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REVISITING A CLIMATE-ECONOMY MODEL WITH CONSIDERATION OF AGENT'S HETEROGENEITY AND INTERACTIONS WITH THE AGENTS

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ABSTRACT

This paper studies not only how heterogeneity in the economic agents and their interactions can be considered into the simulation process of a climate-economy model but also reveals the role that heterogeneous characters play in the functioning of the model. To do so, this paper first reviews the well-known Dynamic Integrated Climate Economy (DICE) model and points out the limitations of such top-down style models in explaining heterogeneity in agents. Then, we suggest an agent-based model (ABM) of Safarzynska and Bergh (2022) to highlight the usefulness of the ABM for incorporating heterogeneous agent's characteristics and its interactions with other agents. Finally, by calibrating the ABM with the 2023 version of the DICE, we discover some simulation results that the long-term temperature is affected by bounded rationality of consumers, renewable preference of electricity producers, and interest rate of loan market. Several implications and important avenues for further research are identified.

KEYWORDS: A climate-economy model, agent-based modelling, bounded rationality, renewable share of electricity, interest rate of loan market.

1. INTRODUCTION

Climate change has the potential to affect the global economic system. In a perspective of global externality, one country's emissions affect all countries by adding to the stock of heat-warming gases in the earth's atmosphere from which warming arises [13]. To assess the relationship within and between the various biogeochemical and socioeconomic components, a number of quantitative models have been developed.

Integrated Assessment Models (IAMs) have been widely used and also continue to grow rapidly in the field of climate-economy system modelling. IAMs rely on aggregate equations that describe how accumulation of carbon emissions by activities affects global temperature, which in turn causes changes in nature and human life. The literature on IAMs is vast as well as spread across various disciplines, such as, earth science, biology, environmental engineering, economics, sociology, etc. However, ironically, such a wide range of disciplines has led to confusion about what exactly IAMs are.

Although the IAMs have been developed in various disciplines, this paper narrows down the *economics* discipline which plays as the academic background for a cost-benefit analysis (CBA) and a general-equilibrium optimization analysis. Specifically, we focus on the well-known DICE (the Dynamic Integrated Climate-Economy) model and review the model to illuminate how it works as well as what are the main results the model generates.[1]

Our review on the DICE leads to a natural curiosity with a question: "For more reliability, is it necessary to incorporate bounded rationality of the agents and interaction between the agents in the climate-economy system?"

As an answer to the question, we suggest an agent-based modelling (ABM) and introduce the case study of Safarzynska and Bergh [17] which incorporates the effect of interactions across agents with heterogeneous characteristics into the existing dynamic climate-economy system. Further, we conduct additional tests for several different assumptions that have not been dealt with by previous studies, which show that interactions across agents with heterogeneous characteristics lead to different results and implications from the existing simulation tests. Finally, this paper discusses the contributions and challenges of agent-based modelling for the climate-economy system.

In summary, the primary purpose of this paper is four-fold: The first purpose is to re-examine the most-recent 2023 DICE model as a representative economy-climate IAM. Second, as a better and alternative way for incorporating interactions between agents with heterogeneous characteristics into the CBA-type IAMs, this paper introduces an existing ABM developed by Safarzynska and Bergh [17] which deals with consumer's bounded rationality, which enables comparing between these two types of climate-economy models. The third purpose of this paper is to test whether substantial changes in the characteristics of the key agents in the ABM, such as consumer's bounded rationality, share of renewables taken by energy firms, etc., contribute to generating meaningful simulation results in the ABM. As the fourth purpose, this paper identifies the usefulness of the climate-economy ABM and the remaining challenges for a better use of the ABM. This article is organized as follows. In the next section, we present an overview of the DICE model which is regarded as one of the representative climate-economy IAMs to understand the basic mechanism of the model. Then, we study the most recent version of climate-economy ABM to shed light on the usefulness of its capability for considering changes in agents' characteristics and their interactions. Also, we suggest what characteristics and interactions should be considered as a key research question. In the next section, using the ABM developed by Safarzynska and Bergh [17], we provide the simulation results on the interrelationship between changes in the characteristics of the key agents and the global temperature. The final section presents conclusions and recommendations for further development and use of ABN-IAMs to study the climate-economy system.

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[1] Among the economics-based IAMs, the choice of the DICE is also motivated by the facts that the DICE is recognized as the first CBA-type model as well as the key model in the history of IAMs [2].

2. Overview of the climate-economy IAM: A case study of the DICE

Among various climate-economy IAMs, this paper investigates the DICE (Dynamic Integrated model of Climate and the Economy) because of its academic reputation and contributions. The DICE is the most widely used CBA-type IAM and recognized as a key model in the history of IAMs [2]. Currently, the DICE is one of three main IAMs used by the US Environmental Protection Agency (EPA) and known to provide intermediate estimates between other two IAMs. Although there are several criticisms, the DICE model has been updated many times and has been cited considerably.

The DICE is a simplified analytical and empirical model that represents the economics, policy, and scientific aspects of climate change [15]. As a globally aggregated model, the model views the economics of climate change in a standard neoclassical economic growth theory known as the Ramsey model. This economic theory views that economies make investments in capital, education, and technologies, thereby making inter-temporal choices between present and future consumption. The DICE extends this theoretical approach by including the "nature capital" of the climate system. The DICE considers concentration of GHGs as negative natural capital, and emissions reductions as investments that raise the quantity of natural capital. As economies devote output to emissions reductions, they have to reduce consumption today to prevent economically harmful climate change and thereby increase consumption possibilities in the future. Figure 1 shows a schematic flow chart of the major modules and logical structure of the DICE.

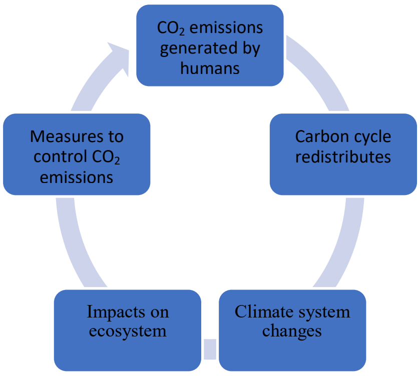

Figure 1: Schematic Flow Chart of the DICE

The DICE assumes that economic and climate policies should be designed to optimize the flow of consumption overtime. It is important to emphasize that consumption should be interpreted as "generalized consumption", which includes not only traditional markets goods and services like food and shelter but also non-market ones such as leisure, health status, and environmental services.

The mathematical representation of this assumption is that policies are chosen to maximize a social welfare function, W, that is the discounted sum of the population-weighted utility of per capita consumption. The notation is that $c(t)$ is per capita consumption, $L(t)$ is population as well as labor inputs, and $R(t)$ is the discount factor. Equation (1) is the objective function represented by standard modern theories of optimal economic growth [3], [14], [18].

$$W = \sum_{t=1}^{Tmax} U[c(t), L(t)]R(t) \qquad (1)$$

Where utility is a function assuming a constant elasticity of the marginal utility of consumption? So, $U[c(t), L(t)] = L(t)[\frac{1}{1-\alpha} c(t)^{1-\alpha}]$when α> 0 and α≠1 or $U[c(t), L(t)] = L(t)[ln\ ln\ c\ ]$ when α=1. The parameter α measures the degree of aversion to generational inequality. As α is close to zero, the consumptions of different generations become substitutes, which represents low aversion to inequality. Meanwhile, as α is higher, the consumptions among generations are highly differentiated, representing high aversion to inequality. The aversion parameter α is calibrated in conjunction with the pure rate of time preference[2].Also, the value of consumption in a period is proportional to the population because $U(c,L)$ is proportional to $L(t)$, where the population and the labor force are exogenous by the simplified logistic-type equations of the form $L(t) = L(t-1)[1+g_L(t)]$.[3] Lastly, $R(t)$is the discount factor with the discount rate which provides the welfare weights on the utilities of different generations; thereby

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

Gross output is $Y(t)$, which is a Cobb-Douglas function of capital(K), labor(L), and energy. Energy takes the form of either carbon-based fuels (such as coal, gas, etc.) or non-carbon-based technologies (such as solar, nuclear power, etc.) Technological change takes two forms: economy-wide technological change and carbon-saving technological change. It is modelled that substitution from carbon to non-carbon fuels takes over time as carbon-based fuels become more expensive, because either the carbon-based fuel becomes exhausted or policies are implemented to limit carbon emissions.

Net output at the time "t" noted as $Q(t)$ is gross output reduced by climate damages and mitigation costs as the following equation (2):

$$Q(t) = \frac{[1-\Lambda(t)]}{[1+\Omega(t)]} Y(t) \quad (2)$$

Where $\Lambda(t)$ and $\Omega(t)$ abatement cost and climate damage, respectively.

The level of total factor productivity, noted as of $A(t)$ in gross output function $Y(t)$ is assumed to be a logistic equation to that of population above. In specific,
$A(t) = A(t-1)[1+g_A(t)]$ Where $g_A(t) = \frac{g_A(t-1)}{(1+\delta_A)}$.

The productivity is assumed to be Hicks-neutral technological change. Thus, according to the form of $A(t)$, total factor productivity growth declines as time goes on like population growth.[4]

The abatement cost $\Lambda(t)$ is set by a reduced-form type model in which the cost of emission reductions are a function of the emission reduction rate $\mu(t)$, as follows:

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[2]There exists a fierce debate about the time discounting rate. Nordhaus's advocates recommend a relatively higher rate, such as, 0.985 while Stern's advocates claim strongly to use a relatively lower rate, such as, 0.999.

[3]gL is the growth rate of population, so that it forms as gLt=gL(t-1)(1+L). The initial population is generally given, and the growth rate declines so that the total world population is set to evolve and approach UN projections.

[4]In the 2013-version DICE specification, A(2010) is set to calibrate the model to gross world product 2010; gA2015=7.9% per five years; and A=0.6% per five years, which leads to growth in consumption per capita of 1.9% per year from 2010 to 2100 and 0.9% per year from 2100 to 2200 [15].

$$\Lambda(t) = \theta_1(t)\mu(t)^{\theta_2}$$

The abatement cost function shows that the costs are proportional to output as well as to a power function of the reduction rate. Thus, Nordhaus and Sztorc (2013) address that the abatement cost function is estimated to be highly convex, which indicates that the marginal cost of reductions rises from zero more than linearly with the reduction rate.

The climate damage $\Omega(t)$ is for explaining that an increase in global temperature reduces output by a function as the following equation (3):

$$\Omega(t) = \Psi_1 T(t) + \Psi_1[T(t)]^2 \text{ (3)}$$

Where $T(t)$the global temperature at time t. is $\Omega(t)$ is a key component in calculating the social cost of carbon widely called SCC. Yet, the climate damage is extremely difficult to estimate over the long run. Nordhaus and Sztorc[15] points out that existing studies generally omit important factors, extreme events, and several difficulties.[5]

According to the 2023 version of DICE[6], the climate damage from 2025 to 2175 is measured for the "Baseline" and "Optimal" case,[7] respectively, in Figure 2. The growth rate of atmospheric temperature started at 1.3 in 2020 over 5 Celsius degree above pre-industrial and will be increasing continuously up to 2175 for the baseline case while it is expected to decrease and turn downward after the year of 2135 at 3.0066 degree for the optimal case. Similarly, climate damage exponentially grows for the baseline case whereas the growth rate decreases for the optimal case.

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[5] For example, the important factors are the economic value of losses from biodiversity, ocean acidification, and political reactions; extreme events are sea-level rise, changes in ocean circulation, and accelerated climate change; difficulties are unexpected catastrophes and uncertainty of virtually all components from economic growth to damages[15].

[6] The DICE model has been being revised and updated. The most recent version and its results are released in April 2023 [1]. The major changes in the results from previous versions are a significantly lower level of temperature of the cost-benefit optimal policy, a lower cost of reaching the 2°C target, and a major increase in the estimated social cost of carbon.

[7] According to Barrage and Nordhaus [1], the baseline and optimal case is designed as follows: From a conceptual point of view, the baseline case represents the outcome of market and policy factors as they currently exist. The optimal case means that climate change policies maximize economic welfare according to the principles of cost-benefit analysis, with full participation by all nations starting in 2025. The optimal base involves a balancing of the present value of the costs of abatement and the benefits of reduced climate damages.

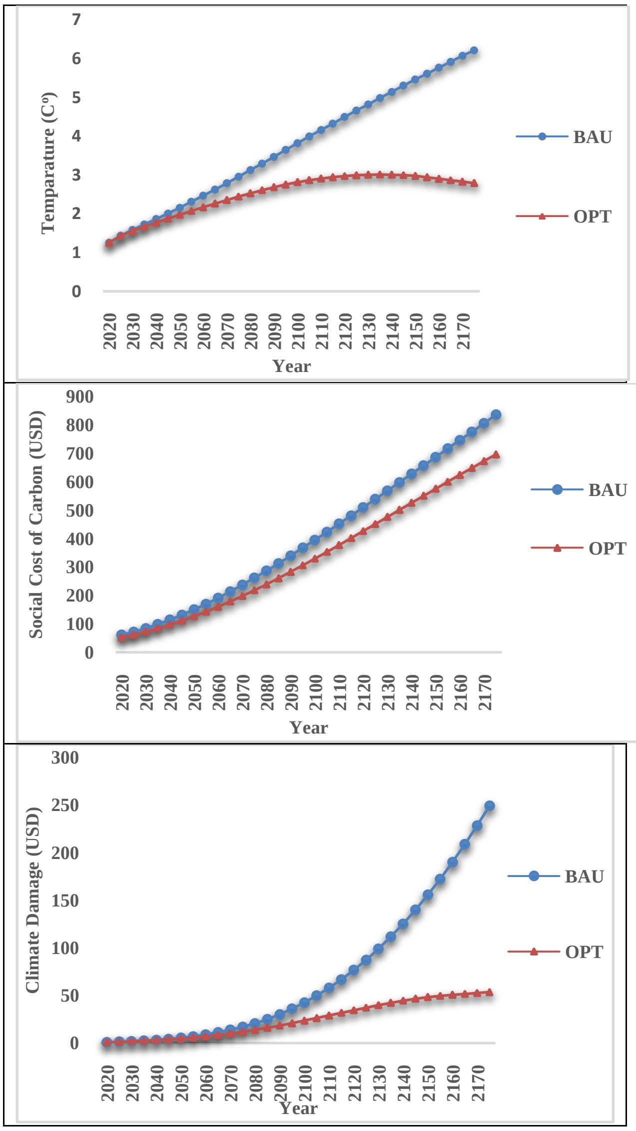


Figure 2: Temperature, Climate Damage, and Social Cost of Carbon: 2020 – 2017.

In order to measure the total CO_2 emissions, the uncontrolled industrial CO_2 emissions are identified. The uncontrolled industrial CO_2 emissions are given by a level of carbon intensity $\sigma(t)$ times gross output. Total CO_2 emissions noted as $E(t)$ are equal to uncontrolled emissions reduced by the emissions reduction rate, $\mu(t)$, plus exogenous land-use emissions as the following equation (4):

$$E(t) = \sigma(t)[1 - \mu(t)]Y(t) + E_{land}(t) \qquad (4)$$

The geophysical equations in the DICE play a role of connecting greenhouse gas emissions to the carbon cycle, radiative forcing, and climate change. The equations of the carbon cycle for three reservoirs, such as the atmosphere, the upper oceans and biosphere, and the lower oceans, are set up as follows:

$$M_j(t) = \omega_{0j} E(t) + \sum_{i=1}^{3} \omega_{ij} M_i(t-1) \qquad (5)$$

The subscript j represents each reservoir for three the atmosphere (AT), the upper oceans and biosphere (UB), and the lower oceans (LO), respectively. The parameters ω_{ij} show the flow parameters between reservoirs per period. All emissions flow into the atmosphere.

The relationship between greenhouse gas accumulations and increased radiative forcing is represented by the following equation (6):

$$F(t) = \tau\{log_2[\frac{M_{AT}(t)}{M_{AT}(1750)}]\} + F_{EX}(t)(6)$$

$F(t)$ is the change in total radiative forcing from anthropogenic sources such as CO_2.$F_{EX}(t)$ is exogenous forcing. The first term in the above equation (6) means the forcing due to atmospheric concentrations of CO_2. This forcing causes warming according to a simplified to-level global climate model as the following equations (7) and (8):

$$T_{AT}(t) = T_{AT}(t-1) + \varphi_1\{F(t) - \varphi_2 T_{AT}(t-1) - \varphi_3[T_{AT}(t-1) - T_{LO}(t-1)]\} \quad (7)$$

$$T_{LO}(t) = T_{LO}(t-1) + \varphi_4[T_{AT}(t-1) - T_{LO}(t-1)](8)$$

Where $T_{AT}(t)$the global is mean surface temperature and $T_{LO}(t)$ is the mean temperature of the deep ocean.

Solving the equations (1)-(8) by optimizing the social welfare function (W) generates the path of all the variables. Then, the DICE defines the social cost of carbon (SCC) at time as the following:

$$SCC(t) \equiv \frac{\partial W}{\partial E(t)} / \frac{\partial W}{\partial C(t)}_2 \equiv \partial C(t)/\partial E(t)(9)$$

The SCC is estimated for several alternative scenarios. The units are US dollars per metric ton of CO_2 and are expressed in terms of consumption in the given year. The 2023 version of DICE estimates the SCC from 2025 to 2150 for the "Baseline" and "Optimal" scenario as above displayed in Figure 2.

3. Bounded rationality and social interactions

The DICE model is useful for evaluating the economic and environmental consequences of different policy scenarios with consideration of the impact of various levels of emissions reductions and the optimal path for mitigating climate changes while considering economic factors. Yet, although it provides valuable insights, it also has been taking criticisms on the neoclassical economics theories which are the substantial assumptions of the model.[8]

The neoclassical economics does not sufficiently allow for the possibility that agents may not be fully rational. So, the DICE is designed for optimizing the inter-temporal aggregate utility which is

[8] The criticisms on the DICE model are well documented, and most of these were about technical limitations. For example, Farmer et al. [6] criticized that the dynamics of the climate system in the DICE could be inconsistent with the current scientific knowledge, which subsequently leads to imprecise estimate of the SCC. But, this paper focuses on the limitations about theoretical economics assumptions, instead of technical limitations.

the sum of the utility functions of the individual agents who are assumed to be perfectly rational. The results based on the rational expectation imply that the aggregated behaviour of a system of utility maximizers can always be expressed as that of a single average utility-maximizing representative agent with perfect rationality. The neoclassical assumption based on representative agents, therefore, ignores diversity of behaviours within a population of heterogeneous agents who are not perfectly rational in the real world.

However, in the real world, the individual agent acts in ways that are not fully rational as behavioural economists suggest a concept of "*Bounded Rationality*", implying that the individual agent makes decisions seeking for heuristic satisfaction rather than individual optimization. In other words, the satisfaction may be not for the agent's self-interests but for societal or even others' interests. Hence, the results based on the optimization process of the DICE model can be altered if it is allowed that the agents have bounded rationality. For example, Howarth [12] estimated higher environmental tax as optimal if agent's preference relies more on social benefits than private benefits value but lower tax was otherwise, which presents a possibility that the results simulated by the DICE model can be altered if the perfect rationality assumption is relaxed in the context of CBA-type general equilibrium models. Also, recent studies using general equilibrium models found the impact of different types of bounded rationality, such as, patience, habit, and social comparison, on the optimal environmental tax which is often measured by the social cost of carbon [4], [10], [11]. Seeking for the heuristic satisfaction rather than self-interest optimization leads to suboptimal choices, which are different from the results from the CBA-type IAMs like the DICE model incorporating the perfect rationality assumptions.

In addition, there exists a greater possibility that different results from the CBA-type IAMs will be generated when the agents with bounded rationality interact with each other. The agents could not be homogeneous but be heterogeneous in socioeconomic characteristics, such as, wealth, education, age, etc. Safazynska and Bergh [17] noticed the heterogeneity in wealth across consumers and found that lower inequality of labor income increases the SCC unlike the result from the DICE model with no wage inequality. Also, Patrinos and Macdonald [16] pointed out the role of education in estimating the SCC. They suggest that higher quality education (defined as the level of cognitive skills attained by workers per unit of cost) mitigates the SCC, implying that investment in education quality contributes to encouraging technological innovation and adaptation as well as reducing inequality.

Therefore, as a solution for incorporating the agent-level characteristics and interactions into the climate-economy model, this paper suggests an agent-based model instead of amending the existing aggregate general-equilibrium optimization models like the DICE. Also, an agent-based model is a bottom-up style while the aggregate optimization models are a top-down style. For this reason, if an agent-based model is calibrated to generate patterns of macroeconomic variables in the DICE model, the calibrated model is an alternative climate-economy system which may change agent-level characteristics and interactions under any reliable situations. For more details on the climate-economy agent-based modelling, we provide the next section.

4. A climate-economy ABM: Safarzynska and Bergh (2022)

This paper suggests a climate-economy ABM developed by Safarzynska and Bergh [17] which includes four types of agents: *consumer*, *firm*, *energy firm*, and *bank*. These agents are heterogeneous and designed to make decisions with consideration of their own constraint and objectives maximization. Figure 3 presents the schematic flow of the ABM to display the basic mechanism of the model simulation over time and across the agents.

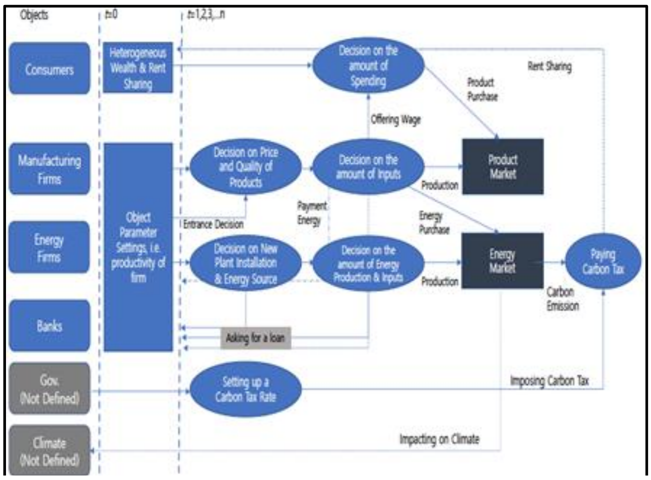


Figure 3: Schematic Flow Chart of the SB-ABM

In addition, in order for more clear understanding, this paper reviews the roles of each key agent and specific mathematical equations working for the model.

As the first key agent, consumers decide how much of their wealth and income to be spent in the current period under the constraint of heterogeneous budget function as the following equation:

$B_{it} = \mu_I PL_{it} + \mu_w D_{it}$(10)

where μ_I and μ_w are the shares of labor income (PL_{it}) and bank deposit (D_{it}), respectively, for the agent i and at time t. Although the shares are identical across consumers, consumers differ with respect to heterogeneous wealth measured by the bank deposit (D_{it}) at the initial time (t=0). As a result, according to the heterogeneous budget for individual consumer, i, purchasing decisions after subsequent times (t=1,2,3,…n) can be different across consumers. Thus, it is possible in the model that the rich consumers with more budget than the poor with less budget choose more expensive products which have better quality.

The wealth (D_{it}) of an individual consumer, i, changes over time, t, by heterogeneous labor wages (PL_{it}), bank deposit gain considered by the interest rate (r), and energy and capital rents (a_t), thereby, the wealth equation is set by $D_{it} = D_{it-1}(1 + r) + PL_{it} + \mu_{si} a_t - C_{it}$. The energy and capital rents (a_t) are computed as spendings by firms on inputs and identical for all the consumers, based on the assumption of a stock-flow consistent model.[9] For an additional help to understand the capital rent, Safarzynska and Bergh [17] provided an explanation that “consumption-good firms pay the energy costs to energy firms, but expenses on fuels by the latter constitute dividends. On the other hand, expenses by consumption-good firms on capital constitute capital rents, which are distributed into consumers.” Eventually, for the purpose of utility maximization, consumers decide which product to purchase through comparing product quality, price, and adaptation rate. When such products are not available in the market, a consumer chooses probabilistically among available products in the market. The utility evaluated by consumer i from adopting product j depends on the product quality x_{jt}, its price p_{jt}, and the number of other consumers who bought the product m_{jt}. So, the utility evaluated by consumer i is expressed as the following equation (11):

[9]The rent is not produced in the model. The rents are designed for ensuring that the model is stock-flow consistent, meaning that all monetary flows are balanced each time period.

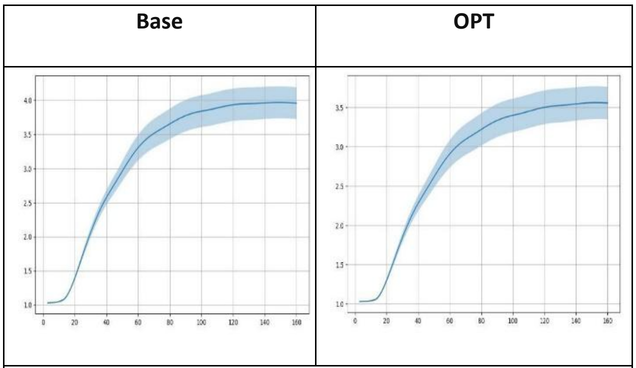
$u_{ijt} = x_{jt}^{\alpha_i} p_{jt}^{\alpha_i - 0.5} m_{jt}^{\alpha}$ (11)

Where α_i captures i's inclination toward the product quality, α is the network elasticity, and m_{jt} is firm j's market share.

Second, *firm* is considered as the key decision-making agent for production. They set the production level for the next time period with a weighted average of the past sales and production. Firms also set prices to compensate for the cost of inputs and capital expansion. A mark-up is imposed on the price according to each firm's market share. Prices depend on labour and energy productivities, which also vary with R&D investment by individual firms. Thus, firm heterogeneity arises from the firm-specific characteristics, such as, production level, market share, productivity, R&D investment, etc. of individual firms. Yet, regarding policy changes, firms in the model do not anticipate changes but adapts to them. For example, a carbon tax increases the prices of energy, and thus the probability of firms' investment in energy efficiency increases. The firms with no market share exit from the market, and new firms enter the market instead.

Third, *energy firms* are considered as another key agent in the model. Energy firms in the model produce electricity with three distinct energy sources: coal, gas, and renewables according to a Cobb-Douglas function of fuel, labour, and capital. Productivities of incumbent firms can change over time due to innovation and learning-by-doing. Electricity output decisions by each firm are modelled as Cournot competition, and the firms decide simultaneously how much electricity to sell on the spot market. When a power plant becomes obsolete, its energy firm starts investing in a new power plant and replacing it with a new one. The decision on the size of and fuel type embodied in an energy firm are based on the discounted value of investments. Each fuel j is characterized by its emission intensityε_j. The total emissions from the energy market in the model are equal to $F_t = \Sigma_i \Sigma_j q_{ijt} \varepsilon_j$ where q_{ijt} is the electricity produced by energy firm i embodying fuel j.

The ABM simulates the climate cycle and damage according to the total emissions generated by the energy firms. In a way of accumulating atmospheric carbon stock, the ABM follows the DICE approach as shown in the equation (4) above. Then, the ABM simulates the atmospheric temperature as the DICE model uses the equation (7). Thus, the energy firms, the agents generating carbon emissions, play a crucial role in affecting the climate cycle in the ABM because the emissions generated by the energy firms are a deterministic factor of the current stock of atmosphere carbon which, in turn, affect the global mean temperature above the pre-industrial level. We present the simulated temperature values from 2015 to 2175 for the baseline scenario and optimal scenario, respectively, in Figure 4. Because the ABM has been calibrated by Safarzynska and Bergh [17], simulation results on temperature and consumption growth are very similar between the 2016-DICE model and the 2023 version of the DICE model. For instance, a consumption growth rate at 2100 is simulated by 2023-DICE as 1.94% for the baseline scenario and 1.96% for the optimal scenario, respectively, while the rate at 2100 is simulated by the DICE as 1.93% for the baseline and 1.95% for the optimal scenario. In the case of temperature at 2100, the value differences between two models are only 0.08 for the baseline scenario and 0.49 for the optimal scenario. Considering that the optional scenarios are not the same for the DICE model and the ABM of Safarzynska and Bergh [17], the simulated results on the future temperature drop are bound to be somewhat different between the two models.



Note: The vertical axis is the temperature (°C) above the pre-industrial level, and the horizontal axis is the simulation round. Base is the baseline scenario in the absence of climate policies with full employment of rational agents, and the Optimal Scenario (OPT) means that the SCC is translated into a carbon tax on electricity. The solid line is the mean value and the shadow indicates the standard deviation.

Figure 4: Temperature Simulation

Finally, *bank* is included as a decision-making agent in the model. The role of the bank in the model is to pay the interest rate on the deposit and collect loan repayments which are due. A bank is designed to be bankrupt if either its equity or its reserve becomes a negative value. Since the model is stock-flow consistent, a bank is designed to ask other banks at the interbank lending market for a loan if it has no sufficient liquidity to give a loan. The model designs a money supply which consists of all the bank money and loans.

Although the government and climate are not defined as the agents who make decisions with their own objectives in the model, but both are crucial factors of the climate cycle which is the other main part of the climate-economy model by influencing the four key agents through imposing carbon tax and temperature. More specifically, when the government imposes a carbon tax which may tighten the consumer's budget for buying products as well as the firm's production level for the future. Also, when the global atmospheric temperature increases by the agents' activities under no carbon tax measures, climate damage increases, which in turn decreases economic activities by consumers, firms and energy firms using fossil fuels.

Table 1: Comparison of The 2023-DICE model and ABM

	2023-DICE		*ABM*	
	Base	*OPT*	*Base*	*OPT*
Consumption growth at 2100	1.94%	1.96%	1.93%	1.95%
Temperature (C^o) at 2100	3.82	2.81	3.74	3.30

5. The ABM TEST: Bounded rationality, Renewable share, Loan-market rate

The ABM developed by Safarzynska and Bergh [17] is useful for incorporating the agent's individual characteristics and interactions into the climate-economy simulation system. For the first agent, we focus on the *consumer*. More specifically, we point out the rationality of consumers for the climate-economy ABM as it has been dealt with in eq. (11).[10] The network elasticity in equation (11) measures the tendency of consumers to follow choices of others. In the model, if the elasticity α is set to 0, then the consumers are assumed to be perfectly rational. As the elasticity values increase, the consumers become more boundedly-rational because higher value of the elasticity means that the weight attached to products chosen by the others is stronger. Thus, as consumers are more boundedly-rational, they are less likely to switch to new products with lower market share than older products with higher market share than boundedly-rational consumers.

As a result, it is expected that the SCC and the temperature (above pre-industrial become greater as consumers are more boundedly-rational in the model which assumes that newer products produced with more efficient techniques in the market results in generating lower emissions than older products. Table 2 displays the changes in the simulated temperature at 2100 as the elasticity value, α, changes from 0 to 1 for the Base case. The simulations appear consistent with conventional assumption. The temperature at 2100 varies from around 3.7 to over 4 when the elasticity changes from 0 to 1 in the model.

Table 2: The effect of consumer's bounded rationality on the temperature at 2100.

α	Temperature **(C^o above pre-industrial levels)**
0.0	3.77
0.1	3.72
0.2	3.75
0.3	3.90
0.4	4.00
0.5	4.03
0.6	4.03
0.7	4.00
0.8	4.02
0.9	4.00
1.0	4.02

Figure 5 shows how dynamics of HHI differs by the elasticity α for the Base case simulation from 2015 to 2100. The simulation result reveals that HHI is higher as the elasticity of bounded rationality is higher. Also, Table 3 shows that cumulative emissions tend to be greater as the elasticity is "significantly" higher, meaning that the emissions tend to increase as the value of α progresses to 0.0, 0.3, 0.4, and 0.5. However, it is simulated that the emissions decrease as the value α progresses to 0.0, 0.1, and 0.2, suspecting that the values from 0.0 to 0.02 are too small to influence the emissions in the model. For confirmation, a more rigorous analysis is needed. Overall, according to the simulation results, it is postulated that the effect of consumer's bounded rationality on temperature can be explained by the channel: Higher bounded rationality → Higher HHI →Higher Emissions → Higher Temperature.

[10]Sarfazynska and Bergh [17] considered consumer's unequal wealth conditions and showed successfully that such inequality heightens the SCC as well as global temperature. In addition, the bounded rationality was taken into account for their simulation to reveal that the SCC was greater as consumers are more boundedly-rational.

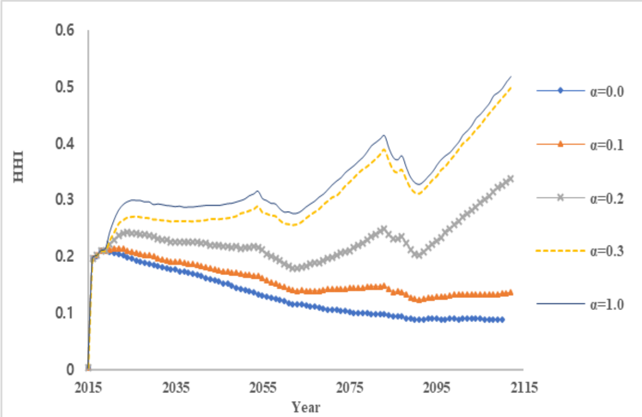


Figure. 5: Dynamics of HHI by the Emissions

For the second key agent in the ABM, we focus on the *energy firms* generating carbon- emission. In the model of Safarzynska and Bergh [17], the energy sources used by the energy firms are equally divided by 33.3% for coal, gas, and renewables, respectively. Yet, considering the most recent report that the world electricity generation by fossil fuel: 61.27%, renewables: 29.55%, and nuclear: 9.18%, it is necessary to take the share of renewables under% in the simulation[5], [8], [9]. So, we set the number of energy firms to four which reallocate renewables share to be 25% of the total electricity generation in the first round simulation. As a result, lower share of renewables in the first round simulation for the Base case increased the temperature at 2100 compared to the setting with 33.3% renewable share. In specific, the temperature above pre-industrial levels was 3.74 at 2100 when the renewable share was set as 33.3%, but it was simulated to be 4.12 at 2100 when the renewable share was 25%. These simulation results are consistent with an intuition that more use of renewable energy contributes to lower emission, enabling the lower growth of temperature.

Also, it is easily assumed that more use of renewable energy leads to less emissions, which in turn results in less increase in global temperature. Figure 7 supports for the assumption by displaying how dynamics of the emissions are different by two types of renewable energy shares, 33.3% and 25%, respectively. The share 33.3% means that only one energy firm out of the total three firms uses renewables for producing electricity, and the share 25% implies that only one renewables-based energy firm exists out of four ones in the system. As shown in Figure 6, the ABM simulates that the 33.3% renewables share generates more emission than the 25% renewables share from 2015 to 2100.

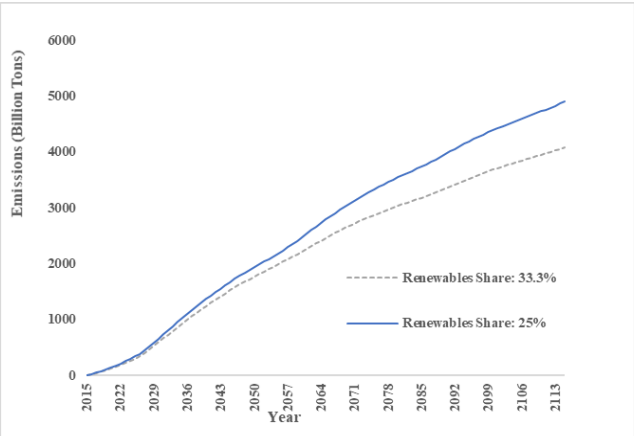


Figure 6: Dynamics of Emissions by Share of Renewables Use

Lastly, we address the remaining key agents, firm and bank. In the model, they are related to each other for a loan. We focus on the system of loan and assume that running business becomes more difficult as an interest rate is higher. Thus, by simply resetting the interest rate parameter in the model changing from 0.02 to 0.10 for the Base case, we generated the simulation results on the temperature. Contrary to our expectation, the temperature did not change at 3.74. According to our observation, the temperature started to decrease when the interest rate became an unrealistic level, such as, 10.00. When the interest rates went over 10.00, firms started to go bankrupt, which in turn influenced the temperature decrease through lower economic growth. These results imply that the firm's business in the model is affected mainly not by the loan from the bank but by the deposits accumulated from operational profits.

6. Concluding remarks: Contributions, challenges, and further studies

This paper sheds light on the usefulness of an ABM in checking heterogeneity in decision-makers and their interactions for simulating the climate-economy outcomes. Such usefulness is different from the widely-used IAMs which are top-down and representative-based models, such as the DICE model. Rather than creating our own ABM, this paper introduces the ABM of Safarzynska and Bergh [17] which is not only one of the most recent climate-economy ABMs but also is calibrated with the DICE. Using this ABM, we conduct simple tests for the agent-specific issues: consumer's bounded rationality, energy firm's share of renewables, and the loan market interest rates.

All the test results are consistent with conventional economics theory. As consumer tends to not make his own decision but just follow decisions by a majority of other consumers, implying that consumer's rationality is more bounded, the global temperature is higher than as consumer is more rational. The underlying reason this paper discovers is that the market concentration measured by HHI increases as more weight attached to products chosen by the others is stronger. Thus, higher HHI induced by higher bounded-rationality leads to greater emission, which, in turn, results in higher temperature. In addition, we found the dynamics revealing that more share of renewables used by energy firms leads to lower temperature growth. This finding also highlights how significant the agents' characteristics are for simulating the climate-economy outcomes. Lastly, we found that when the interest rates went over 10.00, firms started to go bankrupt, which in turn influenced the temperature decrease through lower economic growth. These results show the role of the interest rate is designed into the model. The firm's business in the model is affected mainly not by the loan from the bank but by the deposits accumulated from operational profits.

In conclusion, based on our study, we suggest meaningful ideas for further research issues, which are mainly toward development of the model. First, it is necessary to incorporate psychological satisfaction for environmental protection into an agent's profit maximization function. For instance, if the product quality in the utility function is separated into general quality and environmental quality by different weights, individual agent's preference can be functioned in the model, which consequently helps yielding that the effect of environmental satisfaction on temperature differs by agent's inclination to environmental quality when they purchase good in markets.

Second, it is necessary to include a larger number of agents in the model. In fact, the number of consumers was the issue in Safarzynska and Bergh [17] and already checked by several cases of consumer numbers. Nevertheless, it is a presumable argument that emission could be higher if the number of consumers increase because the larger size of economy highly seems to increase emission. Thus, it is necessary to observe whether the climate-economy ABM generates greater emission and higher temperature as the number of the key agents, such as consumers, firms, energy plants, and banks, increases.

Third, the energy sector in the ABM needs to add nuclear energy to the sources of electricity generation. As our simple simulation test noticed, the nuclear energy has not been considered as an energy source of electricity production in the model. Until the world achieves a net zero society, nuclear can be used consistently for electricity production as an alternative for coal because renewables are not sufficient for covering the use of coal.

Fourth, the firm's business in the model needs to be significantly affected by not only the operational profit but also the financial flows. As our simulation result pointed out, the climate-economy system in the model is not sufficiently sensitive to interest rate. Since the global financial crises tended to occur more recently and its impact on the economy became stronger, it is necessary to incorporate significant inter-relationship between the firm's profits and financial market liquidity situation.

Fifth, it is more realistic that the firm evolves with more investment in technology, implying that older firms can produce goods with lower emission by more investment in higher technology. Evolution of firm is a crucial factor for testing the hypothesis that consumer's bounded rationality increases HHI because older firms may reduce emission if the firms evolve with advanced technology.

Lastly, this paper suggests a region-specific modelling for the further study. For example, a Korean case is suggested as an appropriate case because Korea is a small open economy as well as a leading and higher emission economy in the globe. Moreover, Korea is the 9th largest CO2 emission country in the world in 2019 [7]. We expect that the case of Korea contributes to designing regional policy as well as international cooperation plans for sustainable economic growth.

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