Structural Change and Economic Dynamics 71 (2024) 35–44

Contents lists available at ScienceDirect

Structural Change and Economic Dynamics

journal homepage: www.elsevier.com/locate/strueco

Assessing the economic implications of carbon emissions on climate change: Estimating the impact using methane-adjusted DICE model

Sofia Aleshina [a,*], Laura Delgado-Antequera [b], German Gemar [c]

[a] *Programa de Doctorado de Economia y Empresa, Universidad de Malaga, Spain*
[b] *Departamento de Economia Aplicada (Matematicas), Universidad de Malaga, Spain*
[c] *Departamento de Economia y Administracion de Empresas, Universidad de Malaga, Spain*

A R T I C L E I N F O

Keywords:
Climate change
Global warming
Methane emissions
DICE model

A B S T R A C T

This study aims to highlight the importance of accurately estimating methane emissions, one of the most dangerous and important greenhouse gases in the context of climate change. By incorporating methane emissions as a variable within the integrated assessment model DICE (*Dynamic Integrated Climate-Economy model*), we investigate how these emissions influence temperature changes and subsequently impact economic policies, including climate economic policies, carbon pricing, and non-price factors. We use the existing DICE-2020 and DICE-2023 models as references for our analysis. In addition to industrial emissions that can be detected through satellite observations, we address the challenge of estimating natural emissions from wetlands and permafrost, which leak gradually and are difficult to detect. By considering these emissions, we account for their exogenous nature and their divergence from the current situation. Our study reveals that incorporating methane emissions into the DICE model has significant implications for global temperature outcomes and subsequent policy changes. We find that by implementing existing methane reduction policies, which includes cutting the level of methane emissions in half and increase the carbon price in 4 times to 500 USD per ton, it is possible to achieve the more ambitious goal of limiting the global temperature increase to 1.5 °C by 2100 in an optimistic scenario instead of the common target of 2 °C. More pessimistic scenarios that do not imply big change in methane emissions, but the same numerical data for carbon price, still suggests the possibility of keeping the global temperature below 2 °C. The findings of this study emphasize the importance of estimating methane emissions in efforts to mitigate climate change. Recognizing the impact of methane on global temperature change, policymakers can make informed decisions regarding economic policies, carbon pricing, to effectively address the challenges posed by climate change. This research contributes to the field by incorporating methane emissions into the DICE model, providing a more complete understanding of its influence on global climate outcomes and economic implications. Additionally, by highlighting the potential benefits of methane reduction measures, this study provides information on how to achieve more ambitious climate targets.

1. Introduction

One of the main effects of climate change is global warming that is recognized as one of the most serious threats to the planet (Nordhaus, 2018). One of the main causes of the rise in temperatures is the increase in the concentration of greenhouse gases (GHGs).

In terms of emissions and human-induced climate forcing, after carbon dioxide (CO_2), methane (CH_4) is the second most relevant of these gases (Lynch, 2019). It is responsible for more than 30% of global warming since the onset of Industrial Revolution (Shindell et al., 2021). However, although its lifetime is relatively short (only a decade compared to hundreds of years for carbon dioxide), the potential emissions of methane are much more powerful and efficient in trapping radiation. According to IPCC (2014), methane has a radiative forcing of 0,97 W/m^2. This is almost one third of the total effect of GHGs (Nisbet et al., 2020). Therefore, methane is 84 times more potent than carbon dioxide in its ability to warm the planet in 20 years.

Since the nineteenth century, atmospheric methane concentrations have increased annually at a rate of approximately 0, 9% (doubling in 200 years), and the current concentration has not been higher for the last 800,000 years. Scientists estimate that global methane emissions in 2021 are 15% higher than in the period 1984–2006 (NOAA, 2022).

* Correspondence to: Facultad de Ciencias Economicas y Empresariales, Universidad de Malaga, Calle Ejido, 6, 29013, Spain.
E-mail address: sofia.aleshina@uma.es (S. Aleshina).

https://doi.org/10.1016/j.strueco.2024.06.001
Received 12 October 2023; Received in revised form 23 February 2024; Accepted 4 June 2024
Available online 10 June 2024
0954-349X/

In addition, methane contributes to tropospheric ozone formation, which is another potent air pollutant with effects on people and ecosystems (Shindell et al., 2021). The average life of a methane molecule in the atmosphere is 9.1 ±0.9 years according to Prather et al. (2012). After its removal by oxidation with hydroxide (OH) to carbon dioxide and water, it continues to warm the planet for hundreds of years.

Global methane emissions in the 2008–2017 period were estimated to be 576 Mt/year (Saunois et al., 2020). Of this total, 359 Mt/yr are anthropogenic emissions, accounting for approximately 60% of total methane emissions. Anthropogenic methane emissions come mainly from three sectors: agriculture, production and transport of fossil fuels, and waste (Jackson et al., 2020). The majority is emitted in China due to its population, followed by the United States (International Energy Agency, 2022).

As for natural sources of methane, there are more than 50 described species of methanogens (methane-producing microorganisms), which live in a variety of warm environments such as the digestive tracts of termites and ruminants (mainly cows and sheep), rice fields, wetlands, landfills, marine sediments and freshwater systems, hot springs and submarine hydrothermal vents, as well as in solid rock miles below the earth's surface. Since methane-emitting microorganisms prefer warm environments, they gradually lose more methane as a result of warming, leading to more warming and even more methane, accelerating the processes. In other words, changes in emissions from natural methane sources are likely to create positive feedback loops as emissions increase in a warming climate.

Methane emissions can be estimated in several ways. Bottom-up approaches can use activity data (e.g., number of inputs or extent of operations) multiplied by standardized emission factors (e.g., default values or leakage rates for certain types of emissions) and emissions from equipment. On the other hand, top-down methods tend to measure atmospheric methane concentrations, usually by airborne or satellite sensors, to derive emissions. Bottom-up methods suggest global emissions almost 30% higher than top-down methods (International Energy Agency, 2022). In fact, bottom-up estimates for natural sources such as land-based sources, other inland water systems and geological sources are higher than top-down estimates. Atmospheric limitations of the top-down approach suggest that some of these bottom-up emissions are overestimated.

Estimates are subject to significant uncertainty due to the magnitude of emission sources and their variability. The lack of appropriate land cover databases to scale field-measured methane emissions to circumpolar scales has contributed to a large uncertainty in understanding current and future methane emissions.

Wetlands contribute significantly to total methane emissions. It is considered to be a natural source, although it is influenced by human activities: increased anthropogenic emissions cause temperature increase, which influences natural emissions, and this creates a warming climate cycle. Emissions from wetlands range between 127 and 227 Mt/year due to uncertainty in estimation (see more in Section 2) (Saunois et al., 2020).

Another important source is permafrost (methane exists in 24% of exposed land in the Northern Hemisphere). Rough estimates, based on Turetsky et al. (2019), show that permafrost could release 60–100 Gt of carbon by 2300.

Most influential models being used for climate policy analysis have assumed the absence of uncertainty. All important quantitative relationships and parameters are specified as if they were known with certainty. Uncertainty is introduced by testing the effects of altering the parameters on the modeled results. The impact of methane is a major uncertainty that is considered exogenous in most economic models and is included as a part of the hardcoded "non-CO_2 forcings" parameter.

One of the three main integrated assessment models (IAM) is the DICE model (Nordhaus, 1993).[1] It does climate policy evaluation over sets of many parameter values rather than finding an optimal policy. The DICE model has been actualized and widely used, including in the report of *Intergovernmental Panel on Climate Change (IPCC)*, and is very influential, partly because it has been updated several times and has made the details of the model accessible and public. It integrates neoclassical economics, the carbon cycle, climate science and estimated impacts that allow action to be taken to curb climate change. Its creator, William Nordhaus, won the Nobel Prize for this model because it integrates climate science and economics and shows the relationship between the two.

Some variants of this model are listed below:

1. RICE (Regional Integrated Climate-Economy model), that was originally invented by the same author (Nordhaus and Yang, 1996) can be used to investigate methane emissions in a specific area to find appropriate measures for this region to address it. This model has been constantly updated, the latest versions of it can be found in Yang et al. (2021b,a).
2. DICE-PACE (Model with Flexible Abatement Cost Elements) includes induced technological changes. It presents very different results, for instance, their optimal path would be to invest heavily from the outset in mitigation technology (Grubb et al., 2021).
3. One of the latest updates of the model, which is publicly available, is DICE-2020, which was modified by researchers at the Potsdam Institute for Climate Impact Research (PIK). It has better estimates for the main variables, such as atmospheric temperature (Hänsel et al., 2020).
4. Recently, DICE-2023 was announced by its creator, Barrage and Nordhaus (2023). As in DICE-2020, it is a modification of the DICE-2016 model (Nordhaus, 2017).

We provide a brief outline of the model:

(a) increase in carbon dioxide concentration has a negative impact on future economic production, due to its influence on global mean surface temperature.
(b) The fraction of lost production in each time period is captured through a damage function.
(c) If a portion of the economic output (so called abatement costs) were to be allowed to the reduction of GHGs, future temperature increases and associated climate damage could be avoided.

The idea is to invest part of the economic output in creating capital for the next period of time, while the remaining part is consumed. It is assumed that the utility or "happiness" of the population depends on consumption and the purpose of this model is to optimize utility.

In previous variations of this model, methane emissions were not included as an endogenous variable. However, this should be considered, as these emissions affect climate policy. Additionally, the short atmospheric lifetime of methane means that action now can rapidly reduce atmospheric concentrations and lead to equally rapid reductions in climate forcing and ozone pollution.

Therefore, the inclusion of methane in integrated assessment models is vital to combat global warming. The aim of this work is to show the importance of estimating methane emissions and to evaluate the economic measures that need to be taken to tackle climate change. Addressing the economic implications of carbon emissions involves discussing emission control policy and its cost (See more in Section 4). For this purpose, in this work, methane is considered as a variable to be included in the DICE economic model in what will be called the *methane cycle*. To achieve the results, quantitative data on methane emissions, concentration and radiative forcing was collected and analyzed. The most recent and comprehensive research on methane emissions used in this paper was conducted by Kleinen et al. (2021), where 5 different SSP (socio-economic pathways) scenarios are considered for future anthropogenic and natural emissions up to 3000. SSPs are designed

[1] other two models are PAGE (Policy Analysis of the Greenhouse Effect) (Hope et al., 1993) and FUND (Framework of Uncertainty, Negotiation, and Distribution) (Tol, 1997).

Table 1
SSP scenarios.

Forcing by 2100 (W/m^2)	SSPs description
SSP1-1.9	Very low GHG emissions, cut to net zero by 2050
SSP1-2.6	Low GHG emissions, cut to net zero by 2075
SSP2-4.5	Intermediate GHG emissions, falling after 2050
SSP3-7.0	High GHG emissions, double by 2100
SSP5-8.5	Very high GHG emissions, triple by 2075

to provide socioeconomic contexts for emission modeling, with each representing different pathways (SSP1-5) and the numbers indicating radiative forcing post-policy (1.9/2.6/4.5/7/8.5 W/m^2). SSP scenarios are built based on assumptions of the volume of GHG emissions that may vary due to external factors (see the Table 1), thus SSP1-1.9 is considered to be the most optimistic one called Sustainability ("Taking the Green Road"), ending with SSP5-8.5 (Fossil-Fuel Development). More information about these scenarios incorporated into the DICE model can be found in Yang et al. (2018).

The authors of this work have taken the two latest versions of DICE-2020 by PIK (Hänsel et al., 2020) and DICE-2023 by Barrage and Nordhaus (2023), and combined the actual updates of them. We focus on constructing the methane cycle using dynamic equations. In this work, the equations of methane emissions, methane concentration, and the radiative forcing equation are included in order to evaluate its influence on the atmospheric temperature, economic damages and, as a result, discuss different methods of its reduction.

There is a big variety of the research works addressed to economic implications of carbon emissions and, in particular, discussing methane emissions reduction policies. Well known agencies and programs such as UNEP (United Nation Environmental Programme), IEA (International Energy Agency), EPA (United States Environmental Protection Agency), etc. constantly publish their studies about measured needed to stop climate change (International Energy Agency, 2022; UNEP, 2021; EPA, 2022). However, most of these studies include anthropogenic emissions due to uncertainty in calculations of natural emissions and the policies provided are only applicable for human-induced emissions as others are non-controlled. Our work intends to cover these gaps by providing possible paths for natural methane emissions as well, in order to have a clear picture of the future (see graphs in Section 3).

In Section 2 there is a brief explanation of the latest version of the DICE model and the implementation of the methane cycle, followed by the analysis of the results and the evaluation of different strategies in Sections 3 and 4. In the end there are limitations of the model explained and conclusions related to the results obtained in Section 5.

2. Methodology of DICE model

The DICE model considers the economics of climate change from the perspective of the neoclassical theory of economic growth. The growth of the capital stock depends on the fraction of the world's output devoted to investment, net of capital depreciation. The remainder of the world's output is available for consumption, which together with the level of population determines global welfare (Barrage and Nordhaus, 2023).

2.1. Objective function

The model searches for the policy that maximizes social welfare, W, which is defined as the discounted sum of the population-weighted utility of per capita consumption:

$$W = \sum_{t=0}^{T_{\max}} U[c(t), L(t)] \cdot R(t) \tag{1}$$

where $c(t), L(t)$ and $R(t)$ denote respectively per capita consumption, labor output (total population) and the discount factor. The utility function at time t depends on per capita consumption $c(t)$ and population $L(t)$ as follows:

$$U[c(t), L(t)] = L(t) \cdot \left[\frac{c(t)^{1-\eta}}{1-\eta}\right] \tag{2}$$

Here η is constant elasticity of marginal utility of consumption. The discount factor is exponentially decreasing over time:

$$R(t) = (1+\rho)^{T_0 - t} \tag{3}$$

where ρ is pure time preference and T_0 is the initial year of the model. Note that $\rho \geq 0$; $\eta \geq 0$ and $\eta \neq 1$; but the exact values of ρ and η are subject to debate and value judgement. For the purpose of this work it is assumed the median expert values from Drupp et al. (2015), thus setting $\eta = 1.0000001$; $\rho = 0.005$.

2.2. Economic component

The population $L(t)$ is a model parameter, assumed to be a logistic function with a cap of 11.5 billion people (Peretto and Valente, 2015). Effectively, the only dynamic variable of the model that directly influences our objective function is $c(t)$, consumption per capita. This section outlines its dependency on our policy.

The model is set up in such a way that for each year the total capital $K(t)$ and the atmospheric temperature $T_{AT}(t)$ are known in the initial year of the model, and their values for each next year can be determined if we know the values of all other variables in the DICE model for the current year, as will be described below.

Apart from those two known-in-advance variables, we have two policy variables that the humanity — as a rational agent — has the power to change each year, in order to improve the objective function. These are: saving rate $S(t)$ and emission control $\mu(t)$.

Now, given these four variables, we can readily write down the economic assumptions of the DICE model and express $c(t)$. First, the global gross product variable is expressed via Cobb–Douglas production function:

$$Q_{gross}(t) = A(t) \cdot K(t)^{\gamma} \cdot L(t)^{1-\gamma} \tag{4}$$

The model parameters introduced in this formula are Hicks neutral technological change $A(t)$ and capital elasticity in production γ.

However, before this production can be used for consumption, we account for two factors that come with climate change to express the total output Q:

$$Q(t) = Q_{gross}(t) \cdot (1 - \Lambda(t) - \Omega(t)) \tag{5}$$

The first factor is abatement costs. The more stringent we select our emission control policy $\mu(t)$, the more it will cost for economy. Given the predefined parameters $\lambda(t)$ that represents the fraction of output that is needed to reduce emissions to zero (Barrage and Nordhaus, 2023) and θ, we can express the abatement fraction:

$$\Lambda(t) = \lambda(t) \cdot \mu(t)^{\theta}. \tag{6}$$

The second factor is climate damage. It depends on temperature, and it is generally assumed in economic literature (Nordhaus, 2017) that the dependency is quadratic:

$$\Omega(t) = \psi_1 \cdot T_{AT}(t) + \psi_2 \cdot T_{AT}(t)^2 \tag{7}$$

Now that we know the value of total output $Q(t)$ given by the formula (5), we can also express global investment and global consumption according to our saving rate $S(t)$ policy:

$$I(t) = S(t) \cdot Q(t) \tag{8}$$

$$C(t) = Q(t) - I(t) \tag{9}$$

At last, we can express the consumption per capita:

$$c(t) = \frac{C(t)}{L(t)} \tag{10}$$

To complete the model, we need to show how the values for the next time point of capital $K(t+1)$ and atmospheric temperature $T_{AT}(t+1)$ depend on our policy. For the capital, the dependency is quite simple:

$$K(t+1) = (1-\delta)K(t) + I(t) \tag{11}$$

Here δ is the depreciation rate of global capital. Thus, we can observe the standard trade-off when selecting the saving rate $S(t)$. The more the saving rate, the less consumption (and therefore, the less utility) we get in the current year, but the more capital we preserve for the next one, indirectly benefiting the utility in the subsequent years of the model.

The dependence of atmospheric temperature on our emission control policy $\mu(t)$ is much more complicated. First of all, we can express industrial carbon dioxide emissions using the technological parameter $\sigma(t)$ (carbon intensity of the economy):

$$E_{ind}(t) = \sigma(t) \cdot Q_{gross}(t) \cdot (1 - \mu(t)) \tag{12}$$

Thus, the trade-off here is that the greater value of $\mu(t)$, the more abatement costs we need to incur during this year (as seen in formula (6)), but the less emissions our economy will produce, indirectly decreasing temperature (and hence, the damages, by formula (7)) for the subsequent years.

The remaining equations belong to the climate component of the DICE model and essentially formulate the dependency of $T_{AT}(t+1)$ on $E_{ind}(t)$.

2.3. Climate component

The total carbon dioxide emission $E(t)$ is the sum of industrial emissions and land use emissions:

$$E(t) = E_{\text{ind}}(t) + E_{\text{land}}(t) \tag{13}$$

Land use emissions are considered exogenous, at a gradually decreasing rate (10% per 5 years), as in earlier models, while industrial emissions are given by (12).

Another useful emissions variable is cumulative emissions $E_{\text{cum}}(t)$, which is calculated by the simple formula:

$$E_{\text{cum}}(t+1) = E_{\text{cum}}(t) + E(t)$$

The initial value $E_{\text{cum}}(0) = 597$ GtC is the amount of carbon already emitted since preindustrial times up to the starting year of the DICE model.

To accurately calculate the climate response to emissions, AOGCMs (Atmospheric-Ocean General Circulation Models) are generally used (IPCC, 2021). They subdivide the atmosphere and oceans of Earth into relatively small boxes, outlining the equations of the carbon and temperature dynamics among the boxes. Such models are very complex and inherently difficult to integrate with economic models.

To make the results of AOGCMs more palatable at the cost of slight loss in precision, simple climate models, such as MAGICC[2] and FaIR (Smith et al., 2018) were invented. More updated information on the related topic can be found in Yang et al. (2023). Following Barrage and Nordhaus (2023), we integrate DICE with the FaIR climate model.

The FaIR model uses four boxes containing carbon, and we denote the carbon mass contained in a box number i at time t by $R^i(t)$. However, it is important to note that the boxes are "abstract", i.e. they do not correspond to physical regions of the Earth atmosphere, and so these "masses" can even attain negative values at certain time points. This somewhat counterintuitive quirk is a result of FaIR being not a model built from the ground up but rather an attempt to approximate complex AOGCMs, which are known to be very precise.

The content of the boxes gets summed up to calculate the current presence of carbon dioxide in the atmosphere:

$$C_{AT}(t) = C_{AT}(O) + \sum_{i=1}^{4} R^i(t) \tag{14}$$

Here $C_{AT}(O)$ is the atmospheric carbon dioxide in the pre-industrial times (1750) — not to be confused with $C_{AT}(0)$, the value for the starting year of the DICE model, which can be calculated by this formula since $R^i(0)$ values are known in advance. To calculate the carbon response to emissions (i.e., values of $R^i(t+1)$, using known values for time t, or equivalently, the difference $\Delta R^i(t) = R^i(t+1) - R^i(t)$), we can use the following formula from the FaIR model.

$$\Delta R^i(t) = \psi_i E(t) - \frac{R^i(t)}{\alpha(t)\tau_i}, \tag{15}$$

where ψ_i is a fraction of carbon emissions entering box number i (thus $\sum_i \psi_i = 1$), τ_i is a time characteristic for the given box (in years), and $\alpha(t)$ is a special scaling factor calibrated by the following equality ($\varsigma_0, \varsigma_T, \varsigma_C$ are constant coefficients):

$$\begin{aligned} &\sum_{i=1}^{4} \psi_i \alpha(t)\tau_i \left(1 - \exp\left(\frac{-100}{\alpha(t)\tau_i}\right)\right) = \\ &\varsigma_0 + \varsigma_T T_{AT}(t) + \varsigma_C \cdot \left(E_{\text{cum}}(t) - \sum_{i=1}^{4} R^i(t)\right) \end{aligned} \tag{16}$$

The next step in assessing the climate response is to calculate the radiative forcing, which is given by the formula:

$$F(t) = \kappa \left(\text{Ln}\,\frac{C_{AT}(t)}{C_{AT}(O)}\right) + F_{\text{non-CO}_2} \tag{17}$$

where κ is a constant coefficient and $F_{\text{non-CO}_2}$ is exogenous forcings characterizing all gases other than carbon dioxide, typically taken from SSP models (Riahi et al., 2017).

Finally, radiative forcing $F(t)$ affects atmospheric temperature and is incorporated into the following pair of atmospheric-ocean thermodynamic exchange equations:

$$\begin{aligned} T_{AT}(t+1) = T_{AT}(t) + \xi_1 \cdot (F(t) - \xi_2 \cdot T_{AT}(t) \\ - \xi_3 \cdot [T_{AT}(t) - T_{OC}(t)]) \end{aligned} \tag{18}$$

$$T_{OC}(t+1) = T_{OC}(t) + \xi_4 \cdot \left(T_{AT}(t) - T_{OC}(t)\right) \tag{19}$$

Here T_{OC} is oceanic temperature. Summarizing the climate component, knowing the state values for the given year t of $E_{\text{cum}}, R^i, T_{AT}, T_{OC}$ we can calculate the same set of variables for the following year $(t+1)$ using the above equations, provided that we are supplied with the economy driven value $E_{\text{ind}}(t)$. Since those variables have known values for the initial year, this completes the dependency between industrial emissions and atmospheric temperature.

2.4. Additional constraints

A limit of carbon emissions is bounded by the total amount of fossil fuels:

$$C_{cum} \geq E_{\text{cum}}(t)$$

In practice, this constraint does not change the outcomes of DICE model, since the utility optimization suggests avoiding using all fossil fuels present in the ground.

Policies are generally bounded as:

$$0 \leq S(t) \leq 1;\ 0 \leq \mu(t) \leq 1$$

However, following Hänsel et al. (2020), the possibility of negative emissions technologies is accounted in the model, so for the years since 2050:

$$0 \leq \mu(t) \leq 1.2,$$

[2] magicc.org.

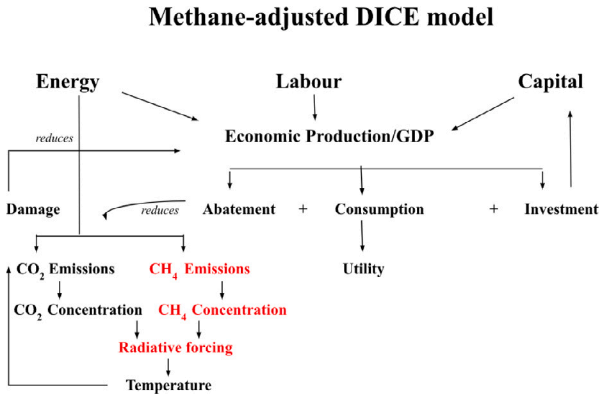

Fig. 1. Schematic illustration of the DICE model.
Source: Own elaboration based on Gupta (2020).

where value $\mu(t) > 1$ indicates negative emission policy. Likewise, as in Hänsel et al. (2020), it is also assumed that we cannot apply stringent policies too fast, which is accounted for by equation limiting rate of change of emissions control:

$$\mu(t+1) \leq \mu(t) \cdot 1.1$$

2.5. Methane-adjusted DICE model

The idea is to add the equations for methane emissions and concentration and to modify the radiative forcing equation in the climate section of the DICE model, in this way we adjust the DICE model by introducing a methane cycle.

Fig. 1 shows the diagram of the methane-adjusted DICE model. The black part represents the original DICE model (see Section 2), and the red ones are the new variables added to the climate component of the model. The structure of the new chain corresponds to carbon dioxide. These are geophysical equations for methane emissions, concentration and radiative forcing that includes both CO_2 and CH_4. These equations are described in the following.

Eq. (12) is replaced by two equations in which $\sigma(t)$ (carbon dioxide intensity) is a different parameter for carbon dioxide and methane:

$$E_{\text{ind}}^{\text{CO}_2}(t) = \sigma^{\text{CO}_2}(t) \cdot Q_{\text{gross}}(t) \cdot [1 - \mu^{\text{CO}_2}(t)] \tag{20}$$

$$E_{\text{ind}}^{\text{CH}_4}(t) = \sigma^{\text{CH}_4}(t) \cdot Q_{\text{gross}}(t) \cdot [1 - \mu^{\text{CH}_4}(t)] \tag{21}$$

For simplicity of optimization, we assume that emission control is equal for the two gases. However, we conservatively disallow negative emissions technologies for CH_4, since little progress is done in this area. Thus, we have:

$$\mu^{\text{CH}_4} = \min(1, \mu^{\text{CO}_2})$$

Similar to Eq. (13) on carbon dioxide emissions, methane emissions consist of endogenous (industrial emissions) and exogenous (natural emissions) components:

$$E^{\text{CH}_4}(t) = E_{\text{ind}}^{\text{CH}_4}(t) + E_{\text{nat}}^{\text{CH}_4}(t)$$

Due to significant uncertainty in future natural methane emissions, we consider 5 different SSP scenarios and run the model 5 times with different values of $E_{\text{nat}}^{\text{CH}_4}$, according to the data in Kleinen et al. (2021).

The concentration of methane in atmosphere $C_{AT}^{\text{CH}_4}(t)$ depends on its quantity in the previous period and on methane emissions, which in simplified way can be spelled as:

$$C_{AT}^{\text{CH}_4}(t) = E^{\text{CH}_4}(t) + \tau C_{AT}^{\text{CH}_4}(t-1), \tag{22}$$

where $\tau \approx 0.9$ is the annual decay rate of methane in the atmosphere. Unlike carbon dioxide, the decay rate needs to be accounted for now because of methane's short atmospheric lifetime.

Finally, the formula (17) is modified to accommodate the concentration of methane present in the model. $F_{\text{non-CO}_2}$ is decomposed into methane forcings, depending on methane concentration as inverse square root (Myhre et al., 1998), and F_{other}, exogenous forcings generated by gases other than methane and carbon dioxide, yielding the formula:

$$\begin{aligned} F(t) = {} & \kappa^{\text{CO}_2} \left(\text{Ln} \frac{C_{AT}^{\text{CO}_2}(t)}{C_{AT}^{\text{CO}_2}(O)} \right) \\ & + \kappa^{\text{CH}_4} \left(\sqrt{C_{AT}^{\text{CH}_4}(t)} - \sqrt{C_{AT}^{\text{CH}_4}(O)} \right) + F_{\text{other}}(t) \end{aligned} \tag{23}$$

Here $C_{AT}^{\text{CO}_2}(O)$ and $C_{AT}^{\text{CH}_4}(O)$ are the pre-industrial concentrations of carbon dioxide and methane respectively, $C_{AT}^{\text{CO}_2}(t)$ and $C_{AT}^{\text{CH}_4}(t)$ are the respective concentrations at current year t, κ^{CO_2} and κ^{CH_4} are empirically fit forcing coefficients, and F_{other} simply extrapolated from the empirical data for all other gases (IPCC, 2021).

The changes in the radiative forcing equation affect the optimal atmospheric temperature according to Eq. (18), which influences other variables of the economic component, and, ultimately, the welfare function (see Fig. 1). In particular, inclusion of methane emissions increases the damage as well as abatement cost, which potentially decreases values of output, investment and consumption (however, the relation between emissions and economic variables is complex, and there is no direct correlation between them). Thus, economic measures discussed in Section 4 aim to strike a balance between environmental goals and economic stability.

3. Main results

The methane-adjusted DICE model is developed using the Python programming language.

GAMS (General Algebraic Modeling System) was the original implementation of the DICE-1993 model that is widely used in optimization problems (Nordhaus, 1993). DICE-2020 was written in AMPL, which is widely used to solve mathematical computations (Hänsel et al., 2020). However, other versions of the DICE model exist also in such languages as R, Julia, Matlab, etc.

Python is selected because of its open source nature, which facilitates the reproduction of the results, as well as its excellent set of external modules that facilitate the visualization of the results. In addition, Python has libraries of methods that solve dynamic optimization problems such as *Pyomo* (Hart et al., 2017) and *SciPy*. While SciPy has in-built optimization routine, it produces less accurate results that those provided by specialized solvers such as Ipopt and Knitro, used by algebraic modeling systems. Thus we implement the model using Pyomo as a modeling environment and the Ipopt as a nonlinear solver. The methane cycle is implemented and then the results are taken into account to propose methane reduction strategies.

Here are graphs of optimal path for main variables of DICE model according to SSP scenarios. Black line represents optimal path for variables of DICE-2020 as DICE-2023 uses different to SSP scenarios and thus, complicates the graphs and future analysis.

As shown on Fig. 2, in every scenario it is suggested that the main drop of methane emissions needs to be done within the next 40 years. It can be done due to short life of methane discussed in Section 4. It can also be seen that the most pessimistic SSP policies suggest bigger reductions of methane by 2050 (see Table 2). The increase in methane emissions after that period in worst scenarios comes mainly from uncertainty of natural methane emissions that cannot be controlled and depends on the path humans choose (see Figs. 3 and 4).

There is a clear path of reducing industrial methane emissions as they can be directly affected with existing measures and in all scenarios can be cut to zero by 2100 (see Table 3). That cannot be said about natural emissions. There is a big uncertainty among its values in Table 4.

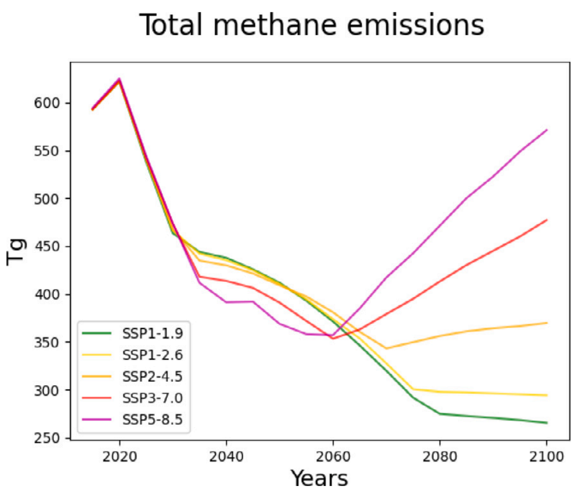

Fig. 2. Optimal path for methane emissions.

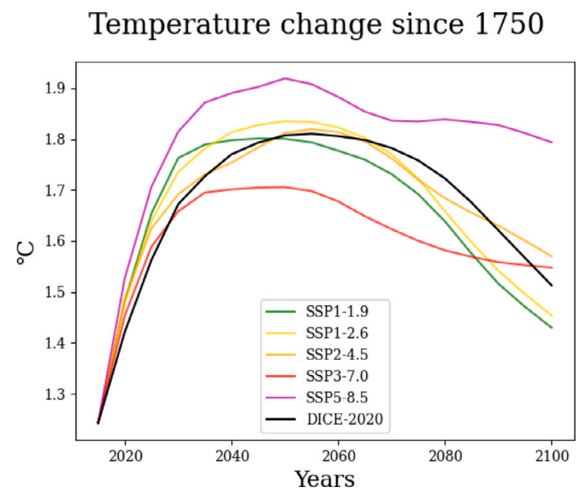

Fig. 5. Optimal path for temperature change.

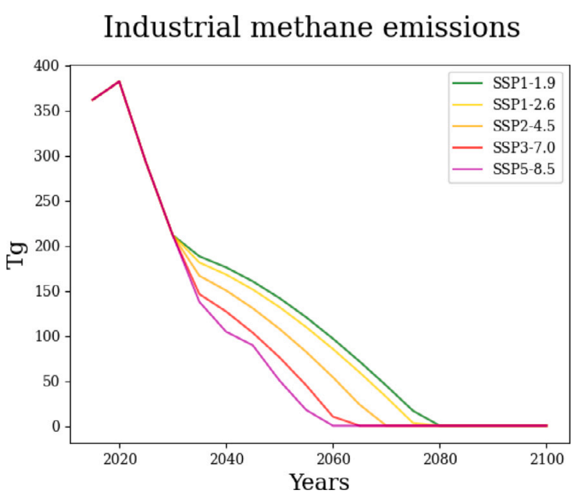

Fig. 3. Optimal path for anthropogenic methane emissions.

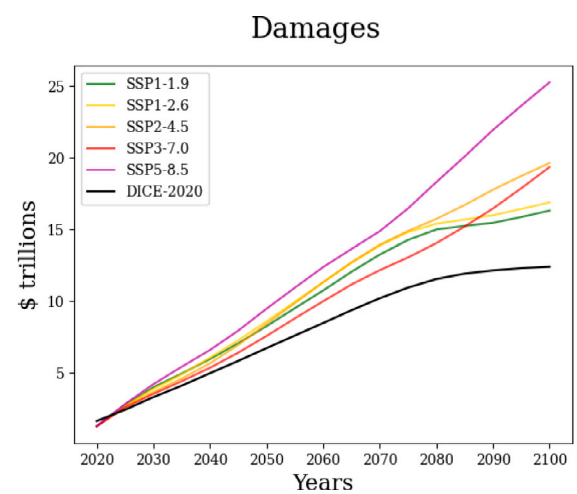

Fig. 6. Optimal path for damages.

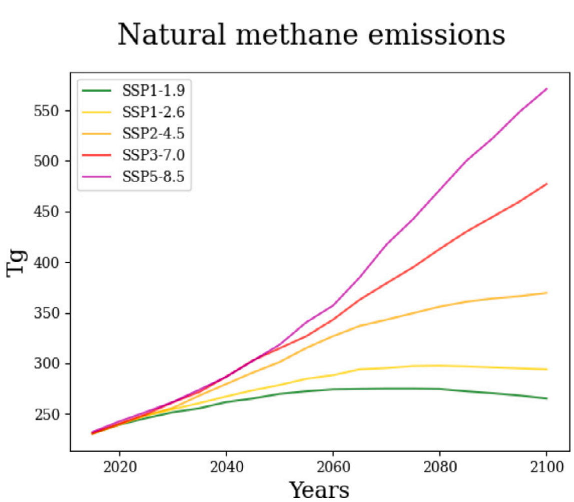

Fig. 4. Optimal path for natural methane emissions.

Table 2
Optimal values for methane emissions.

CH4 EMISSIONS, TG					
SCENARIO	2025	2050	2075	2100	2150
SSP1-1.9	538,39	411,73	291,83	265,52	230,89
SSP1-2.6	540,99	410,47	300,60	294,32	278,14
SSP2-4.5	541,32	409,05	349,64	369,73	401,44
SSP3-7.0	542,32	391,02	394,96	477,17	650,96
SSP5-8.5	544,59	368,81	442,52	571,02	760,67

The inclusion of methane affects the optimal temperature, especially over the next decades as it can be seen from Fig. 5. The Earth is generally regarded as having warmed about 1 °C since around 1750. The authors believe that as it was mentioned previously, with short life of methane there are more opportunities of decreasing the temperature. The cost-effective measure that was mentioned before needed to achieve the 1.5 °C target of the United Nations Framework Convention on Climate Change. It is possible to achieve by 2100 in almost all scenarios (see Table 5).

Damage function establishes connection between climate-related variables and economic ones. Methane emissions affect climate change, which lead to damages (see Fig. 6), including more frequent and severe heatwaves, changes in precipitation patterns, sea-level rise, and disruptions to ecosystems. These damages have economic implications, affecting sectors such as agriculture, infrastructure, health, and more.

Table 3
Optimal values for antropogenic methane emissions.

INDUSTIAL METHANE EMISSIONS, TG					
SCENARIO	2025	2050	2075	2100	2150
SSP1-1.9	290,67	168,62	35,45	0,17	0,18
SSP1-2.6	290,67	159,45	22,50	0,17	0,18
SSP2-4.5	290,67	138,09	0,15	0,17	0,18
SSP3-7.0	290,67	115,88	0,15	0,17	0,18
SSP5-8.5	290,67	88,73	0,14	0,17	0,18

Table 4
Optimal values for natural methane emissions.

NATURAL METHANE EMISSIONS, TG					
SCENARIO	2025	2050	2075	2100	2150
SSP1-1.9	245,95	269,90	275,08	265,37	230,74
SSP1-2.6	248,54	278,64	297,41	294,17	277,99
SSP2-4.5	248,87	301,29	349,51	369,58	401,29
SSP3-7.0	249,84	314,89	394,82	477,02	650,81
SSP5-8.5	252,10	318,45	442,39	570,87	760,52

Table 5
Optimal values for temperature change.

TEMPERATURE CHANGE SINCE 1750, °C					
SCENARIO	2025	2050	2075	2100	2150
DICE-2020	1,56	1,81	1,76	1,51	1,06
SSP1-1.9	1,65	1,80	1,69	1,43	0,96
SSP1-2.6	1,64	1,84	1,72	1,45	1,00
SSP2-4.5	1,63	1,81	1,72	1,57	1,13
SSP3-7.0	1,59	1,71	1,60	1,55	1,29
SSP5-8.5	1,71	1,92	1,83	1,79	1,43

Table 6
Optimal values for damages.

DAMAGES, $ TRILLIONS					
SCENARIO	2025	2050	2075	2100	2150
DICE-2020	2,44	6,74	10,97	12,41	11,48
SSP1-1.9	2,77	8,28	14,28	16,33	13,57
SSP1-2.6	2,72	8,60	14,83	16,90	14,85
SSP2-4.5	2,65	8,44	14,91	19,65	19,27
SSP3-7.0	2,60	7,59	13,06	19,37	25,94
SSP5-8.5	2,83	9,49	16,48	25,28	31,20

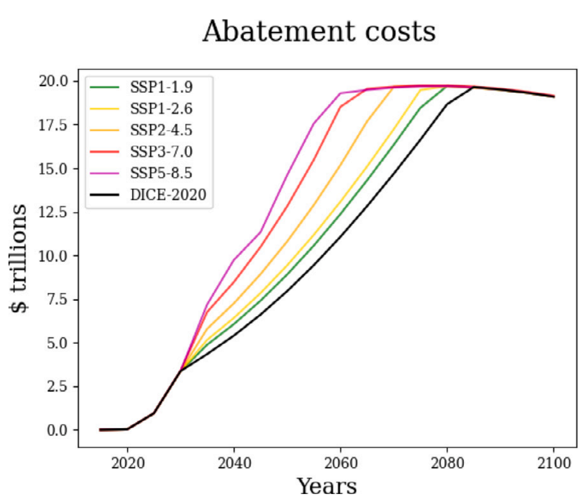

Fig. 7. Optimal path for abatement costs.

As it can be seen from Table 6, even in optimistic scenarios the damage from adding methane emissions is much higher than it was calculated in DICE-2020.

Abatement costs (that is shown in Fig. 7 and Table 7). represent the idea that the policy has to stricter according to the scenario. The cost of reducing methane emissions is closely related to the technologies

Table 7
Optimal values for abatement costs.

ABATEMENT COST, $ TRILLIONS					
SCENARIO	2025	2050	2075	2100	2150
DICE-2020	0,95	7,95	16,64	27,70	23,65
SSP1-1.9	0,98	10,24	24,01	27,70	23,65
SSP1-2.6	0,98	10,80	25,19	27,70	23,65
SSP2-4.5	0,98	12,22	27,36	27,70	23,64
SSP3-7.0	0,98	13,83	27,38	27,77	23,66
SSP5-8.5	0,98	15,92	27,31	27,71	23,63

Table 8
Optimal values for saving rate.

SAVING RATE					
SCENARIO	2025	2050	2075	2100	2150
DICE-2020	0,3105	0,2984	0,2955	0,2918	0,2874
SSP1-1.9	0,3103	0,2983	0,2959	0,2921	0,2874
SSP1-2.6	0,3106	0,2987	0,2958	0,2924	0,2875
SSP2-4.5	0,3112	0,3003	0,2961	0,2929	0,2880
SSP3-7.0	0,3119	0,3023	0,2977	0,2941	0,2892
SSP5-8.5	0,3133	0,3039	0,2985	0,2944	0,2890

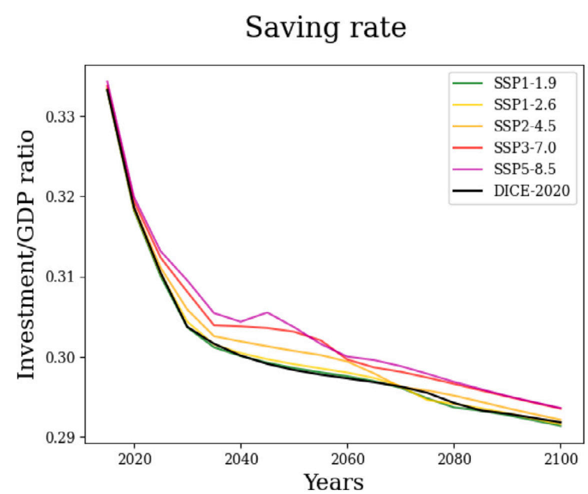

Fig. 8. Optimal path for saving rate.

and strategies used for abatement. Some methods may be more cost-effective than others. For example, fixing leaky infrastructure in the fossil fuel industry could be a relatively straightforward and cost-effective solution, while implementing changes in agricultural practices could involve higher initial costs. Different economic sectors contribute to methane emissions, and the abatement cost can vary between these sectors. The agricultural sector, for example, might incur costs associated with changing agricultural practices, while the energy sector may invest in technology to reduce methane emissions.

The relationship between the saving rate and methane emissions is complex and involves various economic, technological, and policy factors. One of the policies, placing the saving rate higher as shown in Fig. 8 can potentially lead to increased investment in research, development, and implementation of green technologies. This, in turn, could contribute to the adoption of cleaner energy sources and more environmentally friendly practices, potentially reducing methane emissions. Saving rate is one of the policies of the DICE model that can be applied directly. In addition, changes in the saving rate can impact overall economic growth and consumption patterns, however, this relation is indirect and subject to the external circumstances (see Table 8).

One of the main aspects of the economy is the carbon price, which is an effective policy of reducing methane emissions that is mainly used in the DICE model. All scenarios suggest significant increase of carbon price as the main economic strategy (see Fig. 9). Carbon price depends on emission control policy, which reaches its maximum value, for that reason carbon price is the same in all SSP scenarios after 2080 (can be seen in Table 9).

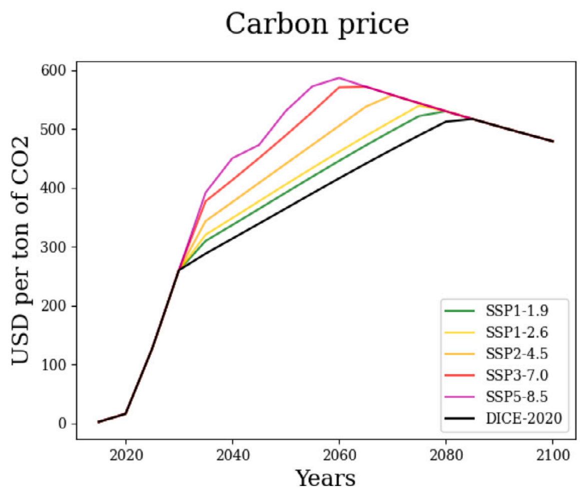

Fig. 9. Optimal path for carbon price.

Table 9
Optimal values for carbon price.

CARBON PRICE, USD PER TON OF CO2					
SCENARIO	2025	2050	2075	2100	2150
DICE-2020	126,71	364,57	488,86	478,77	371,69
SSP1-1.9	126,59	391,27	521,64	478,77	371,69
SSP1-2.6	126,62	405,28	539,35	478,77	371,69
SSP2-4.5	126,67	440,31	543,39	478,77	371,69
SSP3-7.0	126,83	488,73	543,39	478,77	371,69
SSP5-8.5	126,89	530,05	543,39	478,77	371,69

Therefore, inclusion of methane emissions affects on climate and economic variables of the DICE model and existing measures can help to achieve the optimal temperature and prevent global warming.

4. Discussion

The main climate variable of the DICE model is temperature change. Taking into account the most recent DICE updates, both suggest that it is possible to achieve 2 °C of temperature optimum by 2100 (Hänsel et al. (2020) and Barrage and Nordhaus (2023)). However, in our work we prove that with methane reduction policies, it is possible to achieve 1.5 °C in optimistic scenarios, which W.Nordhaus calls "infeasible" in DICE-2023.

In the work of Meinshausen et al. (2020) while SSP5-8.5 is projected to be the scenario with the highest radiative forcing because of high CO_2 emissions, SSP5-8.5 is not the highest CH_4 emissions scenario, with SSP3-7.0 suggesting higher total emission by 2100. However, in our work, we prove that the worst scenario in terms of methane emissions is SSP5-8.5 due to highly unpredicted natural emissions.

The most detailed analysis of methane reduction is described for the anthropogenic sectors in the work (Shindell et al., 2021):

- Available measures could reduce emissions from the oil and gas sector by 29–57 Mt/year and from the coal sector by 12–25 Mt/year. Up to 80% of the measures for oil and gas and up to 98% of the measures for coal could be implemented at negative or low cost.
- Methane emissions from the waste sector could be reduced by 29–36 Mt/year by 2030. The greatest potential lies in improving solid waste treatment and disposal. Up to 60% of specific measures in the waste sector have a negative or low cost.
- The existence of specific measures could reduce methane emissions from the agricultural sector by about 30 Mt/year by 2030. Methane emissions from rice cultivation could be reduced by 6–9 Mt/year. Livestock-specific mitigation potentials are less consistent and range from 4–42 Mt/yr.
- Decarbonization measures, such as transitioning to renewables and improving energy efficiency across the economy, are available. Emissions pricing can be an effective policy that could incentivize substantial methane mitigation and support widespread implementation of methane reduction measures. For example, an increasing global tax on methane emissions starting at about 800 dollars per tonne could reduce methane emissions by up to 75% by 2050.

International Energy Agency (2022) believes that 70% from the energy sector, namely, oil and gas production can be reduced by 75% implementing available measures which correspond with the calculations of the previous author.

In our work we obtain that with methane reduction policy anthropogenic emissions can be reduced by 70% by 2040 with a carbon price of less than 600 dollars per ton.

5. Conclusions

The purpose of this work is to show the importance of including methane emissions in the integration of assessment models to have realistic estimates of climate change and its influence on policies.

Methane is an important greenhouse gas to consider for determining optimal policy in integrated assessment models. Unlike other GHGs, methane can be converted into usable energy. Using these opportunities can help generate new sources of clean energy and mitigate global climate change. When adequate policies are applied, natural methane emissions have a much more significant impact than anthropogenic emissions, yet the current anthropogenic levels are greater. It is needed to take urgent actions since methane has a large reduction potential and cost-effective mitigation technologies are available due to its short lifetime. Taking into account that many of the methane measures are shared with carbon dioxide (because carbon is in common), we can achieve the expected result faster. Furthermore, there is significant uncertainty regarding natural methane emissions. Thus there is a need to collect more data, especially considering that they produce higher impact than industrial. This can help avoid potential climatic tipping points and reduce environmental impacts, especially in the Arctic.

Methane-adjusted DICE model produces more stringent policies (higher carbon price) than original DICE in all our scenarios, even the most optimistic. That is one of the most effective economic methods of reducing emissions. Our results for different SSP runs suggest are relatively similar (suggest to limit warming to 1.4–1.8 degrees by 2100), but still have notable differences, despite methane short lifetime. We believe that with current available measures it is possible to reach optimistic scenario. Previous work on including non-CO_2 GHG in the DICE model was limited and did not consider methane separately. Due to the fact that other gases do not have as much impact as methane, we believe it is necessary to separate it and provide with different strategies to mitigate climate change. The main economic implications are related to carbon price and saving rate. This combination creates economic incentives for businesses and individuals to reduce their emissions to avoid higher costs associated with carbon pricing. A higher savings rate means more funds available for investment in emission reduction initiatives. Governments can align carbon pricing policies with incentives to encourage higher private savings for emission reduction. This alignment can be achieved through tax incentives, subsidies, or other financial mechanisms. In summary, carbon pricing and a higher savings rate can complement each other in the pursuit of decreasing methane emissions. While carbon pricing provides economic incentives and signals the true cost of emissions, a higher savings rate offers the financial resources needed for businesses and individuals to invest in innovative and sustainable solutions.

In June 2022, 11 countries apart from the United States (Argentina, Canada, Denmark, Egypt, Germany, Italy, Japan, Mexico, Nigeria, Norway, and Oman) launched the Global Methane Pledge Energy Pathway to catalyze methane emissions reductions in the oil and gas sector, advancing both climate progress and energy security. To limit warming to 1.5 °C, the world must rapidly reduce methane emissions in addition to decarbonizing the global energy sector and, for that reason, more than 100 countries have launched the Global Methane Pledge (GMP) to reduce anthropogenic methane emissions by at least 30% by 2030 from 2020 levels (US Department of States, 2022). That is the first step towards our ultimate goal.

As mentioned in Kirschke et al. (2013), we are still in need of new advanced methods of estimating methane emissions and creating global methane database as the biggest difficulty of this work was trying to find coefficients to formula of future methane concentration and some assumptions and extrapolations were made due to lack of this information.

Other important greenhouse gases worthy of a special treatment in future work are nitrous oxide (N_2O) and chlorofluorocarbons (CFC) due to their high potential for global warming (Feng et al., 2022). As with methane, its sources need to be studied and modeled properly to assess their effects on climate and economy.

Methane feedback loops and other important climate loops are not considered. Fluctuations in methane emissions can form strong positive feedbacks such as permafrost leaks, wetland methane release, and blackbody radiation to current and future climate warming (NOAA, 2022). The overall impact of climate change on methane emissions remains uncertain, e.g. plant-mediated transport will depend on changes in vegetation cover. Since wetlands are the largest natural methane source, understanding the process is critical to the future of the methane budget.

There is still significant disagreement about the nature of damages and abatement function. To reduce emissions slightly, one does not need to use the most expensive methods but alternative methods with a negative or low cost. However, in order to reduce emissions completely, we have to consider hard-to-abate emissions: the problem is not to find low-cost possibilities, but to remove emissions at the lowest cost (Hänsel et al., 2020).

As it was mentioned in Section 2, the values of constant elasticity of marginal utility and pure time preference are debatable. We used median values as in DICE-2020; however, Nordhaus calculated it in a different way in Barrage and Nordhaus (2023).

OH concentration in the atmosphere is not considered, however, this oxidation has both an influence on the life expectancy of methane and other adverse effects (damage function). More methane is released, less hydroxide remains in the atmosphere, therefore, methane lifetime expands. These uncertainties complicate rapid global methane emissions changes (Kleinen et al., 2021).

CRediT authorship contribution statement

Sofia Aleshina: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Laura Delgado-Antequera:** Conceptualization, Project administration, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **German Gemar:** Writing – review & editing, Conceptualization, Methodology, Project administration, Supervision, Validation.

Data availability

Data will be made available on request.

Acknowledgments

This research has been funded by: the Andalusian Public Foundation Center for Andalusian Studies (ROR: https://ror.org/05v01tw04 and Crossref Funder ID 100019858), through the project PRY081/22 titled: Seeking sustainability of organizations in strategic sectors: tourism and bioeconomy; and the Spanish Ministerio de Ciencia e Innovación, through the project PID2022-139543OB-C42 named: Metodologías para la búsqueda de soluciones en problemas con criterios económicos, sociales y medioambientales. Una aproximación multicriterio. Funding for open access charge: Universidad de Málaga / CBUA.

References

Barrage, L., Nordhaus, W., 2023. Policies, projections, and the social cost of carbon: Results from the DICE-2023 model. SSRN Electron. J. http://dx.doi.org/10.2139/ssrn.4413849.

Drupp, M., Freeman, M., Groom, B., Nesje, F., 2015. Discounting disentangled. Am. Econ. J. Econ. Policy 10 (109-134), http://www.lse.ac.uk/grantham.

EPA, 2022. Understanding global warming potentials. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.

Feng, J.-C., Yan, J., Wang, Y., Yang, Z., Zhang, S., Liang, S., Li, X.-S., 2022. Methane mitigation: Learning from the natural marine environment. Innovation 3 (5), 100297. http://dx.doi.org/10.1016/j.xinn.2022.100297.

Grubb, M., Wieners, C., Yang, P., 2021. Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation. WIREs Clim. Change 12 (3), http://dx.doi.org/10.1002/wcc.698.

Gupta, S., 2020. Has economics caught up with climate science? Ecol. Econ. Soc. INSEE J. 3 (1), 11–30.

Hänsel, M.C., Drupp, M.A., Johansson, D.J., Nesje, F., Azar, C., Freeman, M.C., Groom, B., Sterner, T., 2020. Climate economics support for the UN climate targets. Nature Clim. Change 10 (8), 781–789. http://dx.doi.org/10.1038/s41558-020-0833-x.

Hart, W.E., Laird, C.D., Watson, J.-P., Woodruff, D.L., Hackebeil, G.A., Nicholson, B.L., Siirola, J.D., 2017. Pyomo — Optimization Modeling in Python. Vol. 67, Springer International Publishing, Cham, http://dx.doi.org/10.1007/978-3-319-58821-6.

Hope, C., Anderson, J., Wenman, P., 1993. Policy analysis of the greenhouse effect. Energy Policy 21 (3), 327–338. http://dx.doi.org/10.1016/0301-4215(93)90253-C.

International Energy Agency, 2022. Global Methane Tracker 2022. Tech. Rep., https://www.iea.org/reports/global-methane-tracker-2022.

IPCC, 2014. Summary for policymakers. In: Climate Change 2013 – the Physical Science Basis. Cambridge University Press, pp. 1–30. http://dx.doi.org/10.1017/CBO9781107415324.004.

IPCC, 2021. In: Masson-Delmotte, V., Zhai, A., Pirani, S., Connors, C., Péan, S., Berger, N., Caud, Y., Chen, L., Goldfarb, M., Gomis, M., Huang, K., Leitzell, E., Lonnoy, J., Matthews, T., Maycock, T., Waterfield, O., Yelekçi, R., Yu, B., Zhou (Eds.), Climate Change 2021: The Physical Science Basis. Cambridge University Press, http://dx.doi.org/10.1017/9781009157896.

Jackson, R.B., Saunois, M., Bousquet, P., Canadell, J.G., Poulter, B., Stavert, A.R., Bergamaschi, P., Niwa, Y., Segers, A., Tsuruta, A., 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. Environ. Res. Lett. 15 (7), 071002. http://dx.doi.org/10.1088/1748-9326/ab9ed2.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J.G., Dlugokencky, E.J., Bergamaschi, P., Bergmann, D., Blake, D.R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E.L., Houweling, S., Josse, B., Fraser, P.J., Krummel, P.B., Lamarque, J.F., Langenfelds, R.L., Le Quéré, C., Naik, V., O'doherty, S., Palmer, P.I., Pison, I., Plummer, D., Poulter, B., Prinn, R.G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D.T., Simpson, I.J., Spahni, R., Steele, L.P., Strode, S.A., Sudo, K., Szopa, S., Van Der Werf, G.R., Voulgarakis, A., Van Weele, M., Weiss, R.F., Williams, J.E., Zeng, G., 2013. Three decades of global methane sources and sinks. Nat. Geosci. 6 (10), 813–823. http://dx.doi.org/10.1038/ngeo1955.

Kleinen, T., Gromov, S., Steil, B., Brovkin, V., 2021. Erratum: Atmospheric methane underestimated in future climate projections. Environ. Res. Lett. 16 (11), http://dx.doi.org/10.1088/1748-9326/ac1814.

Lynch, J., 2019. Availability of disaggregated greenhouse gas emissions from beef cattle production: A systematic review. Environ. Impact Assess. Rev. 76, 69–78. http://dx.doi.org/10.1016/j.eiar.2019.02.003.

Meinshausen, M., Nicholls, Z.R., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J.G., Daniel, J.S., John, A., Krummel, P.B., Luderer, G., Meinshausen, N., Montzka, S.A., Rayner, P.J., Reimann, S., Smith, S.J., Van Den Berg, M., Velders, G.J., Vollmer, M.K., Wang, R.H., 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci. Model Dev. 13 (8), 3571–3605. http://dx.doi.org/10.5194/gmd-13-3571-2020.

Myhre, G., Highwood, E.J., Shine, K.P., Stordal, F., 1998. New estimates of radiative forcing due to well mixed greenhouse gases. Geophys. Res. Lett. 25 (14), 2715–2718. http://dx.doi.org/10.1029/98GL01908.

Nisbet, E.G., Fisher, R.E., Lowry, D., France, J.L., Allen, G., Bakkaloglu, S., Broderick, T.J., 2020. Methane mitigation : Methods to reduce emissions , on the path to the Paris agreement. pp. 1–51. http://dx.doi.org/10.1029/2019RG000675.

NOAA, 2022. Increase in atmospheric methane set another record during 2021. https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021.

Nordhaus, W., 1993. Rolling the 'DICE': an optimal transition path for controlling greenhouse gases. Resour. Energy Econ. 15 (1), 27–50. http://dx.doi.org/10.1016/0928-7655(93)90017-O.

Nordhaus, W., 2017. Revisiting the social cost of carbon. Proc. Natl. Acad. Sci. 114 (7), 1518–1523. http://dx.doi.org/10.1073/pnas.1609244114.

Nordhaus, W., 2018. Projections and uncertainties about climate change in an era of minimal climate policies. Am. Econ. J.: Econ. Policy 10 (3), 333–360. http://dx.doi.org/10.1257/pol.20170046.

Nordhaus, W., Yang, Z., 1996. A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies. Tech. Rep. No. 4.

Peretto, P.F., Valente, S., 2015. Growth on a finite planet: resources, technology and population in the long run. J. Econ. Growth 20 (3), 305–331. http://dx.doi.org/10.1007/s10887-015-9118-z.

Prather, M.J., Holmes, C.D., Hsu, J., 2012. Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry. Geophys. Res. Lett. 39 (9), http://dx.doi.org/10.1029/2012GL051440.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environ. Change 42, 153–168. http://dx.doi.org/10.1016/j.gloenvcha.2016.05.009.

Saunois, M., Stavert, A.R., Poulter, B., Bousquet, P., Canadell, J.G., Jackson, R.B., Raymond, P.A., Dlugokencky, E.J., Houweling, S., Patra, P.K., Ciais, P., Arora, V.K., Bastviken, D., Bergamaschi, P., Blake, D.R., Brailsford, G., Bruhwiler, L., Carlson, K.M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P.M., Covey, K., Curry, C.L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M.I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K.M., Joos, F., Kleinen, T., Krummel, P.B., Langenfelds, R.L., Laruelle, G.G., Liu, L., Machida, T., Maksyutov, S., McDonald, K.C., McNorton, J., Miller, P.A., Melton, J.R., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R.J., Peng, C., Peng, S., Peters, G.P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W.J., Rosentreter, J.A., Segers, A., Simpson, I.J., Shi, H., Smith, S.J., Steele, L.P., Thornton, B.F., Tian, H., Tohjima, Y., Tubiello, F.N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T.S., van Weele, M., van der Werf, G.R., Weiss, R.F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., Zhuang, Q., 2020. The global methane budget 2000–2017. Earth Syst. Sci. Data 12 (3), 1561–1623. http://dx.doi.org/10.5194/essd-12-1561-2020.

Shindell, D., Ravishankara, A., Kuylenstierna, J., Michalopoulou, E., Höglund-Isaksson, L., Zhang, Y., Seltzer, K., Ru, M., Castelino, R., Faluvegi, G., Naik, V., Horowitz, L., He, J., Lamarque, J.-F., Sudo, K., Collins, W., Malley, C., Harmsen, M., Stark, K., Junkin, J., Li, G., Glick, A., Borgford-Parnell, N., 2021. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Tech. Rep., https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions.

Smith, C.J., Forster, P.M., Allen, M., Leach, N., Millar, R.J., Passerello, G.A., Regayre, L.A., 2018. FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. Geosci. Model Dev. 11 (6), 2273–2297. http://dx.doi.org/10.5194/gmd-11-2273-2018.

Tol, R.S., 1997. On the optimal control of carbon dioxide emissions: An application of FUND. Environ. Model. Assess. 2 (3), 151–163. http://dx.doi.org/10.1023/A:1019017529030.

Turetsky, M.R., Abbott, B.W., Jones, M.C., Walter Anthony, K., Olefeldt, D., Schuur, E.A.G., Koven, C., McGuire, A.D., Grosse, G., Kuhry, P., Hugelius, G., Lawrence, D.M., Gibson, C., Sannel, A.B.K., 2019. Permafrost collapse is accelerating carbon release. Nature 569 (7754), 32–34. http://dx.doi.org/10.1038/d41586-019-01313-4.

UNEP, 2021. Global Methane Assessment. Benefits and Costs of Mitigating Methane Emissions.

US Department of States, 2022. U.S.-EU joint press release on the global methane pledge energy pathway. https://www.state.gov/u-s-eu-joint-press-release-on-the-global-methane-pledge-energy-pathway/.

Yang, P., Mi, Z., Coffman, D.M., Cao, Y.F., Yao, Y.F., Li, J., 2021a. The impact of climate risk valuation on the regional mitigation strategies. J. Clean. Prod. 313, 127786. http://dx.doi.org/10.1016/J.JCLEPRO.2021.127786.

Yang, P., Mi, Z., Wei, Y.M., Hanssen, S.V., Liu, L.C., Coffman, D., Sun, X., Liao, H., Yao, Y.F., Kang, J.N., Wang, P.T., Davis, S.J., 2023. The global mismatch between equitable carbon dioxide removal liability and capacity. Natl. Sci. Rev. 10 (12), http://dx.doi.org/10.1093/nsr/nwad254.

Yang, P., Mi, Z., Yao, Y.F., Cao, Y.F., Coffman, D.M., Liu, L.C., 2021b. Solely economic mitigation strategy suggests upward revision of nationally determined contributions. One Earth 4 (8), 1150–1162. http://dx.doi.org/10.1016/j.oneear.2021.07.005.

Yang, P., Yao, Y.F., Mi, Z., Cao, Y.F., Liao, H., Yu, B.Y., Liang, Q.M., Coffman, D.M., Wei, Y.M., 2018. Social cost of carbon under shared socioeconomic pathways. Global Environ. Change 53, 225–232. http://dx.doi.org/10.1016/J.GLOENVCHA.2018.10.001.