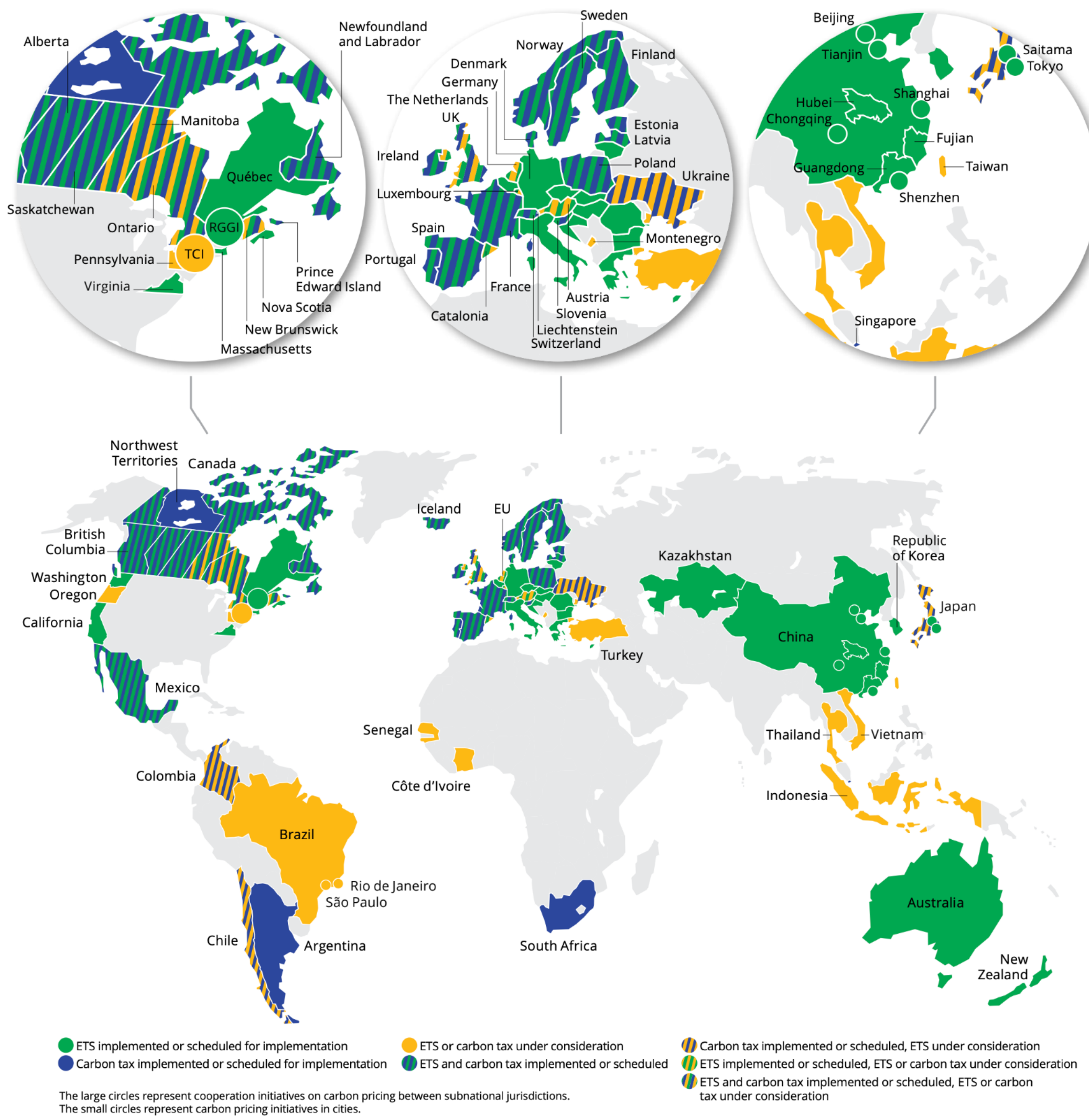

Figure 4: ETS and Carbon tax implemented, schedule for implementation and under consideration [36].

The growing number of carbon pricing initiatives and the geographical distribution of theses is a positive sign which indicates that a global effort is being made to fight climate change. For instance, Mexico launched in 2020 its pilot ETS, which supposes the first ETS in Latin America and other jurisdictions, such as the EU, New Zealand, and Canada are extending their carbon pricing initiatives. Although carbon prices increased in many of these jurisdictions, most carbon prices are still very low, with almost half of the covered emissions priced at less than USD10/tCO_2-eq, a value that is very far from the most recent social cost estimates, as it will be shown in this study.

3.3.1. The use of social cost of GHG in the US

Federal agencies of the United States began including SCC estimates in their regulatory impact analyses in 2008, but it was not until 2010 when the Interagency Working Group was created to develop interim social cost of carbon estimates for use in regulatory analyses. These estimates were periodically updated and, in 2016, interim direct estimates of the social cost of methane and nitrous oxide were also incorporated. The most recent updated values of these estimates have been provided under the Biden Administration in the Technical Support Document published in February 2021 [34]. These estimates are the same as the ones presented in 2016 but adjusted for inflation, so they do not incorporate the best available science. The IWG is commended to provide new estimates that incorporate the best available science in the matter by 2022.

There are several states, including – but not limited to – California, Colorado, Illinois, Minnesota, Maine, New York, and Washington that have started using federal social cost of carbon estimates since 2017 in their policy evaluation analyses. The SCC has been used in several renewable energy decision-making, evaluation of social benefits of zero-emission facilities, assessment of the value of avoided carbon emissions from substituting fossil fuel generation by nuclear generation, and cost-benefit analysis of energy efficiency improvements in general [22]. But, at least until 2017[6], the interim direct social cost of methane estimate has not been specifically used in policy making at state level, and it must be highlighted that these can be used in all the scenarios where social cost of carbon estimates are used.

[6] It has not been possible to find information regarding specific uses of social cost of GHG estimates in policy making at state-level from 2017 onwards.

4. Method & Data choices

This chapter introduces the updated DICE model presented in Hänsel et al. [4], describing the physical and economic principles contained in the climate and economic models. It then indicates what additional elements have been introduced in the model to make methane emissions endogenous and to be able to obtain a direct estimate of the social cost of methane. The modifications needed to transform the model from a policy optimization to a policy evaluation model are also explained. Finally, the data choices for the Base case are presented.

4.1. DICE in a policy optimization mode

The policy optimization model is the preset mode for which DICE has been developed. It links climate and economic models through the damage function that translates temperature increase to economic damages as a fraction of the GPD. In this mode, the model maximizes the welfare function, so costs of damages and abatements are minimized, resulting in an optimal temperature increase. As a result, social cost estimates of carbon dioxide and methane are calculated.

4.1.1. Updated DICE model

The Dynamic-Integrated model of Climate and the Economy is an IAM that represents the economics, policy, and scientific aspects of climate change. It establishes an intemporal general-equilibrium model of economic growth and climate change through a damage function that translates temperature increase into monetary damages. In its approach, economies are lessened today by the cost of reducing emissions but increase consumption possibilities in the future by preventing economically harmful climate events in the next decades [37].

4.1.1.1. Objective function

The social welfare function, W, is defined as the discounted sum of the population-weighted utility per capita consumption

$$W = \sum_{t=1}^{T_{max}} U[c(t), L(t)]R(t) \tag{2}$$

where $c(t)$ is per capita consumption, $L(t)$ is population, and $R(t)$is the utility discount factor.

In this model, the utility of consumption is represented by a constant elasticity function

$$U[c(t), L(t)] = L(t)\left[\frac{c(t)^{1-\eta}}{1-\eta}\right] \tag{3}$$

that assumes a constant elasticity of marginal utility, η, which represents generational inequality aversion. The utility of consumption of future generations is discounted according to

$$R(t) = (1+\rho)^{-t} \tag{4}$$

where ρ is the pure rate of time preference that represents how impatient society is or should be when waiting for future well-being.

The elasticity of marginal utility and the pure rate of time preference are two parameters subject to an intense debate in the scientific literature because of their large impact on the model results and the underlying ethical considerations they represent. Nordhaus considers the elasticity of marginal utility to be 1.45 and the pure rate of time preference 1.5%, while Hänsel et al. [4] adopt the values that correspond to the median expert recommendation described in Drupp et al. [8], 1 and 0.5%, respectively. The latter are the ones kept for the Base case.

4.1.1.2. Economic model

Due to the long-term effect of climate change, the time frame required for its modelling is significantly long compared to other macroeconomic models. This implies that many of the assumptions and projections made in the model are very uncertain.

The global production function is assumed to be a Cobb-Douglas production function in capital, labour, and Hicks-neutral technological change. Gross global output is expressed as

$$Y_{gross}(t) = A(t)K(t)^{\gamma}L(t)^{\gamma-1} \tag{5}$$

where $A(t)$ is the total factor of productivity, $K(t)$ is capital stock and services, $L(t)$ is the labour input (or population acting as labour), and γ is the capital elasticity in the production function, which is considered to be 0.3. The net global output is then

$$Y(t) = Y_{gross}(t)[1 - D(t) - \Lambda_{CO2}(t)] \tag{6}$$

where $\mathrm{D}(t)$ represents the damages as a share of gross global output and $\Lambda_{CO2}(t)$ is the abatement cost function.

Climate damages, $\mathrm{D}(t)$, are represented by the quadratic function

$$D(t) = \varphi_1 T_{AT}(t) + \varphi_2 T_{AT}(t)^2 \tag{7}$$

that translates a temperature change into an economic damage expressed as a fraction of the GDP, where T_{AT} is the increase in atmospheric temperature and φ_1 and φ_2 are the coefficients of the damage function. Nordhaus considers T_{AT} to be the increase in atmospheric temperature since pre-industrial level, while Hänsel et al. [4] chooses 1900 as the reference year. φ_1 is considered to be zero by Nordhaus and Hänsel et al. [4], but Nordhaus' latest value for the coefficient of the quadratic term, φ_2, is 0.00236 [3] while Hänsel et al. [4] choose the value obtained from the meta-analysis of climate damage estimates presented in Howard and Sterner [7], 0.007438. Climate damages are intended to capture all market and non-market impacts on the economy.

The abatement cost function, $\Lambda_{CO2}(t)$, is defined as

$$\Lambda_{CO2}(t) = \theta_1(t)\mu_{CO2}(t)^{\theta_2} \tag{8}$$

where $\mu_{CO2}(t)$ is the emissions reduction rate, and assumes that abatement costs are proportional to output and to a power function of the reduction rate. The exponent of the abatement cost function, θ_2, is 2.6, and $\theta_1(t)$ is the adjusted cost for backstop, expressed as

$$\theta_1(t) \ = pbt(t)\frac{\sigma(t)}{1000\theta_2} \tag{9}$$

where $pbt(t)$ is the payback time and $\sigma(t)$ is the level of carbon intensity.

Consumption is defined as

$$C(t) = Y_{net}(t) - I(t) \tag{10}$$

where $I(t)$ refers to gross investments, per capita consumption is defined as

$$c(t) = \frac{C(t)}{L(t)} \tag{11}$$

and capital stock dynamics

$$K(t) = I(t) - \delta_k K(t-1) \tag{12}$$

undergoes a depreciation (δ_k) rate of 0.1 per year.

4.1.1.3. Climate model

The climate model is formed by variables and equations that express the physical dynamics of greenhouse gases and how they contribute to the increase in the global mean surface temperature.

Total CO_2 emissions is defined as the sum of anthropogenic fossil CO_2 and emissions from land-use

$$E_{CO2} = E_{IND_{CO2}} + E_{LAND_{CO2}}(t) \tag{13}$$

where $E_{IND_{CO2}}$ is expressed as output times the level of carbon intensity $\sigma(t)$, and land-use is considered exogenous and is based on projections developed in Stocker et al. (2013) [19].

$$E_{IND_{CO2}} = \sigma(t)[1 - \mu_{CO2}(t)]Y(t) \tag{14}$$

These emissions are reduced by one minus the emissions control rate, $\mu_{CO2}(t)$, which is the control variable of the model.

Cumulative CO_2 emissions from land and cumulative CO_2 anthropogenic emissions are expressed as

$$CCum_{LAND_{CO2}}(t+1) = CCum_{LAND_{CO2}}(t) + E_{LAND_{CO2}}(t) \tag{15}$$

$$CCum_{IND_{CO2}}(t+1) = CCum_{IND_{CO2}}(t) + E_{IND_{CO2}}(t) \tag{16}$$

and total cumulative CO_2 emissions are simply the algebraic sum of both variables:

$$CCum_{CO2}(t) = CCum_{LAND_{CO2}}(t) + CCum_{IND_{CO2}}(t) \tag{17}$$

The carbon cycle model, taken from the climate model FAIR [5], is a four-box model that partitions anthropogenic CO_2 emissions in four different time scales (τ_i) of carbon uptake by the oceans and the biosphere. These four time constants (τ_i) are scaled by a factor $\alpha(t)$ that is estimated to equality between the 100-year integrated impulse response function *iIRF100* and an expression based on cumulative CO_2 taken up by the ocean and biosphere and global mean surface temperature change expressed as

$$iIRF_{100} = \sum_{i=0}^{3} \alpha(t) a_i \tau_i \left[1 - exp\left(\frac{-100}{\alpha(t)\tau_i}\right)\right] = r_0 + r_c CCum_{CO2}(t) + r_T T_{AT} \tag{18}$$

where a_i is the fraction of anthropogenic CO_2 emissions that correspond to each differing timescale of carbon uptake τ_i, r_0=35, r_c=0.0019, and r_T=4.185. The function of the expression is to calibrate $\alpha(t)$ so that the impulse response function in FAIR numerically emulates the impulse response functions estimated by more complex integrated climate and carbon cycle models where non-linearities in the carbon cycle and the climate carbon cycle feedbacks are explicitly modelled.

An increase of radiative forcing caused by an increase of GHG concentrations in the atmosphere leads to a warming of the atmosphere. This radiative forcing is expressed as

$$F(t) = f_{CO2_{2x}} \left[log_2\left(\frac{M_{AT}(t)}{M_{AT}(1750)}\right)\right] + F_{EX}(t) \tag{19}$$

where $f_{CO2_{2x}}$ is the constant for equilibrium increase of forcing at doubling of CO_2 and is equal to 3.6813, and $F_{EX}(t)$ is the exogenous forcing (non-CO_2 forcing).

The findings of Geoffroy et al. [6] are used to calibrate the energy-balance model (EBM) of DICE. It is a two-layer EBM in which the first layer corresponds to the atmosphere, the land surface, and the upper ocean, and the second corresponds to the deep ocean. The model is described as follows:

$$c_1 \frac{\partial \Delta T_1}{\partial t} = F(t) - \frac{\Delta T_1}{\lambda} - k(\Delta T_1 - \Delta T_2) \tag{20}$$

$$c_2 \frac{\partial \Delta T_2}{\partial t} = k(\Delta T_1 - \Delta T_2) \tag{21}$$

The reference year used for the radiative forcing, $F(t)$, is 1765 (year 0 in the model). ΔT_1 is the change in the mix layer temperature with respect to the temperature level in 1765 and ΔT_2 is the change in the deep ocean temperature with respect to the same year[7]. c_1 and c_2 are the heat capacities [$W \cdot yr \cdot K^{-1} \cdot m^{-2}$] for the mix layer and the deep ocean, respectively[8]. k is the exchange coefficient between the mixed layer and the deep ocean [$W \cdot K^{-1} \cdot m^{-2}$], and λ is the climate sensitivity parameter [$K \cdot W^{-1} \cdot m^{2}$]. The global average surface temperature is assumed to be the same as the mixed layer temperature.

4.1.1.4. Constraints

The concentration of carbon in the atmosphere is limited by maximum cumulative extraction of fossil fuels, which is considered to be equal to 6,000 GtC. Increase in emission reduction of CO_2 until 2045 is constraint to no more than 2 $GtCO_2$ per year, and from 2050 on the growth rate of emissions reduction is constraint to 10% of the previous 5 years (the time step used in the model). From 2050 onwards, negative CO_2 emissions are allowed, but emissions reduction is constraint to 120%.

4.1.2. Additional variables and equations introduced to updated DICE

This section contains the new variables and equations introduced to the DICE model and the new set of constraints so that methane is made endogenous to the model.

4.1.2.1. New variables and equations in the climate model

Methane emissions are expressed as

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[7] Temperatures in the mixed layer and deep ocean are assumed to be in equilibrium in 1765.

[8] 1 W·yr = 365.25·24·60·60 W·s, where 1 W·s = 1 J. The heat capacities are given per m^2 of the earth's surface.

$$E_{CH4}(t) = E_{NAT_{CH4}}(t) + E_{ANTRO_{CH4}}(t)\left[1 - \frac{\mu_{CH4}(t)}{100}\right] \tag{22}$$

where $E_{NAT_{CH4}}(t)$ are methane emission from natural sources, $E_{ANTRO_{CH4}}(t)$ are anthropogenic baseline methane emissions and $\mu_{CH4}(t)$ is the abatement level as share of total anthropogenic baseline emissions (in percent) and is a control variable of the model.

Natural wetland emissions, which are predominantly the main sources of natural methane emissions, have a strong linear relationship with increasing global mean surface temperature. They are expressed as

$$E_{NAT_{CH4}}(t) = m_N T_{AT} + b_N \tag{23}$$

where m_N is the slope and b_N the intercept of the linear function.

Methane concentration in the atmosphere (in ppb) is calculated as

$$\begin{aligned} CON_{CH4}(t+1) = \frac{E_{CH4}(t)}{2.746}\Bigg[1 &+ \left(1 - \frac{1}{LFT_{CH4_{st}}} - \frac{1}{LFT_{CH4_{so}}} - \frac{1}{LFT_{OH}(t)}\right) + \\ &\left(1 - \frac{1}{LFT_{CH4_{st}}} - \frac{1}{LFT_{CH4_{so}}} - \frac{1}{LFT_{OH}(t)}\right)^2 + \\ &\left(1 - \frac{1}{LFT_{CH4_{st}}} - \frac{1}{LFT_{CH4_{so}}} - \frac{1}{LFT_{OH}(t)}\right)^3 + \\ &\left(1 - \frac{1}{LFT_{CH4_{st}}} - \frac{1}{LFT_{CH4_{so}}} - \frac{1}{LFT_{OH}(t)}\right)^4\Bigg] + \\ &CON_{CH4}(t)\left[1 - \frac{1}{LFT_{CH4_{st}}} - \frac{1}{LFT_{CH4_{so}}} - \frac{1}{LFT_{OH}(t)}\right]^5 \end{aligned} \tag{24}$$

where $LFT_{CH4_{st}}$, $LFT_{CH4_{so}}$, and $LFT_{OH}(t)$ correspond to the lifetimes of the three main methane sinks: stratosphere, soils, and atmospheric OH. Atmospheric OH lifetime is expressed as

$$LFT_{OH}(t) = \left[\frac{CON_{CH4}(t)}{1700}\right]^{0.28} \times 10.5 \tag{25}$$

to capture the feedback effect that the methane concentration has on its own atmospheric lifetime [38].

The Effective Radiative Forcing equation is updated to account for the endogeneity of methane. The new EFR equation is then

$$F(t) = f_{CO2_{2x}}\left[log_2\left(\frac{M_{AT}(t)}{M_{AT}(1750)}\right)\right] + F_{CH4}(t) + F_{H20}(t) + F_{O3}(t) + F_{EX}(t) \tag{26}$$

The first term of the expression refers to the ERF of CO_2, which remains unchanged with respect to the expression in DICE. The EFR of methane is defined as

$$\begin{aligned} F_{CH4}(t) = \Big[&0.043 + (-6.5 \times 10^{-7})\left(CON_{CH4}(t) + CON_{CH4_{pi}}\right) - (4.1 \times 10^{-6}) \\ &\left(CON_{NO2_i} + CON_{NO2_{pi}}\right)\Big] \times \left[\sqrt{CON_{CH4}(t)} - \sqrt{CON_{CH4_{pi}}}\right] \end{aligned} \tag{27}$$

where the subscript pi refers to pre-industrial levels and i to initial values.

$F_{H20}(t)$ refers to the ERF caused by stratospheric water vapor from methane oxidation, and it is considered to be 12% of the methane ERF. $F_{O3}(t)$ refers to stratospheric ozone ERF and it is defined as

$$F_{O3}(t) = 1.78 \times 10^{-4} \left(CON_{CH4}(t) - CON_{CH4_{pi}} \right) \tag{28}$$

Finally, the variable $F_{EX}(t)$, which refers to ERF of non-CO_2 GHGs is updated to exclude CH_4 from it, since it is no longer exogenous to the model, simply by subtracting the EFR of methane from the variable $F_{EX}(t)$ that the model used in Hänsel et al. [4] has.

4.1.2.2. New variables and equations in the economic model

The inclusion of methane emissions as endogenous to the model has an impact on how output is defined, since now it is possible to explicitly quantify the costs of methane abatement. Net output is then defined as

$$Y(t) = Y_{gross}(t)[1 - D(t) - \Lambda_{CO2}(t)] - \Lambda_{CH4}(t) \tag{29}$$

where $\Lambda_{CH4}(t)$ expresses methane abatement costs and is defined as

$$\Lambda_{CH4}(t) = E_{ANTRO_{CH4}}(t) \left[\left(\frac{a}{b} e^{b\mu_{CH4}(t)} - 1 \right) - a\mu_{CH4}(t) \right] \tag{30}$$

This expression is derived from the marginal abatement cost curve (MAC) presented in Johansson et al. [39].

4.1.2.3. New constraints

The growth rate of methane emissions reduction is constrained to 3% per year, considering an initial abatement level of 0% in 2015 and a maximum abatement of 100% (no negative methane emissions allowed).

4.2. DICE in a policy evaluation mode

A policy evaluation mode of DICE is used to compare the extra costs derived from the implementation of a policy through a cost-effectiveness analysis. In this case, the costs of limiting global warming to less than 2ºC since 1900 is examined, as well as a more stringent target of 1.8ºC to explore the costs of a well-below 2ºC target indicated in the Paris Agreement. The lowest temperature target, 1.8ºC, has been chosen because it is the lowest feasible. If a ceiling temperature of less than 1.8ºC is imposed, the model cannot find a solution given the constraints included.

Two changes have been implemented in the model to transform it into a cost-effectiveness analysis: the damages are set to zero, i.e., an increase in global mean surface temperature does not affect the annual production, and a maximum temperature increase is exogenously introduced based on the targets set in the Paris Agreement. The main outcomes of interest in this analysis are the shadow prices of carbon dioxide and methane, which are calculated in a similar way as social cost estimates.

4.3. Data choices and scenarios

Data choices presented in this section correspond to new variables and parameters introduced in the model developed in this study. Other data choices not included in this section remain unchanged from the updated DICE model presented in Hänsel et al. [4].

4.3.1. Data choices for the Base case

The Base case scenario contains the preferred set of data choices for this study. It is the scenario that has been subjected to sensitivity analyses of specific parameters.

Anthropogenic methane emissions correspond to the SSP2 baseline “middle of the road scenario” of the Shared Socioeconomic Pathways public database [24] and are assumed to remain constant after 2100. Natural methane emissions are considered to grow linearly with temperature increase. The slope of that function (m_N in eq. (23)) is 23.33 [40] the intercept of the linear function (b_N=221) is calibrated so that natural methane emissions in 2020 are 250 Mt.

The initial concentration of methane is calculated from a model built for the historic concentrations of methane based on estimates of historic emissions taken from RCP Database [25] (from 1765 to 1990 to 2015) and SSP Database [24] (from 1990) and is assumed to be 1,969 ppb. The initial concentration of NO_2 is directly taken from the SSP Database SSP2 pathway and is equal to 327. Pre-industrial concentrations of CH_4 and NO_2

are taken from RCP Database and are 722 and 273 ppb, respectively. Stratosphere and soils lifetimes used to calculate methane concentration are assumed to be 120 and 160 years, respectively, and are the values indicated in the FAIR model [38]. The ERF of non-CO_2 GHGs, $F_{EX}(t)$, is based on the REMIND model SSP2 scenario meeting a target of 2.6 W/m^2 to keep consistency with the results presented in Hänsel et al. [4].

The parameters a and b are taken from the marginal abatement cost curve presented in Johansson et al. [39] and are 5.48 \$/tCH_4 and 0.1 (unitless), respectively. The growth rate of emissions reduction is constrained to 3% per year to prevent unrealistic drastic increases in reductions which would not be technically possible to achieve. NETs applied to methane emissions are also not considered because no advances on this field are forecasted today.

4.3.2. Baseline scenario

The baseline scenario of the model is generated by assuming there are no damages caused by an increase in temperature and no temperature constraints. For this reason, emissions of carbon dioxide and methane are not abated and therefore no extra costs associated with such practices appear. This scenario basically represents a situation as if nothing was done to tackle climate change.

5. Results

This chapter presents the results of the Base case scenario obtained when DICE is run in a policy optimization mode (cost-benefit analysis) and the sensitivity analyses of critical parameters carried out the evaluate the consequences of the data choices made for the Base case. It also shows the results obtained when the model is transformed into a policy evaluation model to carry out a cost-effectiveness analysis comparing different target temperature increases.

5.1. DICE in a policy optimization mode

As it has been previously shown in Hänsel et al. [4], it can be economically optimal to limit temperature increase to well below 2ºC since 1900. More specifically, this optimal temperature should, according to the assumptions in this model, be 1.54ºC by the end of the century, following a parabolic path in which the maximum temperature, 1.79ºC, is reached in 2060. The optimal temperature obtained when methane is considered endogenous is almost exactly the same as the one obtained when methane is kept exogenous in the model as in Hänsel et al. [4]. This was expected since the exogenous ERF pathway in Hänsel et al. [4] accounted for methane abatement.

As observed in Figure 5, large efforts on GHG emissions reductions are needed to achieve this low level of optimal temperature increase. Carbon dioxide emissions start being reduced from 2020, becoming negative from 2065 onwards, which constitutes a tipping point in which more CO_2 is capture from the atmosphere than emitted. Methane emissions reduction increases at a rate of 3% per year, which is the constraint introduced in the model, until 2030. From 2035 onwards, the increase is emissions reduction is much lower due to increasing costs of abatement, reaching a reduction of methane emissions of 64% in 2100.

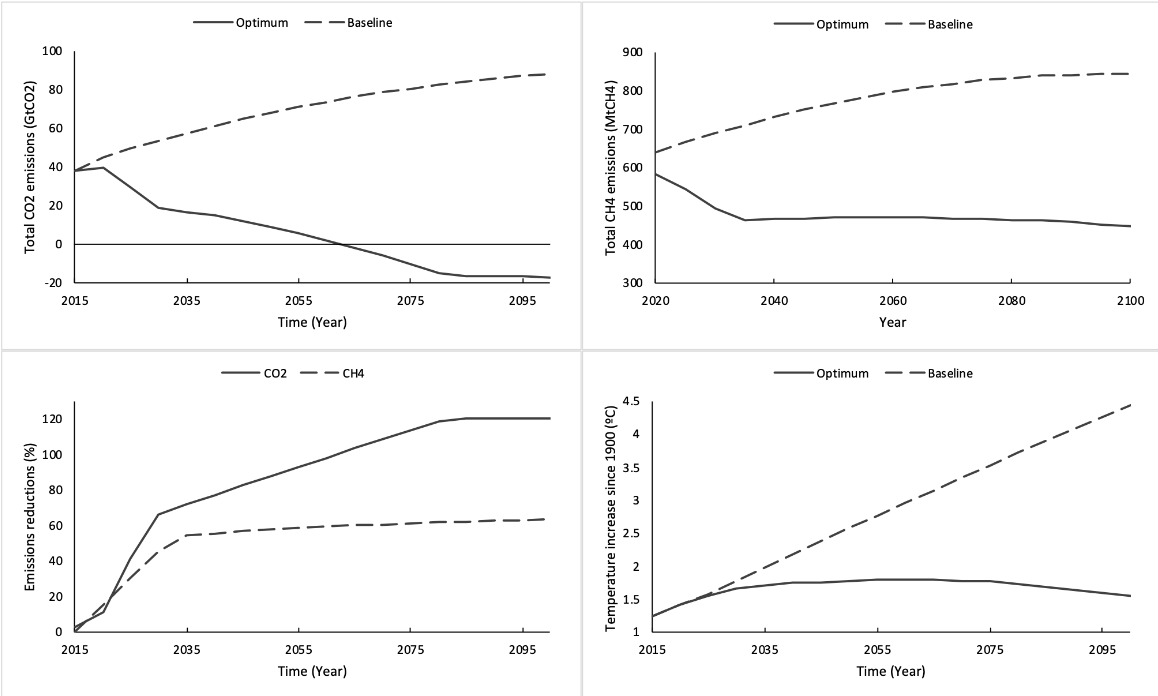


Figure 5: CBA – Optimum and Base line scenarios: Total CO_2 emissions, Total CH_4 emissions, Emissions reductions of CO_2 and CH_4, Temperature increase since 1900.

Social cost of methane is estimated to be 7,000 \$/tCH_4 in 2020 and 15,300 \$/tCH_4 in 2050. Figure 6 shows social cost of methane estimates presented in different studies conducted in the last decade. As it can be observed, the estimates presented in the base case of this study are significantly larger that estimates presented in previous ones, largely due to the revised damage function and the discount rate determinants chosen.

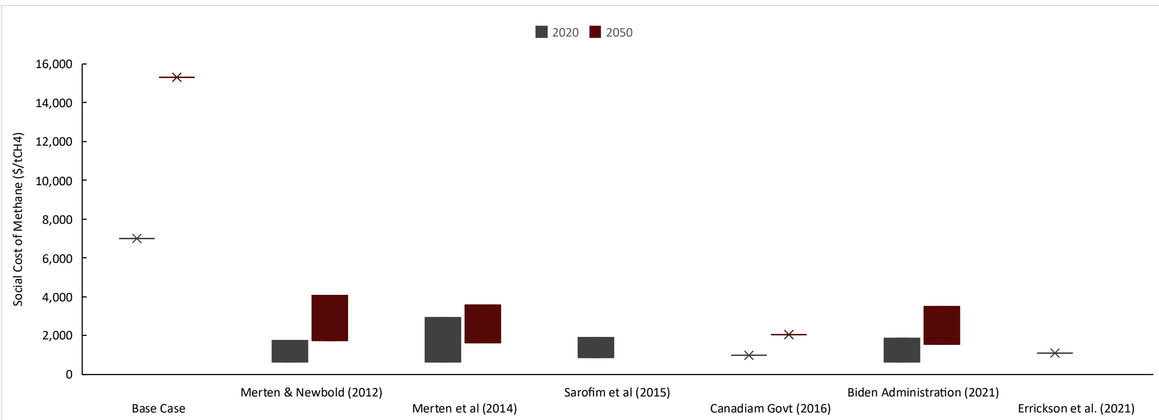


Figure 6: Social Cost of Methane estimates in 2020 and 2050: Base case, Merten and Newbold (2012) [10], Merten et al. (2014) [26], Sarofim et al. (2015) [29], Canadian Administration (2016) [33], Biden Administration [34], Errickson et al. [35].

Both social cost of carbon and social cost of methane grow almost linearly over time, as it can be seen in Figure 7. Social cost of carbon estimate is almost exactly the same as the one presented in Hänsel et al. [4], with a value of 215 $/tCO$_2$ in 2020 and reaching 373 $/tCO$_2$ in 2050.

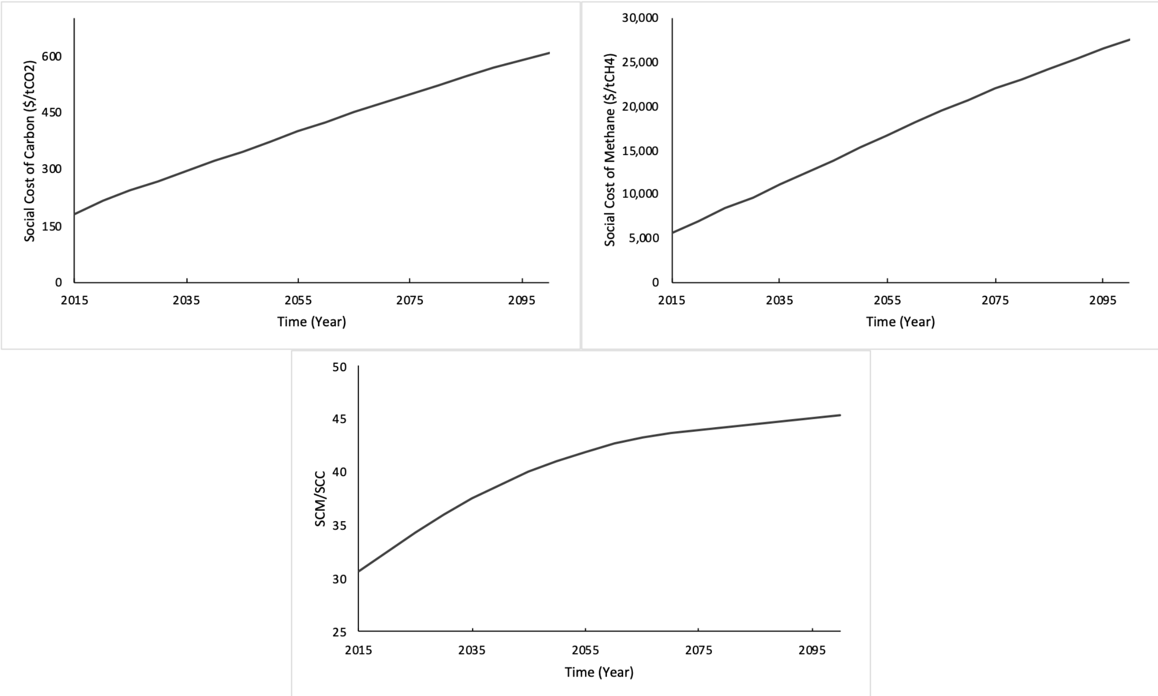


Figure 7: CBA – Base Case: Social Cost of Carbon, Social Cost of Methane, Ratio of SCM to SCC.

The ratio of these two estimates also grows with time, indicating a faster increase of the social cost of methane compared to that of carbon. This is explained by the optimal concentration trajectories of these two gases. As observed in Figure 8, methane concentration peaks in 2020 and soon drops significantly, which translates into a higher radiative forcing per additional ton emitted. Carbon dioxide concentration, conversely, does not peak until the middle of this century and both its increase and decease is much smoother than that of methane, so its radiative forcing does not change substantially per additional ton emitted.

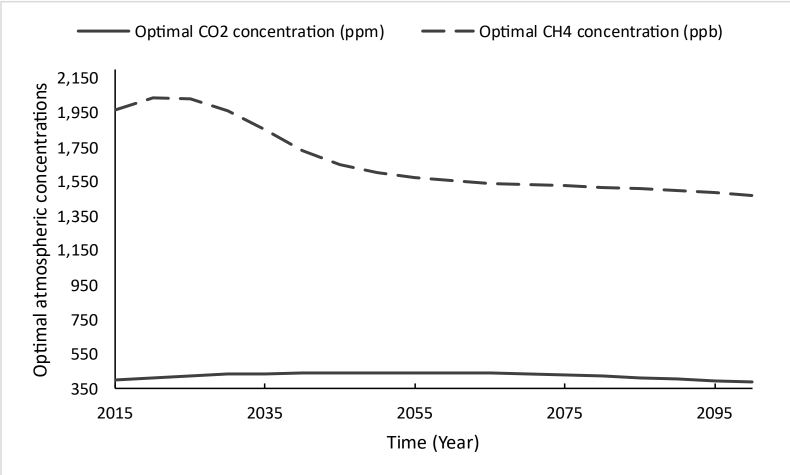


Figure 8: Optimal CO2 and CH4 concentration trajectories.

By 2050, SCM will be 41 times larger than SCC, and almost 49 by the end of this century, while only 32 times as large in 2020. This number can be compared to the GWP_{100} value, which is 34. Figure 9 shows the differences between the SCM directly estimated by making methane emissions endogenous (the Base case) and SCM when it is indirectly estimated by multiplying the SCC by a methane GWP_{100} of 34.

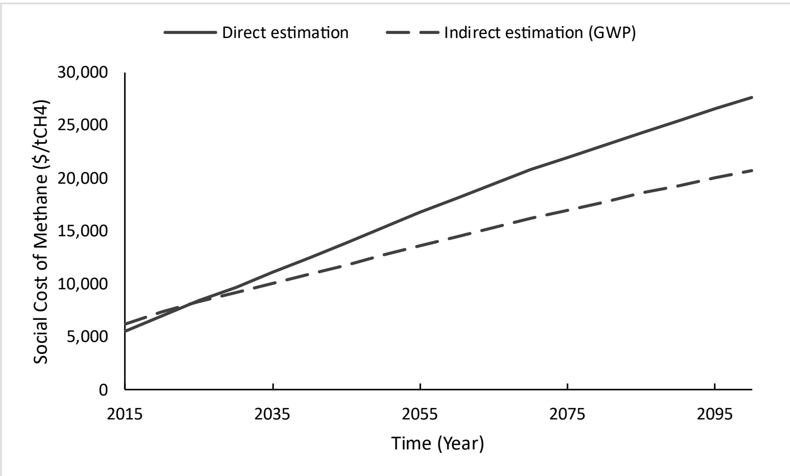


Figure 9: CBA – Comparison between direct estimation of the Social Cost of Methane (Base case) and indirect estimation through the GWP.

As it is observed, the social cost of methane is underestimated when this gas is not made endogenous to the model from 2025 onwards, which is consistent with the findings of Marten and Newbold [10].

As it has been commented before, social cost estimates are highly sensitive to the social discount rate, whose determinants are the elasticity of marginal utility and the pure rate of time preference. It is expressed as

$$SDR(t) = \rho + \eta \times g(t) \qquad (31)$$

where ρ is the pure rate of social time preference, η is the elasticity of marginal utility, and $g(t)$ is the growth rate in annual per capita consumption, introduced exogenously in the model.

There is a wide range of parameters chosen by renowned environmental economists, and there does not seem to be a clear consensus about the most appropriate pair of discount parameters, as shown in Drupp et al. [8]. Figure 10 shows the variation of social cost estimates, ratio of SCM to SCC, and the temperature increase obtained when Median expert (ρ=0.5%, η=1), Nordhaus (ρ=1.5%, η=1.45), Stern (ρ=0.1%, η=1), and Weitzman (ρ=2%, η=2) preferred pair of discount parameters are run in the model.

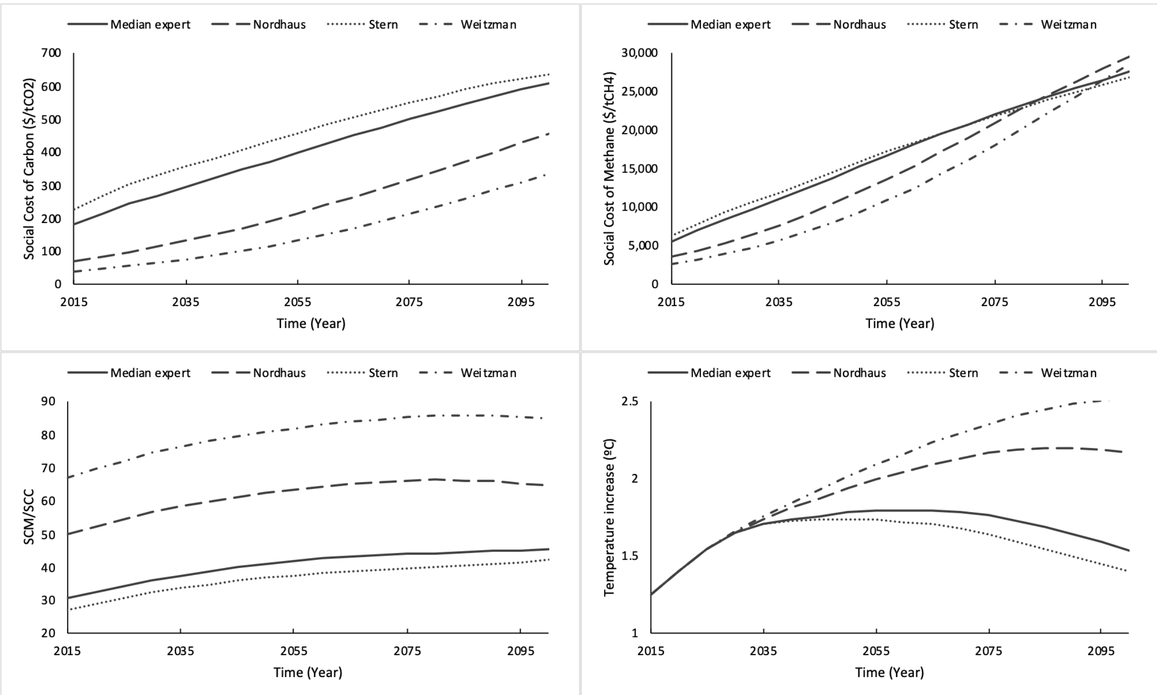


Figure 10: CBA – Comparison of chosen pair of social discount rate determinants: Social Cost of Carbon, Social Cost of Methane, Ratio of SCM to SCC, Temperature increase since 1900.

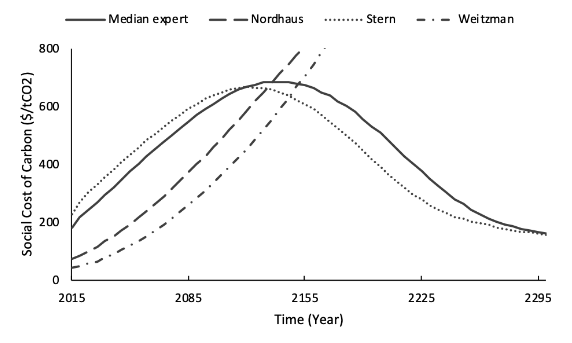
The social discount rate corresponding to the previously introduced preferred social discount rate determinants is estimated using the Ramsey rule (eq. 31), in which the growth rate in annual per capita consumption is assumed to be the average growth over the 2020-2100 period. The SCC, SCM and the ratio of SCM to SCC for 2020, 2050 and 2100 is presented in Table 2.

Table 2. Social Cost of Carbon, Social Cost of Methane, Ratio of SCM to SCC

Estimated SDR	Emissions Year	SCC ($/t$CO_2$)	SCM ($/t$CH_4$)	SCM/SCC
2% (Stern)	2020	269	7,810	29
	2050	429	15,900	37
	2100	637	26,800	42
3% (Base case)	2020	215	7,000	33
	2050	373	15,300	41
	2100	608	27,600	45
4% (Nordhaus)	2020	85	4,440	52
	2050	192	12,000	63
	2100	457	29,500	65
6% (Weitzman)	2020	47	3,290	70
	2050	117	9,420	81
	2100	336	28,500	85

Stern's pair of SDR parameters gives the highest SCC in the 21st century, being 269 $/t$CO_2$ in 2020 and 429 $/t$CO_2$ in 2050, values that are close to the Median expert pair of parameters (which are the ones used in the Base case). The lowest SCC is given by Weitzman's pair of parameters, with a value of 47 $/t$CO_2$ and 117 $/t$CO_2$ in 2020 and 2050, respectively, showing that there is an inverse relationship between SDR parameters and SCC in this century. This is not consistent for the time evolution of the SCM from 2080 and onwards, since higher values of ρ and η give a higher value of SCM after 2080. Thereby, Stern's pair of SDR parameters give the highest SCM in 2020 and 2050, 7,810 $/t$CH_4$ and 15,900 $/t$CH_4$, respectively, but the lowest in 2100, 26,800 $/t$CH_4$, and Weitzman's give the lowest in 2020 and 2050, 3,290 $/t$CH_4$ and 9,420 $/t$CH_4$, respectively, but the second highest in 2100, 28,500 $/t$CH_4$.

This disparity is related with the time frame shown for the analysis. When a longer time frame is shown (Figure 11), it is seen that the social cost estimates calculated with the lower pair of values (Median expert and Stern) follow a parabolic trajectory while the ones obtained with the higher pair of social discount rate determinants (Nordhaus and Weitzman) follow an exponential shape. The social cost estimates obtained with the lower pair of values will also end up reaching a peak, but this happens around 2250 for Nordhaus' and 2370 for Weitzman's, so the degree of uncertainty regarding these values is very high.



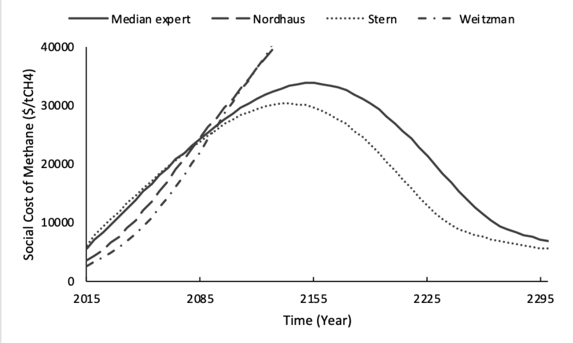


Figure 11: CBA – Comparison of chosen pair of social discount rate determinants for 2015-2300 period: Social Cost of Carbon and Social Cost of Methane.

Therefore, it is just a matter of time for lower values of SDR determinants to give lower estimates of the social cost of carbon and methane. This happens because there are two countervailing mechanisms associated with the social discount rate acting here, and they play out somewhat differently for methane and carbon dioxide.

With a higher discount rate, the SCC and SCM is reduced because the value of future damages matters less. This is the fundamental mechanism. However, in a dynamic model such as DICE, the discount rate will also imply different abatement levels, emissions, concentrations, and eventually temperatures. With a high discount rate, emissions will be abated less, and therefore the temperature will become higher in the future. Given that damages are proportional to the temperature squared, marginal damages are proportional to temperature, so higher temperatures in the future will imply higher social cost of carbon and methane. For this reason, if the discount rate is high, lower social cost of carbon and methane will initially be obtained because of how discount rate affects the NPV of future costs, but this will imply high temperatures and hence higher marginal damages from emissions in the future, which will translate into higher social cost of carbon and methane estimates (because of how the discount rate affects optimal abatement levels). Note that, if the damage function had been proportional to temperature instead of the temperature squared, marginal damages would not have been proportional to temperature, and then this shift would not have been observed.

As it is observed in Figure 10 and Figure 11, the SCM is less sensitive to variations in SDR parameters than the SCC. This is explained by the differences in their lifetimes: carbon dioxide emissions can stay in the atmosphere for hundreds of years, meaning that its emissions today have a long-term impact on the CO_2 concentration in the atmosphere and therefore in the forcing of the gas, while methane emissions stay in the atmosphere around 10 years, so its emissions today do not affect the atmospheric concentration of the gas (and its forcing) in the long term. This implies that the rate at which future values associated with CO_2 emissions (SCC) are discounted has a much larger impact on these than its impact on those associated with methane emissions (SCM).

With respect to the ratio of SCM to SCC, it ranges from 29 to 70 in 2020 and 37 to 81 in 2100, with lower ratios given by Stern's pair of parameters and higher ratios by Weitzman's, hence a higher discount rate tends to lead to a higher ratio in the near term. Stern's pair of parameters gives the lowest temperature increase in 2100, 1.4 ºC and, together with the Median expert temperature increase, it shows it could be optimal to have a global warming target of 1.5 ºC. Nordhaus' and Weitzman's pair of parameters give a temperature increase by the end of the century of 2.17 ºC and 2.52ºC, respectively, exposing that even if relatively high values of elasticity of marginal utility and pure rate of time preference were chosen, it could be optimal or very close to be so to avoid global warming go higher than 2 ºC increase since 1900 values. The reason why these results are obtained here while Nordhaus obtains an optimal temperature increase of 3.4ºC [3] is the fact that we have used an updated climate damage function.

To determine which SDR parameter affects the most each social cost estimate, an individual sensitivity analysis on each of them is carried out. First, the pure rate of time preference is fixed at ρ=0.5% (the Median expert recommendation and the value chosen for the base case) and the elasticity of marginal utility is increased and decreased by 50% from the value chosen for the base case, η=1, which corresponds to the Median expert recommendation (Figure 12). Second, the elasticity of marginal utility is fixed at η=1 and the pure rate of social time preference is increased and decreased by 50% from value ρ=1% (Figure 13).

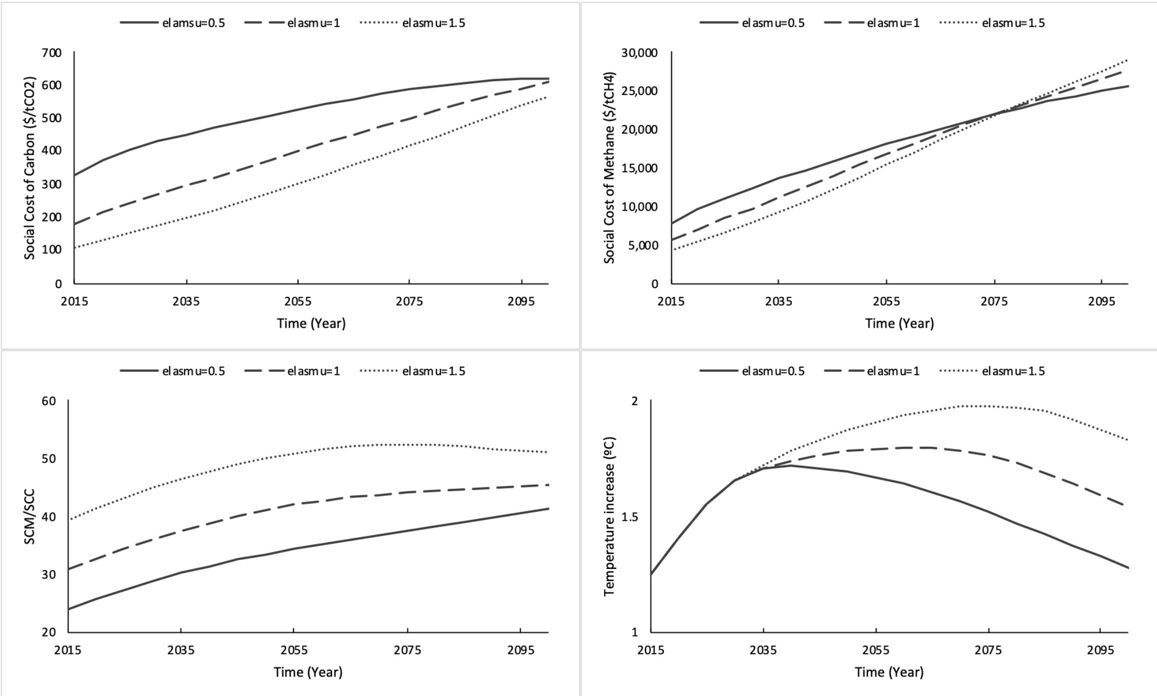


Figure 12: CBA – Sensitivity analysis of elasticity of marginal utility: Social Cost of Carbon, Social Cost of Methane, Ratio of SCM to SCC, Temperature increase since 1900.

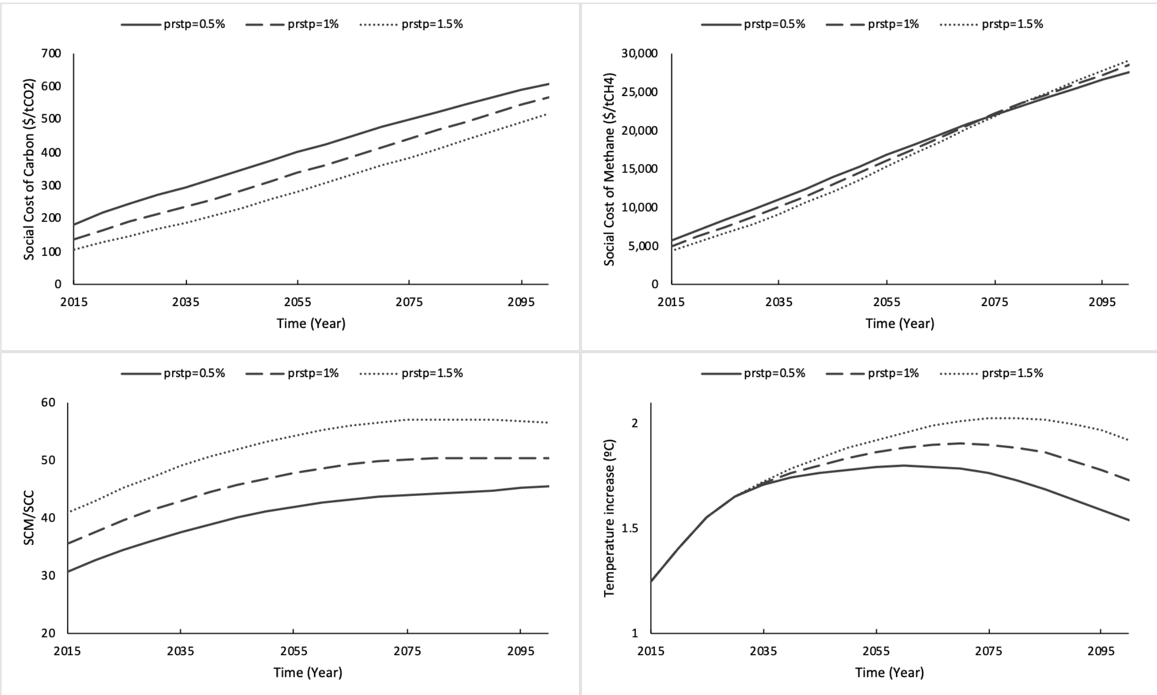


Figure 13: CBA – Sensitivity analysis of pure rate of social time preference: Social Cost of Carbon, Social Cost of Methane, Ratio of SCM to SCC, Temperature increase since 1900.

Figure 12 and Figure 13 show that, for an equivalent increase in the parameters studied, the social cost of carbon and social cost of methane are more sensitive to changes in the elasticity of marginal utility, but this can be more clearly appreciated in the SCC, since the

SCM is less sensitive to both parameters due to its short lifetime. The temperature increase is also more affected by changes in η than ρ.

Another critical part of the economic model in any IAM is the damage function. This function translates temperature increase into monetary costs and has a large impact on the outcome of the model, as it can be observed in Figure 14. Three damage functions are tested with the discount parameters set at the Base case values. The ones proposed in Nordhaus (2017) [3] and Howard and Sterner [7] have the quadratic form given in eq. (7), where Nordhaus assumes a value for the quadratic term φ_2 of 0.00236 and Howard & Sterner of 0.007438. Both studies consider φ_1 to be zero. Weitzman introduces in his equation an additional term to capture the dramatic consequences expected when the temperature increase exceeds 6ºC so that the equation has the following polynomial form instead

$$D(t) = \varphi_1 T_{AT}(t) + \varphi_2 T_{AT}(t)^2 + \varphi_3 T_{AT}(t)^{6.754} \quad (32)$$

where φ_1 is zero, φ_2 is 0.00236, and φ_3 is 5.07×10^{-6} [41].

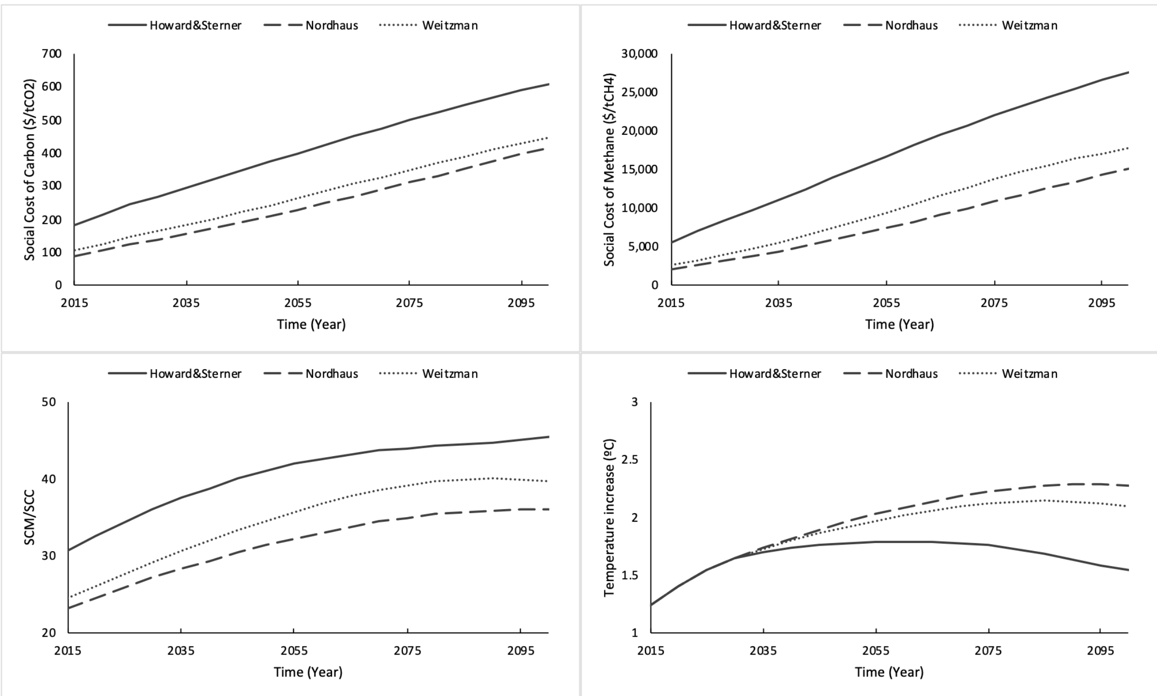


Figure 14: CBA – Sensitivity analysis of the Damage function: Social Cost of Carbon, Social Cost of Methane, Ratio of SCM to SCC, Temperature increase since 1900.

Howard & Sterner's damage equation, the one used in the Base case, gives a SCC estimate 1.7 and 2 times larger in 2020 and 1.5 and 1.8 in 2050 than those of Weitzman's and Nordhaus' damage equation, respectively. A similar relation can be appreciated in SCM estimates: Howard & Sterner's damage equation gives a value 2.1 and 2.7 times larger in 2020 and 1.8 and 2.3 in 2050 than the ones given by Weitzman's and Nordhaus' damage equation. Howard & Sterner's equation gives the highest ratio of SCM to SCC in both 2020 and 2050, and these range from 25 to 33 in 2020 and 32 to 41 in 2050, being Nordhaus' estimates the lowest.

The temperature increase follows a significantly different path in this century depending on the damage function included in the model. While the damage equation proposed by Howard & Sterner (Base case) gives a temperature increase profile that peaks in 2060 at 1.79ºC and starts a decreasing path, reaching a value of 1.54 in 2100, both Weitzman's and Nordhaus' damage functions provides temperature paths that peak at the end of the century, in 2085 and 2090, respectively. Figure 14 also shows that the additional term that Weitzman proposes to add to Nordhaus' damage function does not have a large impact on this model results compared to those provided by Nordhaus' function due to the temperature increase not even getting close this 6ºC temperature increase that is considered to be the tipping point for drastic consequences to occur. This happens because of the discount rate parameters we have chosen, but if Nordhaus' parameters had been used, Weitzman's extra term would have had a larger impact on the results obtained.

The pace at which methane is abated strongly depends on the marginal abatement cost curve of this gas. There is a consensus in academia about the non-linearity of the curve, but there are some variations with respect to the cost that a specific percent of abatement implies. For the Base case, the curve proposed in Johansson et al. [39] is used and a sensitivity analysis with four other MAC curves studied in Harmsen et al. [42] is carried out. All curves show that it is relatively cheap to abate at least until a 45%, where differences among curves arise, as observed in Figure 15. Methane abatement is linear for all curves, with a yearly emissions reduction increase of 3% (constraint to prevent unrealistic drastic reductions) until a point after which the abatement becomes significantly more expensive and it is no longer optimum to keep increasing the rate of abatement.

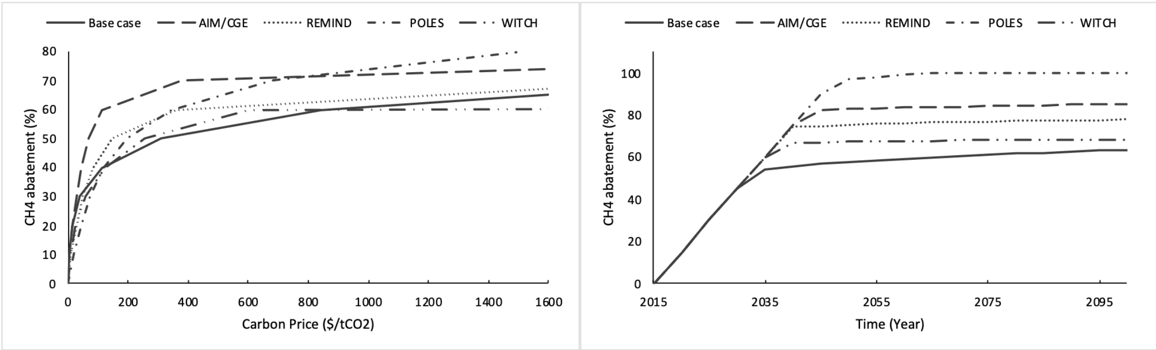


Figure 15: CBA – Impact of methane MACs: Marginal Abatement Cost curves of Methane, Emission reductions of Methane.

The marginal abatement cost curve used for the Base case is the one included in the MiMiC model presented in Johansson et al. [39] and gives the lowest abatement per carbon price[9], which translates into the lowest methane abatement in this century. With this curve, the tipping point at which the increasing pace of emissions reduction is no longer 3% per year happens after 2030 at an emissions reduction level of 45%. The model still projects a considerably large increase of emissions reduction of almost 10% the next five years (reaching 54% of emission reductions in 2035), and from 2035 and onwards the increasing pace is drastically reduced, only further increasing by 9% until the end of the century. On the other extreme of the picture, the MAC curve proposed in POLES model projects a 3% yearly increase emissions reduction until 2045, when methane emissions are reduced by 90% from baseline emissions (no abatement), and methane emissions are expected to disappear in 2070.

The highest SCC estimate is given by the MAC curve used in the Base case and the lowest is given by the curved used in POLES model, which establish a direct relationship between higher costs of methane abatement and higher SCC estimates. When the cost of abating methane emissions is lower, a higher percentage of emissions reduction is optimum so less emissions are released, reducing atmospheric methane concentration and therefore its forcing. This means that an additional unit of carbon dioxide emitted to the atmosphere will have a lower impact on the temperature increase due to climate carbon cycle feedbacks because the temperature is lower thanks to the reduction in methane emissions. Further, an additional effect is that the marginal damage of temperature is smaller if the temperature is

[9] Most marginal abatement cost curves of methane are given in 2015USD per ton of CO_2 for simplicity when comparing them with marginal abatement cost curves of carbon dioxide. In the model, the unit is converted to 2015USD per ton of CH_4.

smaller since the damage function is quadratic. The difference between these two extremes of the range examined is 28 $/$tCO_2$ in 2020 and 160 $/$tCO_2$, a 15% and 20% variation, respectively. The difference in SCM estimates provided by the tested MAC curves is almost negligible in 2020 and 2050.

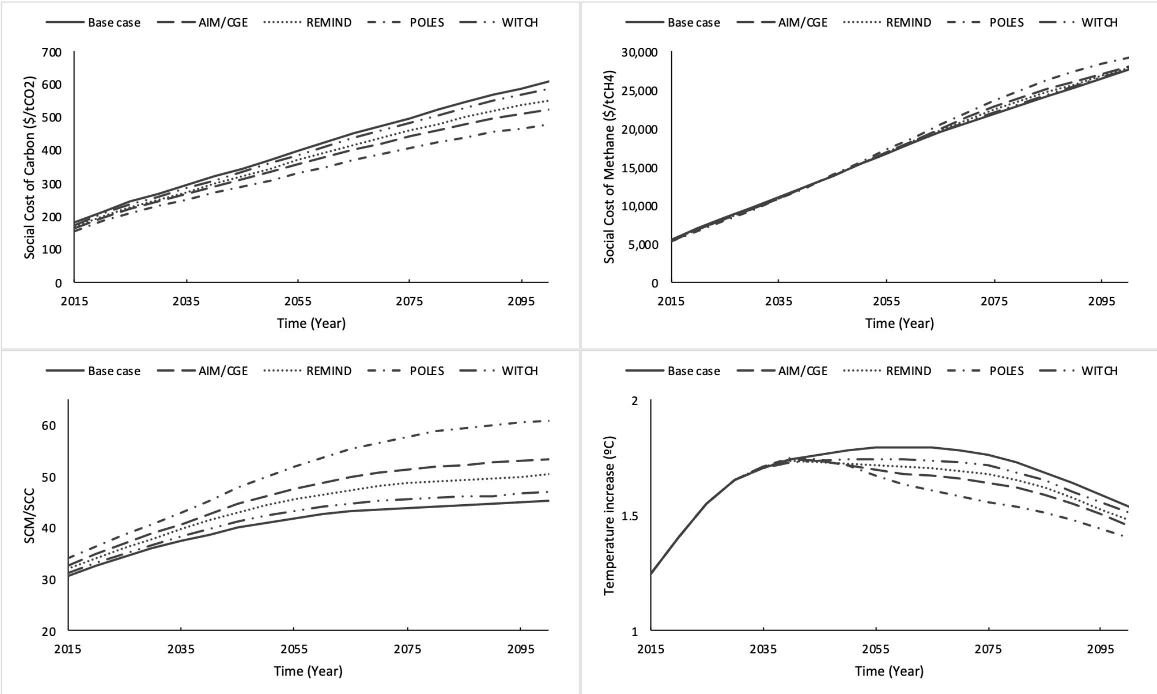


Figure 16: CBA – Sensitivity analysis of the Methane MAC curve: Social Cost of Carbon, Social Cost of Methane, Ratio of SCM to SCC, Temperature increase since 1900.

The ratio of SCM to SCC ranges from 33 to 36 in 2020 and 41 to 50 in 2050, which is in line with values obtained in previous sensitivity analysis. The temperature increase since 1900 is identical for all MAC curves studied from 2015 to 2045, point from when the divergence occurs, resulting the temperature increase given by POLES curve the lowest with a value of 1.4ºC by the end of this century. The highest temperature increase is given by Base case curve, 1.54ºC, which implies a 9% of variation in the range studied.

5.2. DICE in a policy evaluation mode

There is a political agreement expressed in the COP of Paris 2015 to limiting global warming to well below 2ºC by 2100, so an alternative approach to a cost-benefit analysis to find the optimal level of abatement of GHG emissions is a cost-effective analysis whose outcomes are the shadow prices of these gases when a specific ceiling temperature increase (the one that has a political consensus) is introduce in the model. The two target temperatures chosen are 2ºC and 1.8ºC. The former is chosen because it is the less ambitious target temperature of the range expressed in the Paris Agreement. The latter is chosen because it is the lowest feasible value that can be considered in the model before it cannot find a solution, but a 1.8ºC target temperature is comparable with the CBA because, at it has been shown before, in the CBA the optimal temperature trajectory peaks at 1.79ºC.

Figure 17 shows total CO_2 and CH_4 emissions and emissions reduction paths of these two gases from 2015 to 2100.

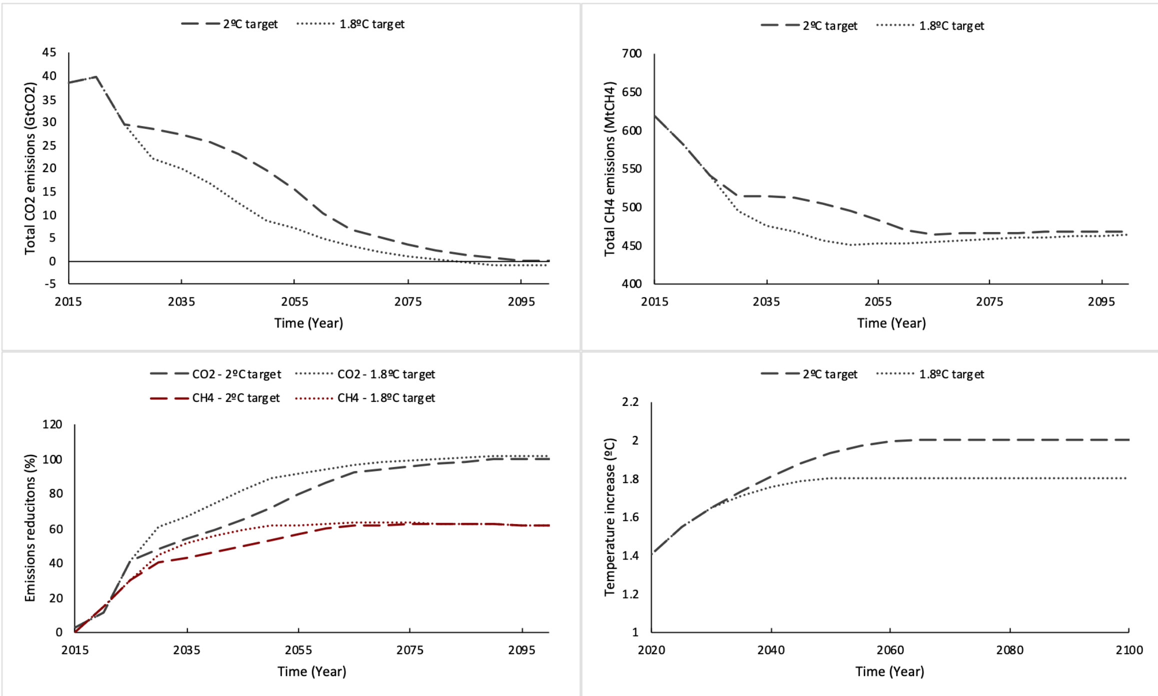


Figure 17: CEA – Total CO_2 emissions, Total CH_4 emissions, Emissions reductions of CO_2 and CH_4.

Both CO_2 and CH_4 emissions reductions in 2020 are the same no matter what the temperature target is. These are 11% and 15%, respectively. From 2025 onwards, the rate of abatement of CO_2 diverges depending on the target temperature, being in 2030 61% when the target temperature is 2ºC and 48% when this is 1.8ºC. For methane, this divergence appears in 2030, with a 40% of abatement with a target temperature of 2ºC and 48% for 1.8ºC. For both gases, the increase in emissions reduction is smoother when the target temperature is higher, but both targets require a similar level of abatement in 2100. CO_2 emissions reduction reaches 102% by the end of the century, meaning that more CO_2 is been captured than emitted, thanks to NETs. This same year, methane emissions are reduced a 62% after reaching its reduction peak in 2070 with more than 63%. The differences between the two target temperatures appear mainly between 2030 and 2060, when emissions reductions for the 2ºC scenario are significantly lower.

Shadow price of carbon estimates for both target temperatures scenarios reach their peak about when their target is met and then start slowly decreasing until the end of this century. For the lower target temperature, the peak happens earlier in the century, in 2065, at a price of 405 $/tCO_2$, while the higher temperature target scenario peaks at 381 $/tCO_2$ in 2080.

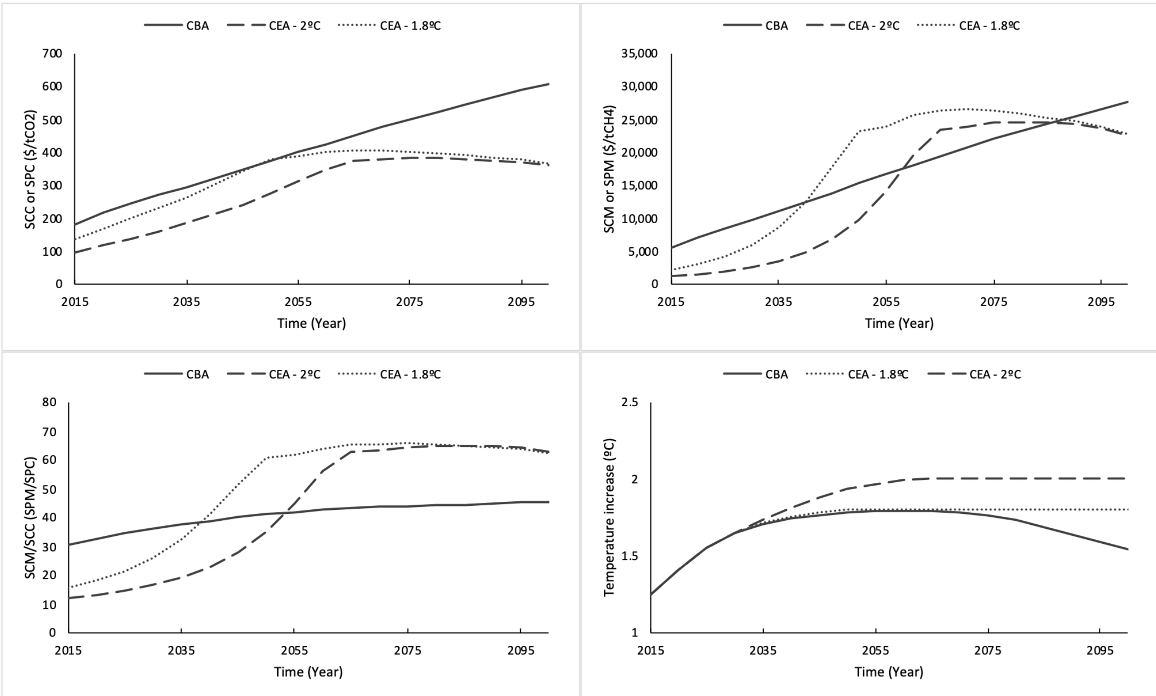


Figure 18: CEA & CBA – Comparison between CBA and CEA models: Social Cost of Carbon or Shadow Price of Carbon[10], Social Cost of Methane or Shadow Price of Methane, Ratio of SCM to SCC or Ratio of SPM to SPC, Temperature increase since 1900.

A similar situation is appreciated with the shadow price of methane. The 2ºC target SPM peaks in 2080 at 24,600 $/tCH_4$ and starts decreasing, while the 1.8ºC shadow price of methane reaches its peak 10 years earlier at 26,500 $/tCH_4$. The ratio of SPM to SPC grows exponentially in both scenarios until reaching the tipping point, the time when the target temperature is reached.

In 2020, the shadow price of carbon for the 2ºC target scenario is 116 $/tCO_2$ and 167 $/tCO_2$ for the more stringent one. These values are slightly larger in 2030, 160 $/tCO_2$ and 229

[10] Social Cost estimates correspond to cost-benefit analyses and Shadow Price estimates referrer to cost-effective analyses.

$/tCO$_2$, respectively. In 2050, the SPC for the 2ºC scenario is 273 $/tCO$_2$ and 380 $/tCO$_2$ for the 1.8ºC target, very close to its peak.

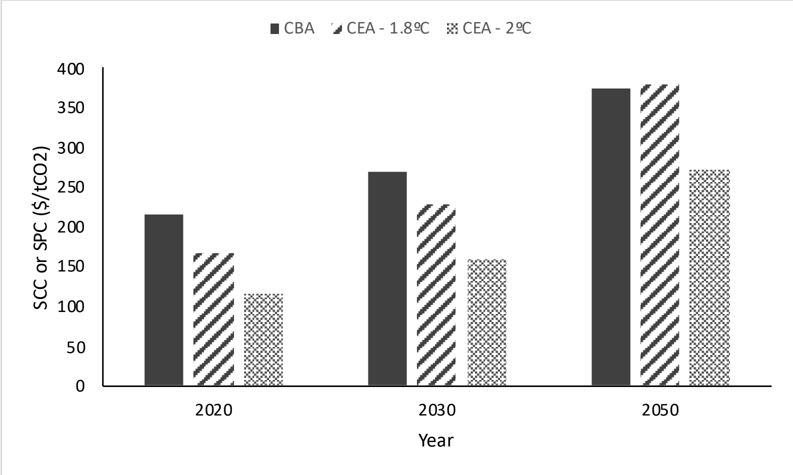


Figure 19: Social Cost of Carbon (Base case) vs Shadow Price of Carbon (1.8ºC and 2ºC target scenarios) in 2020, 2030, and 2050.

When these values are compared with the social cost of carbon estimated in the Base case (see Figure 20), it is observed that both are smaller in 2020 and 2030, while the SPC in 2050 for the 1.8ºC target scenario is slightly larger than the SCC. This coincides with the moment when the maximum temperature allowed is reached. The SPC obtained in the 2ºC scenario is always smaller than the SCC because the maximum temperature achieve in the model is higher.

The SPM in 2020 for the 2ºC and 1.8ºC target scenarios are 1,540 $/tCH$_4$ and 3,030 $/tCH$_4$, respectively, and 2,640 $/tCH$_4$ and 5,550 $/tCH$_4$ ten years after (in 2030). By mid-century, the SPM is 9,640 $/tCH$_4$ for the 2ºC scenario and 23,200 $/tCH$_4$ for the more stringent one.

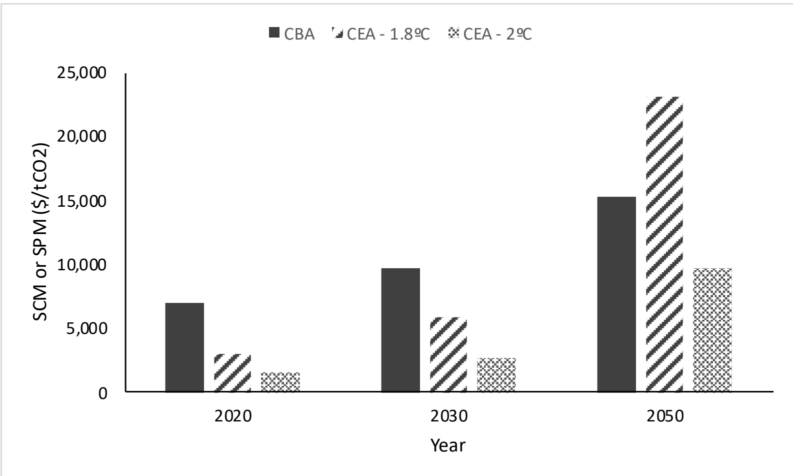


Figure 20: Social Cost of Methane (Base case) vs Shadow Price of Methane (1.8ºC and 2ºC target scenarios) in 2020, 2030, and 2050.

The difference between the social cost of methane and the shadow price of methane is larger than that of the social cost of carbon and shadow price of carbon because the increase of the shadow price of methane is exponential. This implies that, from 2015 to 2030-2035, the shadow price of methane increases very slowly, and after 2035 it experiences a sharp increase until the ceiling temperature is reached. However, the shadow price of carbon increases almost linearly until reaching the maximum temperature allowed.

The ratio of SPM to SPC in 2020 and 2030 is 13 and 17 for the 2ºC scenario and 18 and 26 for the 1.8ºC scenario. By the middle of the century, these ratios are 35 and 61, respectively.

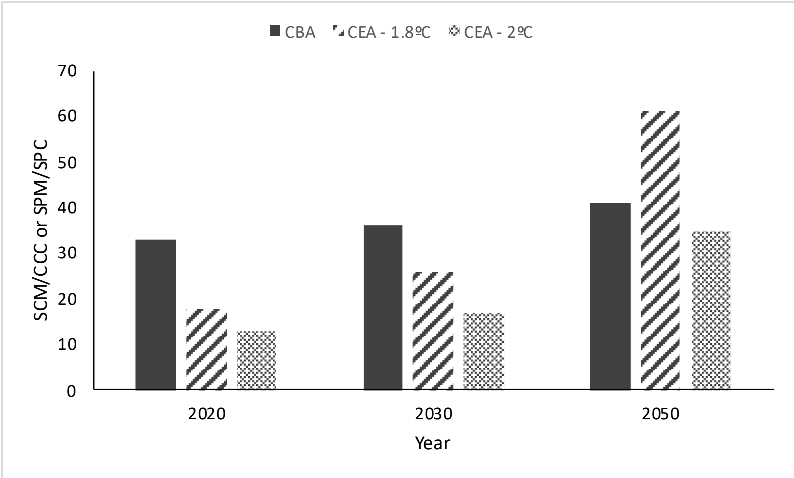


Figure 21: SCM/SCC (Base case) vs SPM/SPC (1.8ºC and 2ºC target scenarios) in 2020, 2030, and 2050.

These numbers reflect what have been previously explained: the shadow price of methane grows much slower than that of carbon in the first 15 to 20 years of the time period observed, which, together with the relatively low initial values of the shadow prices of methane, translates into lower ratios. In 2050, the shadow price of methane reaches its maximum value for the 1.8ºC scenario, which explains why the ratio of SPM to SPC is much larger than the ratio of SCM to SCC. The ratio of shadow prices for the 2ºC target scenario in the first half of the century is always smaller than that of social costs because it does not reach the maximum temperature allowed until 2065.

6. Discussion

Methane emissions represent the second largest contributor to climate change today and the emissions are projected to keep steadily increasing if no measures are taken. The United Nations Environment Programme and Climate Change and Clean Air Coalition [43] provides an in-depth analysis of the potential benefits that mitigating CH_4 may have in order to quickly reduce its atmospheric concentration and therefore its forcing, due to its short lifetime and relatively strong forcing impact by unit gas in the atmosphere. This could be a key contribution that would allow to meet the climate targets established in the Paris Agreement. But the levels of methane mitigation needed to meet such targets cannot be achieved by broader decarbonization strategies alone, so focused strategies exclusively targeting methane emissions reductions will be needed.

In order to abate greenhouse gases in a cost-effective manner, one needs to find an appropriate way to compare them and put them in a common scale. Most often, this is done using the GWP_{100}, but there is no objectively correct way to choose how to compare greenhouse gases. There is a disagreement about what to compare: radiative forcing, integrated temperature or maybe even economic damages. There is also disagreement about over which time horizon the climate impacts should be compared, and if a discount rate should be used or not.

This paper builds up on the work done in Hänsel et al. [4], in which the DICE model is recalibrated and updated. We have further developed this model by implicitly including methane emissions and having its abatement level as an endogenous variable, so that the social cost of methane can be directly estimated.

The base case of our model shows that methane emissions should be halved by 2035 and further reduced by 64% in 2100 to achieve an optimal temperature increase of 1.54ºC since 1900. We find that the social costs of carbon and methane both grow almost linearly through this century. The ratio of SCM to SCC also grows initially, starting at 31 in 2015, but the growth is reduced with time, stabilizing at around 40 to 45. It then can be inferred that the social cost of methane grows faster than the social cost of carbon in the first half of this century. This metric is particularly interesting if one wants to analyze the impact that indirect estimations have on the social cost of methane. Indirect estimations are usually obtained by converting a direct estimation of the social cost of carbon obtained from a IAM to social cost of methane through the global warming potential of the latter gas, so their ratio is time independent. When our direct estimation of the social cost of methane obtained in this study is compared to an indirect estimation using a GWP_{100} of 34, we see that the social cost of methane would be underestimated from 2025 and onwards by the indirect method. One can arrive to the same conclusion by simply looking at the year in which the ratio of SCM to SCC is larger than the global warming potential.

Social cost of methane estimates are significantly less sensitive to variations in the elasticity of marginal utility and the pure rate of social time preference than social cost of carbon estimates. This is explained by the differences in lifetimes of these gases: carbon dioxide emissions last much longer in the atmosphere than methane emissions, meaning that CO_2 emissions today have a long-term impact on its atmospheric concentration while present methane emissions do not affect the atmospheric concertation of the gas decades into the future. For this reason, the rate at which future costs associated with carbon dioxide emissions (SCC) are discounted has a much larger impact on its net present value than those related with methane (SCM). The same reasoning explains why lower values of these two parameters give lower ratios of SCM to SCC: a decrease of SCM caused by an increase in elasticity of marginal utility and pure rate of social time preference is smaller than the corresponding decrease in SCC.

When the time period of 2015-2300 is shown, it is clearly observed that a higher discount rate only implies lower social cost estimates for the first decades. After some years (around 60 for CO_2 and 130 for CH_4), a lower discount rate gives lower social cost estimates. This happens because there are two countervailing mechanisms acting here: on one hand, a higher discount rate reduces the SCC and SCM because the value of future damages matters less; on the other hand, in a dynamic model such as DICE a high discount rate will also imply less emissions abated, and therefore higher temperature in the future and higher damages, so the social cost estimates will be higher. Therefore, it is just a matter of time for lower social discount rates to give lower social cost of carbon and methane estimates.

The damage function links the climate model to the economic model by translating temperature increase to economic damages as a fraction of the gross domestic product. After evaluating three damage functions proposed by well-known environmental economists, it can be concluded that the choice of the damage function has a significant effect on the social cost estimates and on the optimal temperature increase. The one chosen for the Base case (Howard & Sterner's) gives the highest carbon and methane social cost estimates and the highest ratio of SCM to SCC, and Nordhaus' damage function gives the lowest values of these three metrics.

The damage function proposed by Weitzman adds to Nordhaus' function an extra term to capture the dramatic consequences that a temperature increase above 6ºC will have, but this effect is not seen because such high temperatures are never reached with the current calibration of the model. It is therefore more relevant to try to capture more precisely the consequences that relatively lower temperature increases have in economic terms than focusing on capturing the effects of significantly high temperature increases in a context where there is a global consensus about keeping temperature increase below 2ºC by the end of the century.

The pace at which methane emissions are reduced is strongly dependent on its marginal abatement cost curve. There is a wide consensus in the literature about the non-linearity of this curve, in the sense that emissions can be reduced at a relatively low cost up to a certain level and become rather costly at higher levels, but there are differences with respect to the cost that a specific percentage of emissions reduction entails. The sensitivity analysis of the marginal abatement cost curve carried out in the study seeks to shed some light to the implications that these differences have in the social cost estimates calculated.

The main differences between these curves are rooted in the discrepancies in estimates of the sectoral reduction potentials. Agriculture and waste, and fossil fuel production and use represent 63% and 17% of total anthropogenic methane emissions, respectively [9], so optimistic assumptions on reductions in these sectors, especially agriculture and waste, were expected to provide the highest methane abatement path, which is precisely what is observed. In this regard, the methane abatement path provided by POLE's curve is particularly remarkable. POLE's curve sets the reduction potential in the waste and agricultural sectors to 74%, and projects a 100% anthropogenic methane abatement by 2070 when it is used in the model. There is an obvious contradiction between these last two percentages commented, and this is related to the way in which these MAC curves have been included in our model.

The curves presented in Harmsen et al. [42] only show the percentage of emissions reduction for a carbon price range of 0 to 1,500 $/tCO_2$. Therefore, if one wants to consider the emissions reduction for higher carbon prices, the function that better fits these curves must be estimated. We have done it using the least square method, which is subjected to errors as the contradiction found with POLE's curve commented before. What is made clear is that the marginal abatement cost curve chosen for the Base case is the most conservative of the ones tested and therefore there is room for higher methane abatement emission reduction paths and lower optimal temperature increases in cost-benefit analyses.

The relation between the marginal abatement cost curve of methane and social cost estimates (both for carbon and methane) might not seem straightforward. However, it is related to the climate impact of methane, how methane interacts with the carbon cycle and the non-linearity of the damage function. In the policy optimizing model, the welfare function is maximized so that the optimum level of abatement is calculated by balancing the benefits and costs of abatement. Therefore, the cost of methane abatement influences directly the cost side of the balance (costs of abating methane) and indirectly the benefit side (benefits from reducing emissions).

A cheaper methane abatement implies a larger reduction of methane emissions and therefore a lower concentration and lower temperature increase. This causes the social cost of carbon to drop for two reasons: First, an additional unit of carbon dioxide emitted will have less marginal damage since the temperature will be slightly lower due to more methane being abated. Second, the atmospheric lifetime of CO_2 increases with increasing temperature. If the temperature is reduced due to more methane being abated the atmospheric lifetime of CO_2 will drop and so its concentration, causing CO_2 emissions less marginal damage. As opposed to the social cost of carbon, the social cost of methane is about the same for different abatement cost functions. Three factors play a role for this to happen: (1) The marginal ERF decreases with increasing concentration. (2) The CH_4 lifetime increases with increasing concentration. (3) The marginal damage increases with increasing temperature. This means that a change in the concentration of methane have different effects that push its social cost estimate in different directions, so some effects are compensated with others.

Whether cost-benefit analysis is the most appropriate approach to evaluate the measures that should be taken to tackle global warming, or a cost-effectiveness analysis is the best evaluation system for such purpose is a debate that has been around for some years now. Johansson and Hedenus [44] suggest that the uncertainties surrounding benefit estimates concerning climate measures, together with the political consensus around limiting global warming to well below 2ºC, makes it more reasonable to focus on cost-effectiveness analysis and shadow prices. Price et al. [45] argue that shadow prices are more versatile in making sure that policy decisions adopted in different government programs are compatible with the climate goals set by governments. This ensures that shadow prices can be adjusted to reflect the policy and technological environment, as opposed to social cost estimates that are determined just by our understanding of the damage caused by global warming and how we evaluate this in economic terms. Stern and Stiglitz [46] explain that most IAMs that focus on cost-benefit analyses do not capture some key aspects of the interrelationship between the economy and the environment, which leads costs of climate action being overestimated and benefits underestimated. As a consequence, some of these models, like the DICE model presented in Nordhaus [3], suggest that a temperature increase of around 4ºC should be accepted from a cost-benefit perspective while climate scientists warn that a temperature increase of such a magnitude could lead to catastrophic consequences, so it would therefore be more reasonable to focus on the GHG prices that would guide decisions to achieve an agreed temperature increase that would avoid those catastrophic situations. Contrary to this idea, Nordhaus [1] points out that setting too stringent a temperature target that would require very high abatement costs and could, for example, lead to reductions in living standards in poor countries, so the "solution" would be worse than the "problem". Wagner [47] states that a cost-effectiveness approach could only be used as a complementary analysis because, for it to be enough by itself, reducing GHG emissions to meet a climate goal should be a central pilar of all policies, and it is not the case for many regions, so there is a need to quantify the benefits of reducing these emissions.

The shadow prices obtained in the cost-effectiveness analysis differ substantially depending on the target temperature set and the time until this temperature level is reached. When the target temperature is reached, shadow prices tend to stabilize. Given our choice of damage function and social discount rate determinants, the social cost of carbon is higher than the shadow price of CO_2 for the two temperature targets studied (1.8ºC and 2ºC), following the fact that the temperature increase peaks at almost 1.8ºC in the cost-benefit case, and starts decreasing afterwards. It therefore leads to more ambitious temperature levels reached. In the cost-effectiveness case, the shadow price for CO_2 increases almost linearly until the temperature constraint starts to bite, causing the shadow price of CO_2 for more stringent temperature targets to be significantly higher in the near term.

The shadow price of methane, however, increases exponentially until the target temperature is reached. This translates into significantly lower shadow prices for both target temperatures compared to the SCM in the first 20 to 40 years analyzed (depending on the target temperature), and significantly higher prices after then until the temperature constraint starts to bite. The shadow price of the 2ºC target temperature scenario is significantly lower than the shadow price for 1.8ºC case until these temperatures are met. After the temperature is stabilized the shadow prices also stabilize and tend to be about the same irrespective of the temperature target levels, as in the case of the shadow price of carbon.

The ratio of SPM to SPC is also lower than the ratio of SCM to SCC until 2040 (1.8ºC target) and 2055 (2ºC target). This implies that, in a cost-effectiveness analysis, the relative importance of reducing methane emissions as compared to carbon dioxide is reduced. The reason for it is that the shadow price of an emission is not affected by the temperature response until the constraint temperature is reached. Since the target temperatures are not met at least until 2050, and considering the relatively short lifetime of the temperature response of methane reductions, the shadow price of this gas in 2020 and 2030 is significantly lower compared to its social cost.

Today, countries that represent about 70% of the world economy are establishing climate neutrality targets, and more are expected to do the same in the upcoming years. The private sector is also joining this trend: some of the largest GHG emitters are committing to become carbon neutral by 2050, and over 1,000 corporations have adopted science-based targets to measure carbon reductions [48]. Although these initiatives imply a change in the narrative and are a necessary step to fight the climate crisis, they are not enough by themselves.

The huge system change that is needed to achieve the 2ºC to 1.5ºC limit established in the Paris Agreement needs efforts from both public and private sector. This transition requires immense investments that cannot exclusively come from public funds. In fact, many experts suggest that public funding should be the kickstart of those investments, but the large part of them must come from private actors. To incentive the participation of the private sector in the transition, an effective carbon pricing is crucial, which allows them to establish a business case for the decarbonization of the economy.

The role that reliable social cost of GHG estimates can play on the design of carbon pricing schemes is very significant. At the end, what the social cost of a greenhouse gas tells is the cost of damages caused by an additional ton of the gas emitted, so it is a metric that can be used as a reference in any cost-benefit analysis. Public administrations can find social cost of GHG estimates particularly interesting to evaluate any policy-making process design to reduce greenhouse gas emissions. Until now, the vast majority of these policies have only used social cost of carbon estimates or indirect estimations of the social cost of methane. The estimated social cost of methane provided in this study could be used as a reference metric for both public and private sectors to perform cost-benefit analyses on possible measures to reduce the emissions of this gas, which has been proven to be key to reduce the temperature increase in the short-term.

7. Conclusion

This study has further developed the DICE model presented in Hänsel et al. [4] by incorporating a methane cycle and abatement cost function to provide a direct estimate of the social cost of methane. Summarizing the research questions, this master's thesis concludes the following:

- When a methane cycle and a methane abatement cost function are included in the model so that the methane abatement level is an endogenous variable, the optimal temperature increase obtained by the end of the 21st century is 1.54ºC, which is the same as the one obtained when methane is kept exogenous in the model as in Hänsel et al.
- To achieve such temperature increase optimally, methane emissions must be halved by 2035 and further reduced by 64% in 2100 compared to the baseline scenario.
- In our Base case, the social cost of methane is 7,000 $/t$CH_4$ in 2020 and 15,300 $/t$CH_4$ in 2050. The ratio of SCM to SCC in 2020 and 2050 is 32 and 41, respectively. When these values are compared with the GWP_{100} presented in the IPCC 5th Assessment Report (which has a value of 34), it can be concluded that the social cost of methane would be underestimated from 2025 and onwards if it were indirectly estimated with the GWP.
- The social cost of methane is more sensitive to variations in the SDR than the social cost of carbon because of its shorter lifetime. A higher SDR gives lower social cost estimates of both CO_2 and CH_4 in the first decades, but it is just a matter of time for higher SDR to give higher social cost estimates.
- Both social cost of carbon and social cost of methane are more sensitive to variations in the elasticity of marginal utility than the pure rate of time preference.
- A higher damage function gives higher social cost of carbon, social cost of methane, and ratio of SCM to SCC.
- A cheaper methane abatement implies a lower social cost of carbon, but the social cost of methane is almost unaltered by changes in its MAC function. The MAC function used in the Base case is the most conservative function tested in the

sensitivity analysis, so there could be room for a larger methane abatement at cheaper costs.

- In the cost-effectiveness analysis, two target temperatures are evaluated: 2ºC and 1.8ºC.
    - 2ºC target temperature scenario: The shadow price of carbon in 2020, 2030, and 2050 is 116, 160, and 273 $/tCO_2$, respectively. The shadow price of methane in 2020, 2030, and 2050 is 1,540, 2,640, and 9,640 $/tCH_4$, respectively.
    - 1.8ºC target temperature scenario: The shadow price of carbon in 2020, 2030 and 2050 is 167, 229, and 380 $/tCO_2$, respectively. The shadow price of methane in 2020, 2030, and 2050 is 3,030, 5,550, and 23,300 $/tCH_4$, respectively.
- The SPC is lower than the SCC for the two target temperatures studied.
- The SPM is significantly lower than the SCM the first 20 to 40 years and then it is significantly larger, due to its exponential growth until the target temperatures are met.
- The social cost of methane tells the cost of damages caused by an additional ton of methane emitted. It is therefore a metric that can be used in any cost-benefit analysis. It can be used in rulemaking that addresses GHG emissions, electricity ratemaking and regulation, natural resource valuation and royalty settings, and setting GHG emissions caps and taxes.

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