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Analysis of the economic and environmental impacts of climate change using RICE model adjusted by methane

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Abstract

This work presents a modified version of the integrated economic-climate model RICE-CH_4. The aim of the work was to expand the basic RICE model by explicitly accounting for methane (CH_4) emissions along with traditional carbon dioxide (CO_2) emissions, as well as the subsequent analysis of the economic and climatic effects of implementing various emissions control strategies. The development was based on the open implementation of RICE in Python using the Pyomo library and the IPOPT solver. The model was modified as follows: a separate methane cycle block was implemented, including both industrial and natural CH_4 emissions; the radiative forcing function was adapted taking into account the contribution of methane; a new control variable was built in to reduce CH_4 emissions; the logic of two climate policy scenarios, cooperative and non-cooperative, was implemented. In addition, parameterization and aggregation of input data for 12 regions were conducted based on open sources. The model covers key blocks of integrated assessment: the dynamics of capital, investment, savings, production, consumption, and emissions, as well as climate indicators—greenhouse gas concentrations, atmospheric and ocean temperatures, radiative forcing, and climate change damage. Simulations were conducted for the 2025–2115 horizon, and the objective function indicators were calculated. The resulting RICE-CH_4 model can be used as a tool for quantitative analysis of climate policy, assessing the social cost of emissions, and sustainable development strategies in a regional representation of global data. A flexible implementation structure provides the potential for future expansion of the model: adding new types of emissions, complicating the country interaction block, and integrating it with external risk and resilience assessment modules.

Keywords: climate change, global warming, methane emissions, RICE model

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1. Introduction

The problem of climate change remains one of the most significant global challenges of the 21st century, affecting both environmental and socio-economic systems. Rapid growth of the global economy, accompanied by increased energy use and resource intensity of production, leads to a steady increase in greenhouse gas emissions, primarily CO_2 and CH_4. These processes create long-term risks for sustainable development, including rising temperatures, changing precipitation, degradation of ecosystems, and reduced agricultural productivity. Integrated assessment models (IAMs) explore possible development trajectories that balance economic goals and climate constraints, combining macroeconomic dynamics, carbon and climate cycles, as well as decision-making mechanisms on climate policy in a single numerical structure.

One of the main integrated assessment models (IAM) is the DICE model (W. Nordhaus, 1993.)[1] It evaluates optimal climate policy over sets of many parameter values. The DICE model has been widely used, including in the reports of *Intergovernmental Panel on Climate Change (IPCC)*, IPCC, 2021) and is very influential, partly because it has been updated several times and the details of the model are accessible and public. It integrates modern economic growth, the carbon cycle, climate change, its impacts, and action to curb climate change. Its creator, William Nordhaus, won the Nobel Prize for this model because it integrates climate science and economics. Recently, DICE-2023 was announced by its creator, Barrage and Nordhaus, 2023. DICE-1992 (Peck and Teisberg, 1992, W. D. Nordhaus, 1992) was among the first to formulate the problem of optimal management of economic development in the light of climate change, proposing to numerically determine such a trajectory of emission reductions that maximizes aggregate welfare in the context of global warming. However, the classical version of DICE treats the world as a single, homogeneous macroeconomic system, ignoring structural differences between countries.

Unlike the DICE model, which aggregates the entire global economy into a single whole, the RICE model is decentralized W. Nordhaus and Yang, 1996. Each region has its own parameters and variables: population, GDP, capital stock, total factor productivity, emissions, abatement

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

costs, and warming damages. Regions are linked through a common climate—the combined global emissions of CO_2 and CH_4 determine the change in global temperature, which then affects the economy of each region. Thus, RICE allows us to analyze the strategic interaction of regions by modeling:

- *a cooperative regime*, when all regions jointly optimize global welfare and coordinate emission reductions;
- *a non-cooperative regime*, when each region acts in its own interests, without regard to the effect of its emissions on other countries.

This approach makes the model especially valuable for studying the collective action dilemma in international climate policy. RICE allows us to assess regional winners and losers of global cooperation, and the importance of the mechanisms for distributing benefits and costs.

The original version of RICE W. Nordhaus and Yang, 1996 includes 6 regions. In subsequent extensions, the number of regions increased to 12, as in the RICE-2020 model (Rogna and Vogt, 2022). In addition, there is a version RICE-50+ Gazzotti et al., 2021, which works with 50 or more regions, while maintaining the structure of the original model. In RICE-CH_4 12 main regions are used but model can be extended.

To account for geo-economic heterogeneity, RICE (Regional Integrated Climate-Economy model) is a variation of DICE and can be used to investigate methane emissions in a specific area to find appropriate measures for this region to address it (W. Nordhaus and Yang, 1996) and allows modeling the interaction between countries with different demographic, technological, and climatic characteristics. Although both models are widely used in scientific and policy practice, they have long considered only carbon dioxide (CO_2) emissions, while methane (CH_4), the second most important greenhouse gas, has either been excluded from the analysis or accounted for as an exogenous component. This limitation reduces the credibility of climate policy scenarios, especially in the short and medium term, where the influence of methane can be decisive. Per molecule, methane has a much larger warming effect than carbon dioxide, but it degrades from the atmosphere much more quickly.

An increase in the concentration of either greenhouse gas has a negative impact on future economic production, due to its influence on global mean surface temperature. The fraction of lost production in each time period is captured through a damage function. If a portion of economic output (abatement costs) is sacrificed for the reduction of GHGs, future temperature increases and associated climate damage could be partially avoided.

The idea is to invest part of economic output in creating capital for the next period of time, while the remaining part is consumed. It is assumed that the utility of the population depends on consumption. The assumed social planner maximizes total utility.

In previous versions of the RICE model, methane emissions were not included as an endogenous variable (the DICE model extended by methane can be found in Aleshina et al., 2024). However, this should be considered, as these methane 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.

Therefore, the inclusion of methane in integrated assessment models is vital to understand policies to combat global warming. The main objective of this work is to show the importance of estimating methane emissions. The standard RICE framework is complemented by the dynamics of the methane cycle, including both managed (industrial) and exogenous (natural) emission sources. Methane is integrated not only into the climate module (via concentration and radiative forcing), but also into the optimization loop, which allows us to consider the costs and benefits of CH_4 emission reduction policies. The model demonstrates that reducing anthropogenic methane emissions in the coming decades can substantially affect global temperature dynamics and increase the feasibility of climate targets. For this purpose, in this work, methane is considered as a variable to be included in the RICE model in what will be called the *methane cycle*. To achieve the results, quantitative data on methane emissions, concentrations, and radiative forcing were collected and analyzed.

The extended RICE model retains an aggregate approach to the economy, treating the world as a single decision-making entity. It focuses 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. This level of abstraction prevents taking into account key differences between countries, both in the level of development and emissions patterns, sensitivity to climate risks and willingness to implement climate policies. This is particularly important in the context of methane, as the contribution to its emissions and the potential to reduce them vary considerably across regions, from agriculture and wetland ecosystems in developing countries to leakages in the fuel and energy complex of industrialized economies. This raises the need for a regionalized model that accounts for both global impacts and the differential economic impacts of climate policy for individual macro-regions. The extension of the RICE model, which combines the regional structure of the RICE model and the approach to accounting for methane emissions implemented in RICE, makes it possible to fill this gap and form the basis for analyzing cooperative and non-cooperative scenarios of climate interaction, taking into account short-lived greenhouse gases.

The paper proceeds as follows. First, the methodology of RICE-CH_4 model is described, followed by the results of the main variables of the model. At the end, the RICE limitations and future steps are discussed.

2. RICE model

2.1. Mathematical part

Let $\mathcal{M}$ be a finite set of regions, and let $t = \overline{1, T}$ be discrete time corresponding to the years $\{2015,\ 2025,\ 2035,\ ..., 2005 + 10 \cdot T\}$.

Objective function. In the general case, one solves the conditional problem of maximizing *total* welfare, namely,

$$\sum_{m \in \mathcal{M}} \sum_{t=1}^{T} U_{m,t} \longrightarrow \max_{\mu_{m,t}, S_{m,t}} . \tag{1}$$

The summand $U_{m,t}$ symbolizes the welfare of region m at time t and is expressed as

$$U_{m,t} = \frac{L_{m,t}}{(1 + \rho_m)^{10 \cdot t}} \cdot \left[\frac{1}{1 - \alpha_m} \left(\frac{C_{m,t}}{L_{m,t}} \right)^{1 - \alpha_m} + 1 \right], \tag{2}$$

where $L_{m,t}$ denotes the population in region m at time t and reflects both labor force and consumer demand. The quantity $C_{m,t}$ represents the total consumption in the corresponding region and point in time, which is interpreted as the final amount of resources directed to meet the current needs of the population. The parameter ρ_m defines the norm of time preference of the region m and determines the degree of discounting of future utility: the higher the value of ρ_m, the less significant for the region the remote benefits in time become. In turn, α_m describes the degree of curvature of the utility function, i.e. characterizes the propensity to intertemporal substitution: the higher α_m is, the more (less) sensitive the region is to fluctuations in consumption at low (high) levels of consumption.

The standard RICE model optimizes two key sets of control variables for each region m and time t: $\mu_{m,t}$ and $S_{m,t}$. The variable $\mu_{m,t}$ determines the fraction of carbon dioxide emissions that will be reduced by the GDP allocation, ranging from 0 (no climate policy) to 1 (full coverage; some implementations allow a maximum of 1.2). Similar to the CO_2 situation, the extended model includes a third set of control variables $\mu_{m,t}^{CH_4}$ that defines the same variables for methane emissions. The variable $S_{m,t}$ specifies the savings rate, that is, the fraction of net output devoted to capital investment and future consumption. All variables are bounded by the interval from zero to one:

$$\begin{cases} 0 \leq \mu_{m,t} \leq 1.2 \\ 0 \leq \mu_{m,t}^{CH_4} \leq 1 \\ 0 \leq S_{m,t} \leq 1. \end{cases} \tag{3}$$

All control variables enter the target function implicitly: they affect consumption $C_{m,t}$, capital $K_{m,t}$ and net output $Y_{m,t}$, which in turn determine utility $U_{m,t}$.

CO_2 concentration in the atmosphere. The mass of carbon in the atmosphere accumulates according to the equation:

$$M_{at,t} = M_{at,t-1} \cdot b_{11} + \Delta t \cdot E_{\text{tot},t-1}^{CO_2}, \tag{4}$$

where b_{11} is a coefficient reflecting the degree of carbon retention in the atmosphere.

CH_4 concentration in the atmosphere. A similar equation with a different natural decay coefficient applies to methane:

$$M_t^{CH_4} = M_{t-1}^{CH_4} \cdot b_{11}^{CH_4} + \Delta t \cdot E_{\text{tot},t-1}^{CH_4}, \tag{5}$$

where the coefficient $b_{11}^{CH_4}$, similar to carbon dioxide, reflects the lifetime of the CH_4 molecule.

Industrial CO_2 emissions. The carbon dioxide emissions in region m at time t are determined by the following formula:

$$E_{m,t}^{CO_2} = \sigma_{m,t} \cdot (1 - \mu_{m,t}) \cdot Q_{m,t}, \tag{6}$$

where $\sigma_{m,t}$ is the intensity of CO_2 emissions per unit of output. The control value $\mu_{m,t}$ reduces the volume of emissions, while maintaining the residual $1 - \mu_{m,t}$.

Industrial CH_4 emissions. The control of methane emissions in the model is implemented as a function of the main variable $\mu_{m,t}$, which determines the level of climate policy. However, unlike CO_2, for CH_4 different possible approximations are used. In practice, two approaches are used; hard and smooth approximation, in previous work (Aleshina et al., 2024) hard one was applied, in this work it is expanded, meaning, methane and carbon dioxide are independent.

Smooth approximation:

$$\mu_{m,t}^{CH_4} = \frac{1 - e^{-0.314 \cdot \mu_{m,t}}}{0.314}, \tag{7}$$

where the coefficient 0.314 is chosen so that for $\mu_{m,t} = 1.2$ getting $\mu_{m,t}^{CH_4} \approx 1$. This form ensures the smoothness of the function.

Using the value of $\mu_{m,t}^{CH_4}$, industrial methane emissions are calculated using the formula:

$$E_{m,t}^{CH_4} = \sigma_{m,t}^{CH_4} \cdot (1 - \mu_{m,t}^{CH_4}) \cdot Q_{m,t}, \tag{8}$$

where $\sigma_{m,t}^{CH_4}$ is the intensity of methane emissions per unit of output.

Natural CH_4 emissions.

The model takes into account exogenous greenhouse gas emissions that are unchanged by the optimization process, denoted as *natural emissions*. These emissions reflect the contribution of natural sources and land use. Natural emissions vary between SSP scenarios.

Natural emissions are represented by two types:

- $E_{m,t}^{\text{land}}$ —natural emissions of carbon dioxide (CO_2) by region and year;
- $E_{m,t}^{CH_4,\text{land}}$ —natural emissions of methane (CH_4) by region and year.

Initially, the aggregated values were set equal to the multi-regional RICE model, which includes disaggregation of data by region. Trajectories were then recalculated to take account of the time step of the model. The values are specified as time series and do not depend on the control parameters.

Total emissions. Total global emissions of CO_2 and CH_4 include contributions from industry and land use:

$$E_{\text{tot},t}^{CO_2} = \sum_{m\in\mathcal{M}} \left(E_{m,t}^{CO_2} + E_{m,t}^{\text{land}}\right), \tag{9}$$

$$E_{\text{tot},t}^{CH_4} = \sum_{m\in\mathcal{M}} \left(E_{m,t}^{CH_4} + E_{m,t}^{CH_4,\text{land}}\right). \tag{10}$$

2.2. Cooperative/non-cooperative scenarios

The model can be solved in two fundamentally different ways: full cooperation of all regions and full non-cooperation. These modes differ in the formulation of the optimization problem and the interpretation of decision-making.

Cooperative mode. In the cooperative scenario, all regions act in a coordinated manner, as a single whole, and strive to maximize the total welfare of humanity. The optimization problem has the form:

$$\sum_{m\in\mathcal{M}} \sum_{t=1}^{T} U_{m,t} \longrightarrow \max_{\mu_{m,t},\, S_{m,t}}, \tag{11}$$

where maximization is performed simultaneously for all control variables of all regions. Thus, a set of strategies is selected that provides the best overall result for the entire system. In this case, decisions made in one region take into account their consequences for others. This regime corresponds to ideal global coordination of climate policy. Since the decision in the cooperative regime is determined simultaneously, the problem is formulated as a classical optimal control problem with complete information.

Non-cooperative regime. In contrast to the previous one, the non-cooperative regime describes a situation in which each region acts independently and is guided solely by its own interests. In this case, each region m solves its own problem:

$$\sum_{t=1}^{T} U_{m,t} \longrightarrow \max_{\mu_{m,t}, S_{m,t}}, \tag{12}$$

assuming that the strategies of all other regions are given and unchanged. The solution process is iterative: at each step, each region revises its strategies, assuming that the strategies of the others are fixed. Sequential updating continues until the strategies stabilize and convergence is reached. Note that convergence is not guaranteed in general; in our case, however, the solution quickly converges.

Between cooperation and non-cooperation, there is partial cooperation. This is typically studied with d'Aspremont cartels (Aspremont et al., 1983, Barrett, 1994). We do not consider this here. Neither do we consider side payments to stabilize the grand coalition Chander and Tulkens, 1995.

3. Results and discussion

The results of RICE adjusted for methane are presented below. Outcomes are shown for the period 2025-2115.

3.1. Atmospheric temperature

The global mean atmospheric temperature is one of the key output indicators of integrated assessment models (IAM). The variable $T_{at,t}$ reflects the deviation of temperature from the pre-industrial level in degrees Celsius.

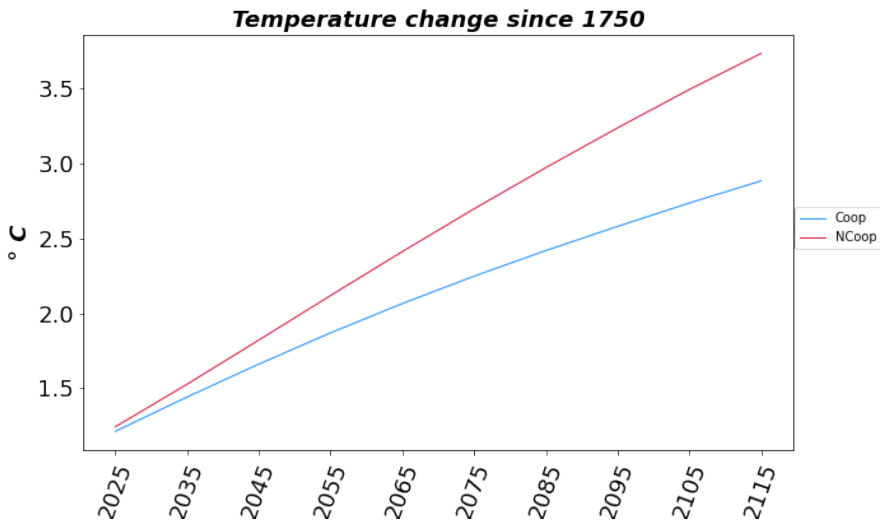


Figure 1: Dynamics of the global average atmospheric temperature in the cooperative and non-cooperative regimes in 2025-2115 of the original RICE model.

Fig 1 shows that the temperature in the cooperative scenario exceeds 2.5 °C by 2115 while without cooperation it is over 3.0 °C.

Fig. 2 presents the trajectories of change in $T_{at,t}$ in the cooperative and non-cooperative modes of operation of the RICE-CH_4 model. The abscissa axis shows the forecast time, and the ordinate axis shows the temperature in degrees Celsius.

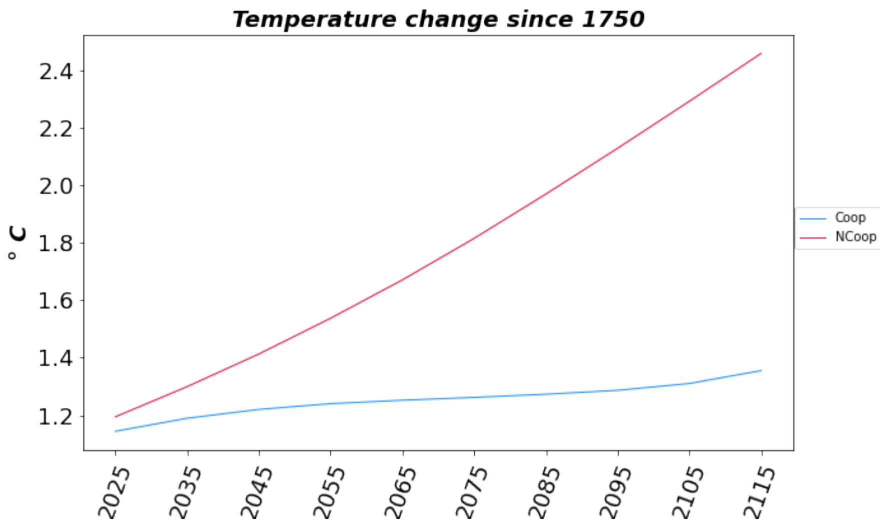


Figure 2: Dynamics of the global average atmospheric temperature in the cooperative and non-cooperative regimes in 2025-2115 of RICE-CH_4 model.

Cooperative regime. In the global cooperation scenario, temperature growth slows down by the middle of the 21st century and stabilizes at a level of about 1.3 °C by 2115, which indicates the effect of climate inertia with a complete or almost complete reduction in emissions. The temperature dynamics in this scenario correspond to the climate containment policy aimed at implementing the goals set out in international agreements. It also shows that including methane is beneficial in this scenario.

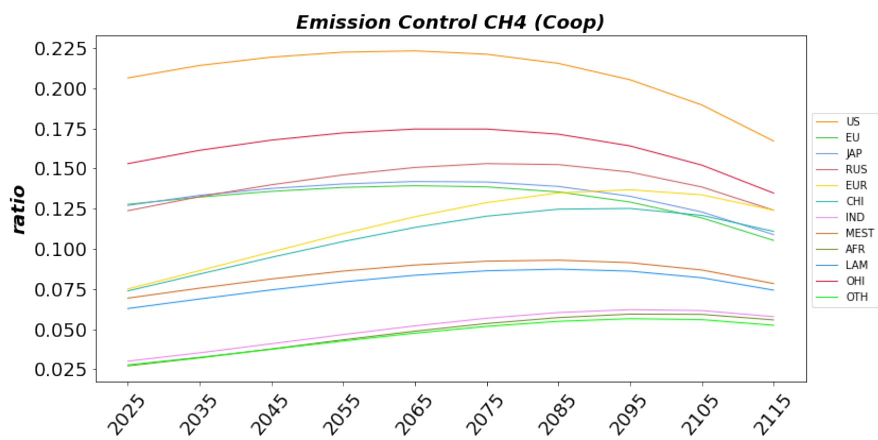
Non-cooperative regime. Without cooperation between regions, the temperature shows a steady upward trajectory and reaches a value about 2.5 °C by the end of the forecast period. Including methane in the model makes this scenario looks worse, as countries cooperate on neither carbon nor methane. Such values substantially exceed the agreed levels set out in the *Paris Agreement* (2015), in which the parties undertake to "hold the increase in average global temperature to well below 2 °C above pre-industrial levels and to make efforts to limit the increase to 1.5 °C".

Going beyond 2 °C, as observed in the non-cooperative trajectory, is associated with a high probability of irreversible changes in ecosystems and degradation of climate resilienceIPCC, 2014. In this context, the model confirms the need for and effectiveness of globally coordinated measures.

3.2. Methane

Methane (CH_4) is the second most important greenhouse gas after carbon dioxide, with much higher near-term warming. The control variable $\mu_{CH4,t}$ reflects the fraction of industrial methane emissions subject to reduction and takes values from 0 (no reduction) to 1 (complete elimination of emissions).

Fig. 3 shows the trajectories of the variable $\mu_{CH4,t}$ for all regions of the model. In all cases, there is a significant difference between the regimes: the cooperative scenario generally assumes a higher level of methane reduction.



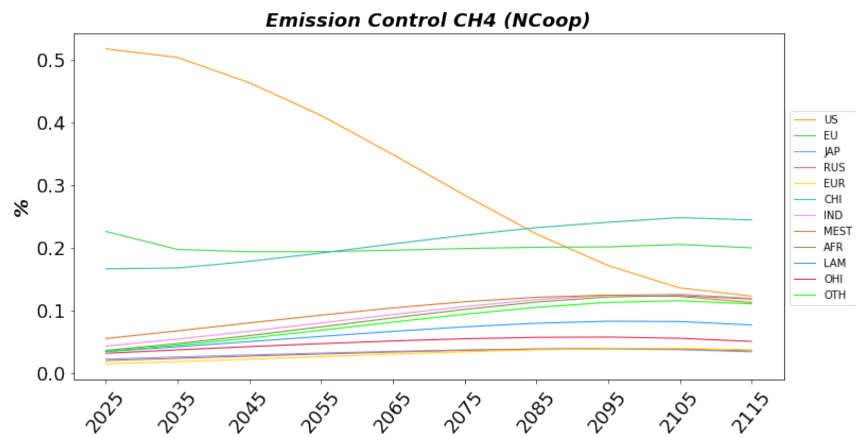
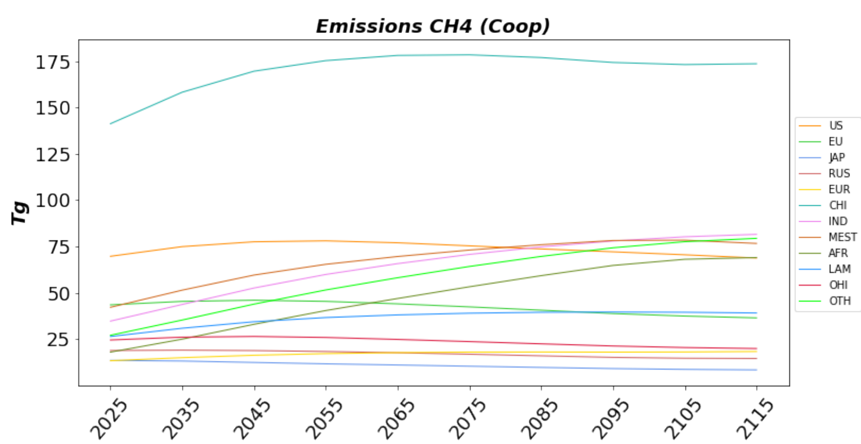


Figure 3: Dynamics of CH_4 control by region: cooperative and non-cooperative scenarios.

The emissions control value in most countries guarantees the reduced value of methane emissions, which can be seen in the next Figure 4, meaning, emission control in other countries reduces the value of domestic emission control. The most significant change can be seen for China.



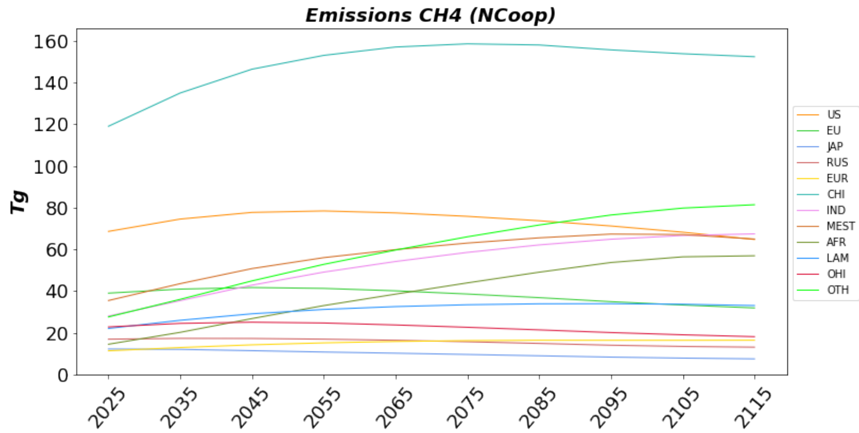


Figure 4: Industrial methane emissions in cooperative and non-cooperative scenarios.

A key output of the model is the social cost of methane, which represents the marginal damage caused by emitting methane in cooperative and non-cooperative scenarios. Figure 5 shows the Social Cost of Methane (SC-CH_4): in either case, it increases over time. Moreover, in a non-cooperative scenario, each region acts based on its own self-interest, with no shared burden or transfer of benefits. This results in higher regional costs due to less effective global mitigation. However, it also leads underpricing of methane relative to global optimum. All regional values increase steadily over time. That indicates that the marginal damage of methane emissions rises, due to cumulative warming effects and greater vulnerability to climate impacts. US has the highest social cost over the period due to rich economy and large population.

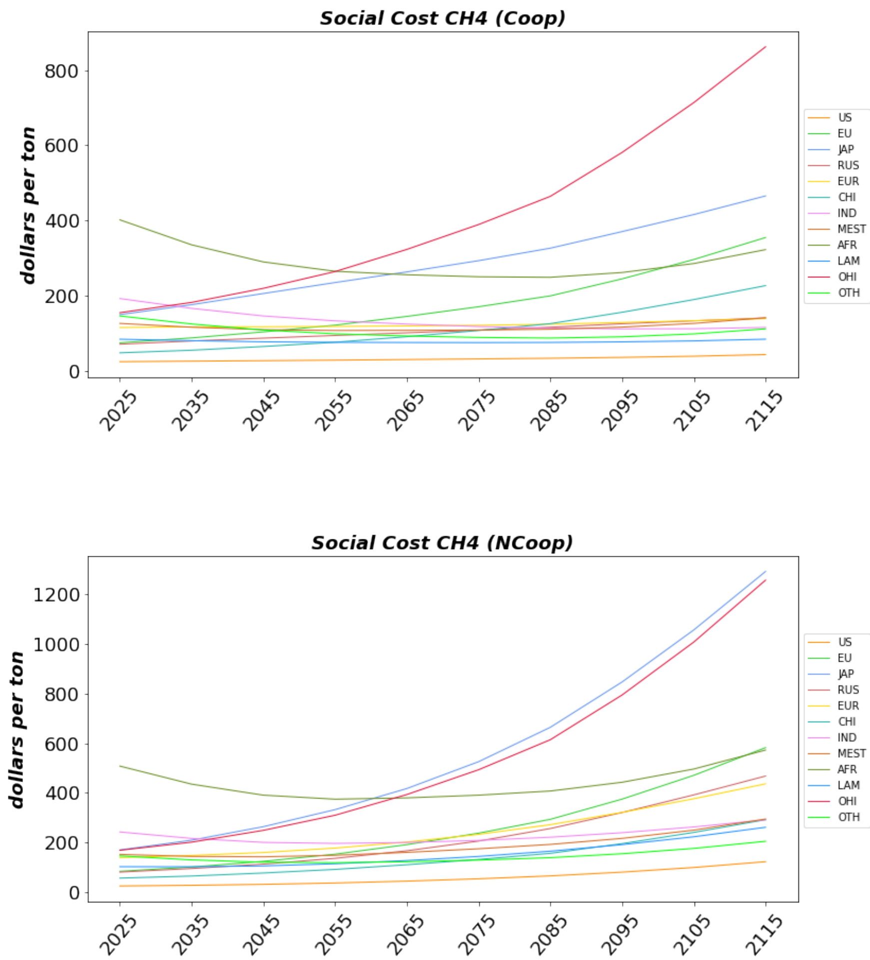


Figure 5: Social cost of methane by regions in cooperative and non-cooperative scenarios.

3.3. Damages

Economic damage from climate change is reflected by the variable $D_{m,t}$, which is interpreted as the share of the loss of gross output in region m at time t caused by an increase in global temperature. As can be seen from the expression for damage (Eq. A.8), $D_{m,t}$ is given as a function of the atmospheric temperature $T_{at,t}$ and can include both quadratic and power-law components. The absolute monetary equivalent of damage is defined as:

$$\text{DamageCost}_{m,t} = \frac{D_{m,t}}{1 + D_{m,t}^{\Delta t}} \cdot Q_{m,t}, \tag{13}$$

where $Q_{m,t}$ is the gross output, and $\Delta t = 10$ is the time step. This indicator is involved in the net output equation (Eq. A.4), thereby determining the direct monetary damage from climate change.

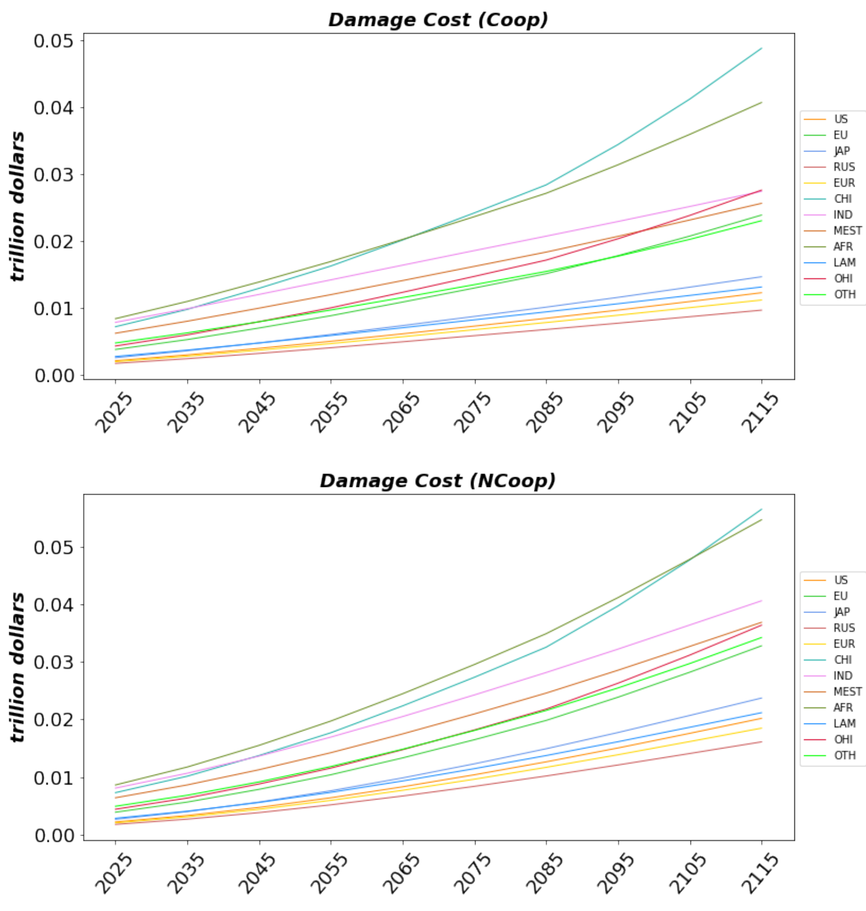


Figure 6: Damage costs values in the cooperative and non-cooperative regimes in 2025-2115 in original RICE model.

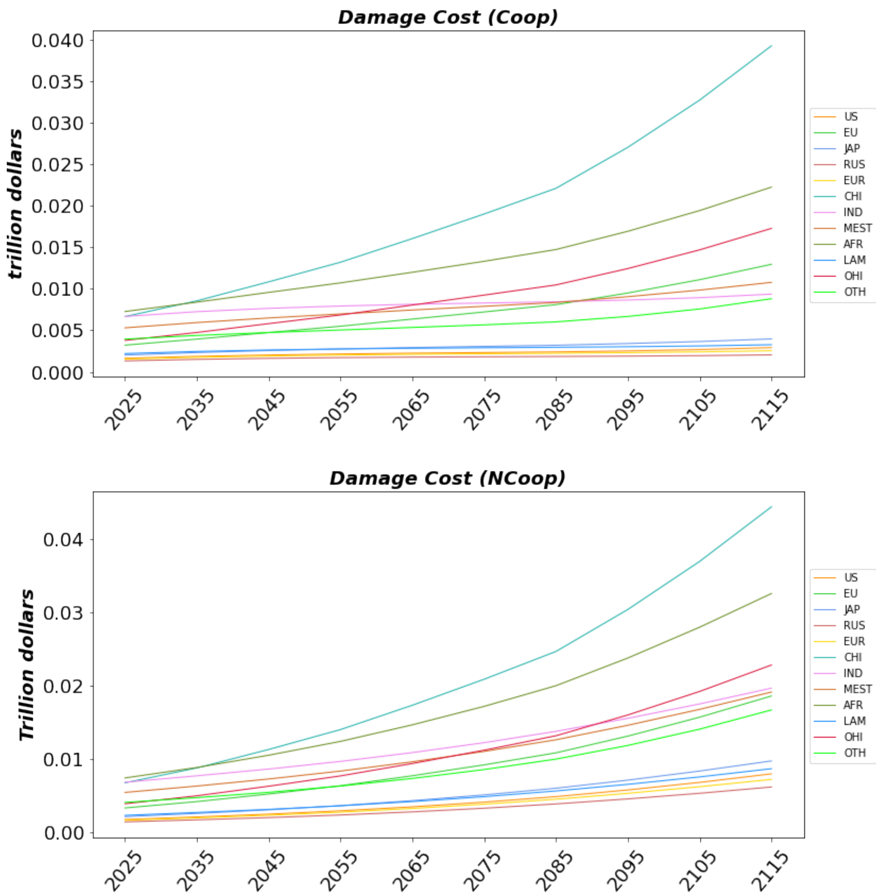


Figure 7: Damage costs values in the cooperative and non-cooperative regimes in 2025-2115.

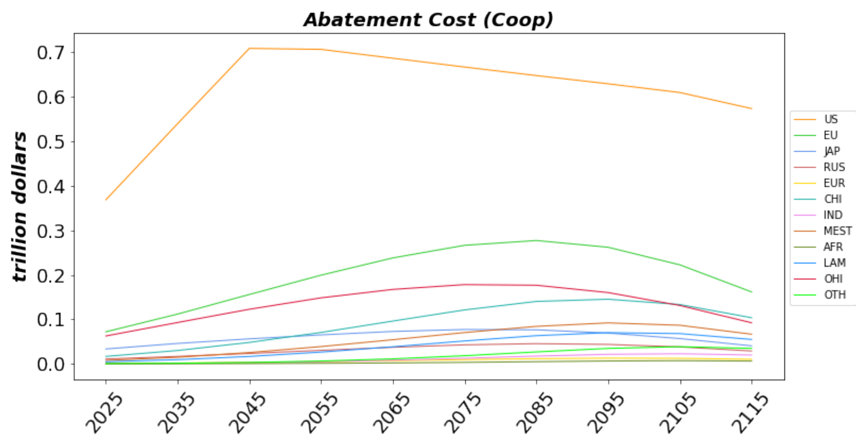
The main trend remains the same for both scenarios, however, it is necessary to pay attention to the numerical values and different approach of countries like China.

3.4. Abatement cost

The parameter $AB_{m,t}$ describes the share of gross output $Q_{m,t}$ that is lost as a result of climate policy in region m at time t. This value reflects the economic price of measures to reduce greenhouse gas emissions—switching to low-carbon technologies, improving energy efficiency, introducing carbon capture and sequestration, changing the production structure, and other measures.

In the model, costs are defined as a function of the climate policy level $\mu_{m,t}$ (CO_2 component) (A.7).

Similar to climate change damage, the monetary equivalent of the cost of reducing emissions enters into the net output equation $Y_{m,t}$ as a fraction of $Q_{m,t}$:



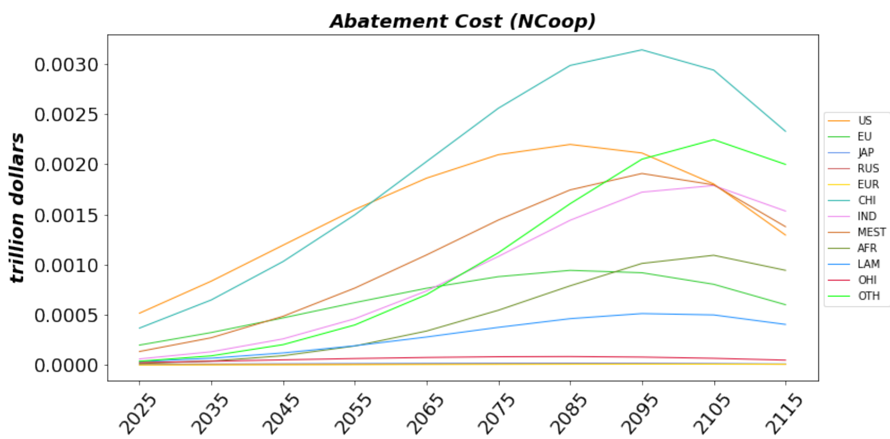


Figure 8: Abatement costs values in the cooperative and non-cooperative regimes in 2025-2115 in original RICE model.

Looking at the trends, the values in the cooperative scenario stabilize over time, whereas in the non-cooperative case abatement costs tend to increase. Figure 9 below shows the values of the abatement costs after including the methane. Apart from the significant change in values there is a declining trend in cooperative case vs. close to zero values in non-cooperative scenario.

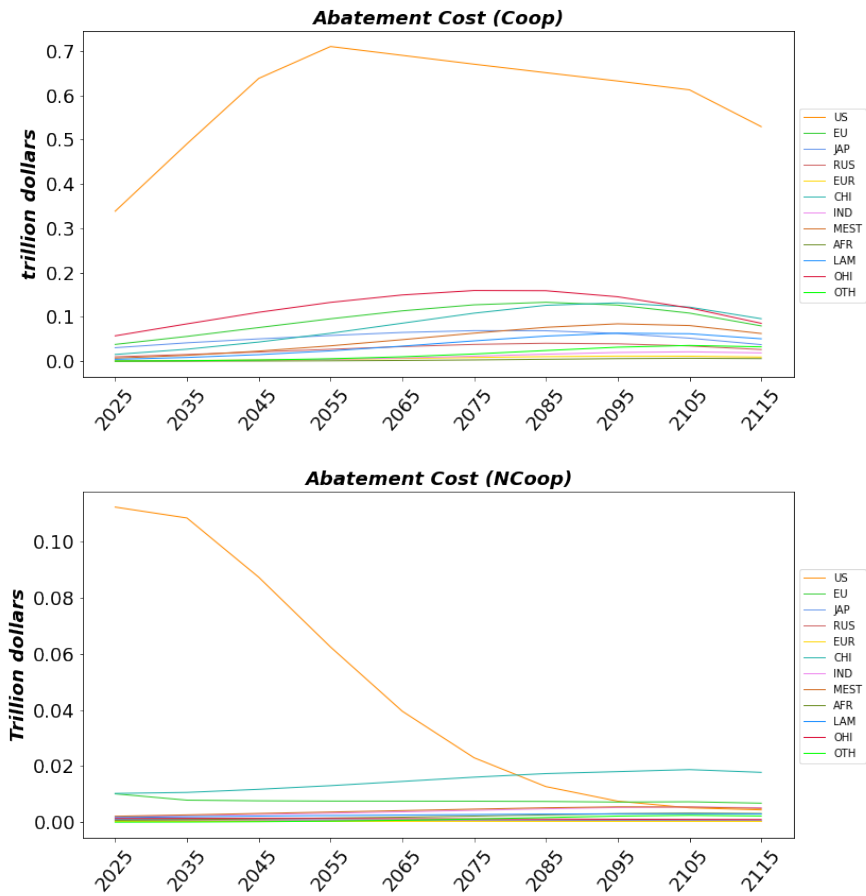


Figure 9: Abatement costs in the cooperative and non-cooperative regimes in 2025-2115 in RICE-CH_4 model.

The cost of reducing methane emissions is closely related to the technologies and strategies used for abatement. Some methods may be more cost-effective than others. 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 (EPA, 2022, IEA, 2025). Methane abatement costs are calibrated using bottom-up engineering data, sector-specific technology assessments, observed adoption behavior, and empirical cost studies.

3.5. Output

The variable $Y_{m,t}$ represents the net economic output of region m at time t, taking into account climate costs and the costs of implementing environmental policy. Unlike gross output $Q_{m,t}$, this indicator reflects the portion of output that remains after subtracting economic losses associated with climate change damage and the costs of reducing emissions.

For most of the economic values, it is hard to see the difference due to scale; that is, neither climate change nor climate policy dominates economic growth. Therefore, the graphs below show the original output in the cooperative scenario, the difference between the cooperative and non-cooperative scenarios in the original RICE model, followed by output difference between the RICE-CH_4 model and the version without methane controls.

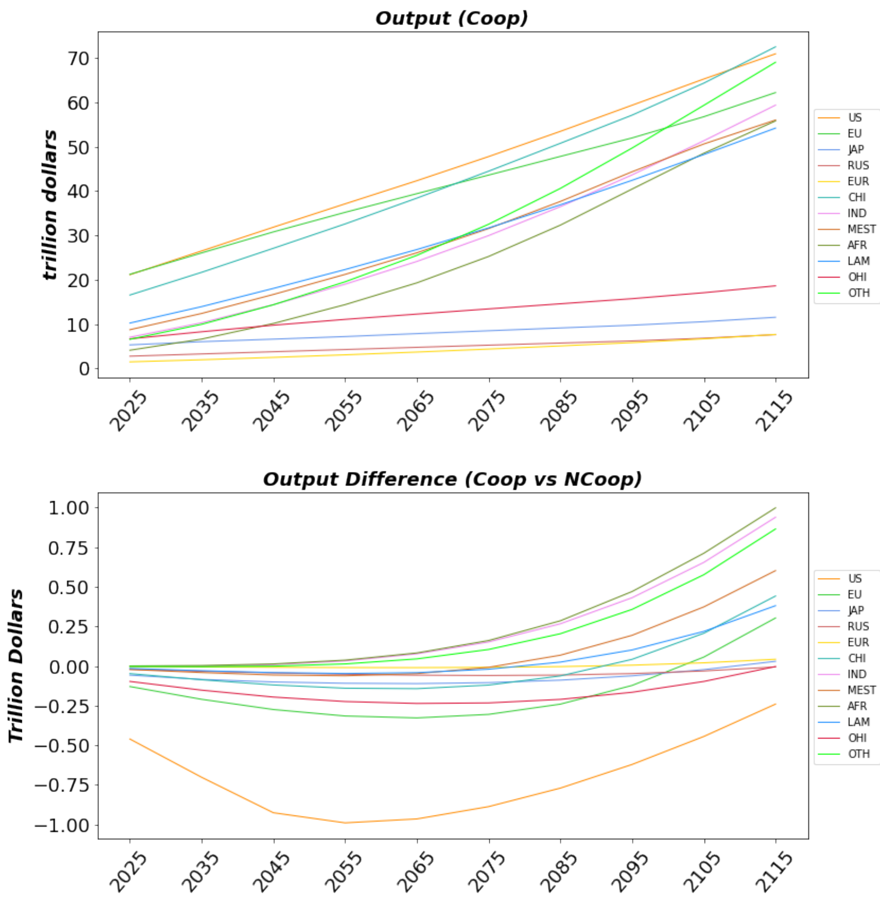


Figure 10: Output by regions in the cooperative scenario and the difference between the non-cooperative scenarios and cooperative scenarios in the original RICE model.

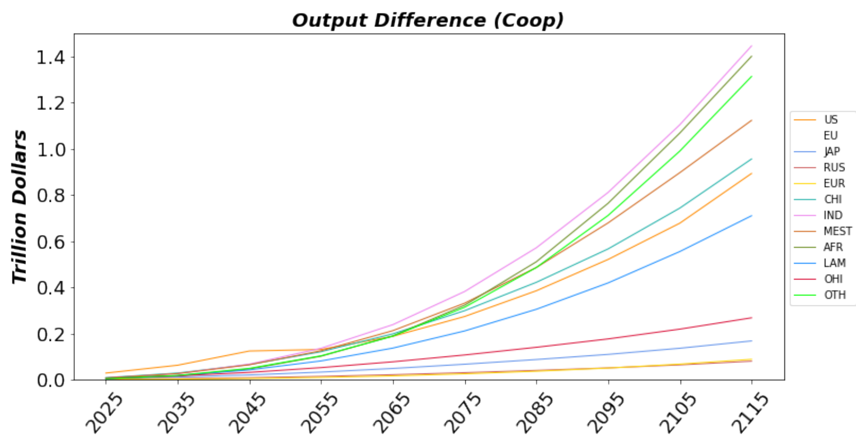


Figure 11: Output difference between RICE-CH_4 and original RICE model in the cooperative scenario.

Thus, the observed change in the dynamics of $Y_{m,t}$ reflects the long-term effectiveness of climate policy: despite the initial economic costs in the form of high $AB_{m,t}$ values, the cooperative trajectory ultimately ensures more sustainable growth in net output by limiting damage. It is worth noting that, despite the small relative differences in the scale of the graphs, the actual monetary values differ by millions of dollars.

The same trends are observed for the other economic variables: capital, investment, and consumption. In the simplest static game possible (see Appendix B), the difference between the cooperative optimum and the non-cooperative Nash equilibrium grows if a second greenhouse gas is added, and if the synergistic effect of the two gases on climate change and its impacts is larger. That is, international cooperation is more difficult with multiple greenhouse gases.

4. Limitations

The constructed RICE models are extensions of the original integrated assessment model with the inclusion of methane (CH_4) as the second key greenhouse gas. However, this modification opens up a wide range of directions for further development of the model, both in theoretical and applied aspects.

Firstly, an important direction is the expansion of the spectrum of greenhouse gases. In addition to CO_2 and CH_4, nitrous oxide (N_2O), and other long-lived gases also make a significant contribution to the radiative forcing. Their inclusion in the model will require an appropriate description of emission trajectories, mechanisms of impact on the climate system, and an assessment of management capabilities. Such a modification would increase the reliability of the model and bring it closer to a structure with full control over any types of emissions.

Secondly, an important direction is a detailed representation of natural methane emissions. In the current implementation, exogenous emissions from wetlands, permafrost, and other natural sources are specified based on scenario SSP trajectories. However, the potential for positive climate backstops, such as permafrost thawing or degradation, requires a dynamic endogenous model of natural emissions that is sensitive to temperature, soil moisture, and other climate parameters. Implementation of such a mechanism would allow a more accurate assessment of the risks of self-sustaining growth in atmospheric CH_4 concentrations.

The third area of development is to deepen the economic part of the model. In particular, it is possible to replace the simplified form of the utility function with a more realistic one, for example, taking into account the minimum level of consumption, endogenous changes in preferences, or heterogeneity of households. It is also possible to integrate an extended capital structure that takes into account its industry or "green" component, as well as a more detailed consideration of investments in adaptation technologies. A multi-sector growth model would also add to the model, as carbon dioxide and methane originate in different parts of the economy. Such improvements will allow the model to more accurately reproduce the behavior of real economies in the face of climate change.

The next important step is to complicate strategic interactions between regions. The current implementation of the model supports two polar scenarios—full cooperation and full non-cooperation. However, in reality there is a wide range of intermediate strategies, including partial agreements, coalitions, unilateral commitments, and strategic dynamics. Expanding the model to a multi-period game structure with the ability to form coalitions, taking into account the reputation of agents, would allow for analyzing the feasibility of international climate agreements and the behavior of countries under uncertainty.

Another promising direction is further spatial disaggregation of the model. In the current version, the world is divided into 13 large regions, which allows for interregional differences in the economy, population and emissions to be taken into account. However, if the relevant data are available, further fragmentation of regions is possible, including the allocation of individual countries or even subnational units. This will provide a higher spatial resolution of the model and make it possible to apply it at the national level for climate policy purposes.

It is also possible to develop the climate block of the model. The current climate module implements a linear model of heat transfer between the atmosphere and the ocean with specified coefficients. In the future, it is possible to implement updated versions of physically based climate models (for example, MAGICC or FaIR), which allow for nonlinear feedbacks, changes in the radiation balance, and the inertia of the climate system to be taken into account more accurately.

Particular attention can be paid to the mechanism for assessing climate risk and uncertainty. In the current implementation, the model operates in a deterministic setting, based on specified parameters and scenarios. Adding a stochastic component, including distributions of climate sensitivity, emission trajectories, and the cost of emission reductions, will make it possible to use risk theory methods and take into account “high probability of a catastrophic outcome” scenarios. This will be especially important when analyzing strategies for preventing unlikely but extremely dangerous climate scenarios.

Finally, a possible upgrade is the integration of the RICE model into broader frameworks that incorporate the social and political-economic aspects of climate decisions. This could include interaction with sustainable development models (SDG models), macroeconomic modules, or global financial flow allocation tools. Such an interdisciplinary approach would provide a more comprehensive analysis of climate policy implications and enhance the applied value of the model.

Thus, the presented model can serve as a basis for a whole class of further studies — from the analysis of emission dynamics to the assessment of the consequences of global agreements, the risk of irreversible changes and the social cost of greenhouse gases. Its flexible structure, modularity and adaptability to different data sources allow the model to be used both in academic research and for applied purposes of strategic planning and climate policy formation.

5. Conclusions

The paper extends the RICE economic and climate model to take into account methane emissions (CH_4) and to analyze the impact of emission reduction strategies on economic and climate indicators in cooperative and non-cooperative modes of interaction between countries. To achieve the result, the following tasks were solved: existing economic and climate models were studied, as well as approaches to including the impact of greenhouse gases in them; a critical analysis of the limitations of the basic model was carried out; a modified model structure was proposed and implemented with the inclusion of the CH_4 block; the model was parameterized based on open international databases; a numerical optimization algorithm was implemented using the Pyomo library and the IPOPT solver; modeling was performed according to two scenarios of country coordination.

As a result of the work done, a new version of the RICE model was obtained. It includes a separate methane dynamics block, taking into account both industrial and natural emissions, as well as their control by countries. Based on the classic DICE/RICE variable responsible for controlling carbon dioxide emissions, a similar variable for methane emissions was developed, and possible scenarios for its approximation were taken into account during its development. Data were collected and processed for all 13 regions of the model, including initial conditions, production function parameters, climate change damage characteristics, and radiation coefficients.

The results of numerical modeling showed a significant difference between the cooperative and non-cooperative trajectories for many indicators. The cooperative regime shows a more pronounced reduction in CH_4 and CO_2 emissions, a lower trajectory of atmospheric temperature growth, and lower total losses from climate change. At the same time, despite the high initial costs of reducing emissions, the cooperative strategy demonstrates a steady increase in net output, which indicates the compatibility of climate policy with economic growth. This is confirmed, in particular, by the dynamics of the costs of reducing emissions and the dynamics of damage from climate change, calculated in monetary terms. The graphs by region in the cooperative scenario illustrate the economic efficiency of investments in climate policy and the reduction of damage by the end of the century.

From the point of view of scientific novelty, the work includes an extension of the classic RICE model by explicitly including methane in the emissions, radiative forcing, and control block, which makes it possible to analyze the short-term climate effects of CH_4. In addition, the parameters were calibrated based on current IPCC reports and scientific literature. Thus, the proposed implementation can serve as a platform for further development of climate models oriented towards multilateral policies and carbon-methane balance.

The practical significance of the work lies in the possibility of using the obtained model to analyze national and international strategies for climate cooperation. It can be used to compare climate policy scenarios, assess the benefits of participating in international agreements, and calculate the economic consequences of climate change at the level of individual regions. The universality of the model structure and the modularity of its software allow it to be adapted to new tasks: inclusion of additional types of emissions, demographic growth scenarios, technological progress, and socio-political restrictions.

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Appendix A. RICE model

Population dynamics equation. Population growth is given exogenously, based on pre-calculated growth rates. For each region m and time $t > 1$, a recursive relation is satisfied:

$$L_{m,t} = L_{m,t-1} \cdot \exp\left(g_{L,m,t} \cdot \Delta t\right), \tag{A.1}$$

where $g_{L,m,t}$ is the exogenously given population growth rate in region m, and Δt is the time step (in our implementation $\Delta t = 10$ years). The initial value of $L_{m,1}$ is set based on empirical data.

Consumption. The key argument of the utility function (2) is per capita consumption $C_{m,t}$. In the model, consumption is calculated as the fraction of net output remaining after investment is substracted:

$$C_{m,t} = Y_{m,t} - I_{m,t}, \tag{A.2}$$

where $Y_{m,t}$ is the net output in region m at time t and $I_{m,t}$ is the amount of investment.

Investment. Investment is defined as the share of net output given by the savings rate $S_{m,t}$, one of the control variables of the model:

$$I_{m,t} = S_{m,t} \cdot Y_{m,t}. \tag{A.3}$$

Thus, the variable $S_{m,t}$ directly affects the pattern of resource utilization between current consumption and capital accumulation.

Net output. Net output $Y_{m,t}$ is obtained from gross output $Q_{m,t}$ adjusted for two types of losses:

1. The damage from climate change
2. The cost of reducing greenhouse gas emissions.

Formally:

$$Y_{m,t} = Q_{m,t} - \frac{D_{m,t} \cdot Q_{m,t}}{1 + (D_{m,t})^{\Delta t}} - AB_{m,t} \cdot Q_{m,t}, \tag{A.4}$$

where:

- $D_{m,t}$ is an indicator of climate change damage;
- $AB_{m,t}$ - climate policy costs (abatement).

Gross output. Total (gross) output $Q_{m,t}$ is modeled using a Cobb-Douglas function that accounts for the contributions of capital and labor:

$$Q_{m,t} = A_{m,t} \cdot K_{m,t}^{\gamma_m} \cdot L_{m,t}^{1-\gamma_m}, \tag{A.5}$$

where $A_{m,t}$ is total factor productivity, $K_{m,t}$ is capital, $\gamma_m \in (0, 1)$ - parameter characterizing the elasticity of output by capital.

Capital. The accumulated capital in each period is formed from the savings of the previous period, taking into account depreciation:

$$K_{m,t} = \begin{cases} K_{m,0} \cdot (1 - \delta_m)^{\Delta t} + \Delta t \cdot I_{m,0}, & t = 1, \\ .K_{m,t-1} \cdot (1 - \delta_m)^{\Delta t} + \Delta t \cdot I_{m,t-1}, & t > 1. \end{cases} \tag{A.6}$$

where δ_m is the depreciation rate, Δt is the time step (10 years), and $I_{m,t}$ is the investment.

Costs of emission reductions. Region m can take steps to reduce emissions by limiting industrial activity or adopting green technologies. This comes at a cost that depends on the intensity of control $\mu_{m,t} \in [0, 1]$. The absolute cost of reduction is defined by the formula:

$$AB_{m,t} = \theta_{1,m,t} \cdot \mu_{m,t}^{\theta_{2,m}}, \tag{A.7}$$

where:

- $\theta_{1,m,t}$ is the temporally varying abatement cost factor;
- $\theta_{2,m}$ is the cost nonlinearity parameter.

Thus, absolute costs increase with output $Q_{m,t}$ and with climate policy stringency.

Climatic damage. The value $D_{m,t}$ characterizes the relative economic damage in region m at time t due to the global temperature increase $T_{at,t}$ and, additionally, the damage from sea level rise, often referred to as Sea Level Rate (SLR). It is calculated using the formula from Rogna and Vogt, 2022:

$$\begin{aligned} D_{m,t} = &\left(d_{1,m} \cdot T_{at,t} + d_{2,m} \cdot T_{at,t}^{d_{3,m}}\right) \cdot 0.01 \\ &+2 \cdot \left(d_{SLR,m}^{(1)} \cdot SLR_t + d_{SLR,m}^{(2)} \cdot SLR_t^2\right) \cdot \left(\frac{Q_{m,t}}{Y_{m,0}}\right)^{0.25}, \end{aligned} \tag{A.8}$$

where:

- $d_{1,m}$, $d_{2,m}$, $d_{3,m}$ are the temperature damage coefficients;
- SLR_t - sea level rise at time t;
- $d^{(1)}_{SLR,m}$, $d^{(2)}_{SLR,m}$ - SLR damage parameters;
- $Y_{m,0}$ - output of region m at the initial moment of time.

Atmospheric temperature. The rise in global atmospheric temperature $T_{at,t}$ is modeled as a response to radiative forcing, taking into account the inertia of heat exchange with the ocean. The temperature evolution is given by Eq:

$$\begin{aligned} T_{at,t} &= T_{at,t-1} + \\ & c_1 \cdot (F_t - c_2 \cdot T_{at,t-1} - c_3 \cdot (T_{at,t-1} - T_{o,t-1})), \end{aligned} \tag{A.9}$$

where:

- F_t is the cumulative radiative forcing (see below);
- $T_{o,t}$ is the temperature of the ocean;
- c_1, c_2, c_3 - parameters of the heat transfer model.

Ocean temperature. The ocean temperature $T_{o,t}$ evolves according to the equation:

$$T_{o,t} = T_{o,t-1} + c_4 \cdot (T_{at,t-1} - T_{o,t-1}), \tag{A.10}$$

where c_4 is the heat transfer coefficient between the atmosphere and the ocean. The initial values of $T_{at,1}$ and $T_{o,1}$ are set from historical data.

Radiation Forcing. The total radiation forcing F_t consists of three components:

- CO_2;
- CH_4;
- Exogenous factors (other greenhouse gases).

Final formula:

$$\begin{aligned} F_t = \eta \cdot & \frac{\ln\left(\frac{M_{at,t}}{M_{1900}} M_{1900}\right)}{\ln 2} \\ & + \eta_{CH_4} \cdot \left(\sqrt{M_t^{CH_4}} - \sqrt{M_{1900}^{CH_4}}\right) + F_t^{\text{other}}, \end{aligned} \tag{A.11}$$

where:

- $M_{at,t}$ is the atmospheric concentration of CO_2;
- M_{1900} is the historical CO_2 concentration (also referred to as the pre-industrial rate in some works);
- $M_t^{CH_4}$ - methane concentration;
- $M_{1900}^{CH_4}$ —historical CH_4 concentration;
- F_t^{other} —exogenous component that accounts for other greenhouse gases;
- η —sensitivity factor for CO_2 doubling;
- η_{CH_4} is the analogous coefficient for CH_4.

Appendix B. A static game

Let the costs of emission reduction be given by

$$AB_i = 2\theta_{i,CO_2} \cdot \mu_{i,CO_2}^2 + 2\theta_{i,CH_4} \cdot \mu_{i,CH_4}^2 \tag{B.1}$$

and its benefits by

$$B_i = \beta_i \sum_j \left(\mu_{j,CO_2} \cdot E_{j,CO_2} + \mu_{j,CH_4} \cdot E_{j,CH_4} + \lambda \mu_{j,CO_2} \cdot \mu_{j,CH_4} \cdot E_{j,CO_2} \cdot E_{j,CH_4} \right) \tag{B.2}$$

In the non-cooperative case, the first-order conditions are

$$\theta_{i,CO_2} \cdot \mu_{i,CO_2} = \beta_i \cdot E_{i,CO_2} + \lambda \mu_{i,CH_4} \cdot E_{i,CO_2} \cdot E_{i,CH_4} \tag{B.3}$$

and

$$\theta_{i,CH_4} \cdot \mu_{i,CH_4} = \beta_i \cdot E_{i,CH_4} + \lambda \cdot \mu_{i,CO_2} \cdot E_{i,CO_2} \cdot E_{i,CH_4} \tag{B.4}$$

which solves as

$$\mu_{i,CO_2}^* = \frac{\beta_i \cdot E_{i,CO_2} \left(1 + \lambda \frac{E_{i,CH_4}^2}{\theta_{i,CH_4}}\right)}{\theta_{i,CO_2} - \lambda^2 \frac{E_{i,CO_2}^2 \cdot E_{i,CH_4}^2}{\theta_{i,CH_4}}} \tag{B.5}$$

and

$$\mu_{i,CH_4}^* = \frac{\beta_i \cdot E_{i,CH_4} \left(1 + \lambda \frac{E_{i,CO_2}^2}{\theta_{i,CO_2}}\right)}{\theta_{i,CH_4} - \lambda^2 \frac{E_{i,CO_2}^2 \cdot E_{i,CH_4}^2}{\theta_{i,CO_2}}} \tag{B.6}$$

In the cooperative case, the solution is

$$\mu_{i,CO_2}^+ = \frac{\beta \cdot E_{i,CO_2} \left(1 + \lambda \frac{E_{i,CH_4}^2}{\theta_{i,CH_4}}\right)}{\theta_{i,CO_2} - \lambda^2 \frac{E_{i,CO_2} \cdot E_{i,CH_4}}{\theta_{i,CH_4}}} \tag{B.7}$$

and

$$\mu_{i,CH_4}^+ = \frac{\beta \cdot E_{i,CH_4} \left(1 + \lambda \frac{E_{i,CO_2}^2}{\theta_{i,CO_2}}\right)}{\theta_{i,CH_4} - \lambda^2 \frac{E_{i,CO_2}^2 \cdot E_{i,CH_4}^2}{\theta_{i,CO_2}}} \tag{B.8}$$

where $\beta := \sum_i \beta_i$.

The difference between cooperative and non-cooperative emission reduction is thus

$$\Delta_{CO_2} := \mu^{+}_{i,CO_2} - \mu^{*}_{i,CO_2} = (\beta - \beta_i)\frac{E_{i,CO_2}\left(1 + \lambda\frac{E^2_{i,CH_4}}{\theta_{i,CH_4}}\right)}{\theta_{i,CO_2} - \lambda^2\frac{E^2_{i,CO_2}\cdot E^2_{i,CH_4}}{\theta_{i,CH_4}}} \tag{B.9}$$

And ditto for Δ_{CH_4}. This difference grows with $\lambda > 0$.

In other words, cooperative joint emission reduction is larger relative to non-cooperative joint emission reduction if emissions of one greenhouse gas increase the marginal impact of the emissions of the other greenhouse gas.

In case the option to reduce methane emissions is not there, $\mu_{i,CH_4} = 0$,

$$\mu^{*}_{i,CO_2} = \frac{\beta_i \cdot E_{i,CO_2}}{\theta_{i,CO_2}} \tag{B.10}$$

$$\mu^{+}_{i,CO_2} = \frac{\beta \cdot E_{i,CO_2}}{\theta_{i,CO_2}} \tag{B.11}$$

and

$$\Delta_{CO_2} := \mu^{+}_{i,CO_2} - \mu^{*}_{i,CO_2} = (\beta - \beta_i)\frac{E_{i,CO_2}}{\theta_{i,CO_2}} \tag{B.12}$$

which is the same as above for $\lambda = 0$.

In other words, cooperative joint emission reduction of one gas is larger relative to non-cooperative joint emission reduction of that gas if the emissions of the other greenhouse gas cannot be reduced.