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Impact of climate model uncertainties on socioeconomics: A case study with a medium mitigation scenario

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ABSTRACT

Carbon dioxide (CO_2) emissions are strongly associated with economy. The amount of CO_2 that human society can emit in order to achieve a climate target depends on physical and biogeochemical properties in the climate system; these vary among climate models or earth system models (ESMs). Thus, uncertainties in such models, the spread remained when we both consider the range of existing models and observational data for key variables, can affect analysis of future global economy. In this study, using a computable general equilibrium model, we analyze the impacts on socioeconomics under a medium climate mitigation scenario by following three emission pathways considering uncertainties in existing ESMs (the lower and upper bounds as well as the mean). The results indicate that the impacts are larger in the lower bound case, despite the fact that economic and energy demands will increase continuously. In a comparison between the upper and lower bound cases, the carbon price of the latter case is approximately three times higher than that of the former case in 2100. Consequently, primary/final energy demand in the lower bound case becomes 1.0%/14% lower, and more renewables and carbon capture and storage are required to be used. Furthermore, the gross domestic product in the lower bound case is 4.1% smaller. Thus, within the scenario, the socioeconomic impacts caused by ESM uncertainties are not insignificant, but are smaller than the differences in annual and cumulative emissions.

1. Introduction

Several climate change scenarios have been developed related to the Intergovernmental Panel on Climate Change (IPCC), including the Special Report on Emission Scenarios (SRES) [1] and the Representative Concentration Pathways (RCPs) [2–4]. Most recently, the RCP scenarios were developed primarily for the fifth IPCC Assessment Report [2]. These scenarios describe four possible climate futures for the year 2100, as defined by four predicted radiative forcing (RF) trajectories. Four separate integrated assessment modeling teams analyzed different scenarios using their own models and predicted greenhouse gas (GHG) concentration and emission pathways [5–8]. However, multiple GHG concentration and emission pathways can be generated for each predicted 2100 RF (or concentration) level [5–11]. For example, in the RCP scenarios [5–8], each modeling team showed its own GHG emission pathway scenario and the emission pathways of the other scenarios, thus demonstrating that different emission pathways can attain a certain RF level.

Several studies have compared the socioeconomic feasibility and impact of specific GHG concentration (or RF) scenarios using multiple integrated assessment models (IAMs) [9–11]. These studies show varied GHG emission pathways at certain concentration levels because of differences in model types, timing of the emission reductions, assumed technology, and other assumptions, such as future economic and demographic growth.

Using an IAM and a simplified climate model, Rogelj et al. [12] implement a systematic scenario analysis of how different levels of short-term emissions would impact the technological and economic feasibility of achieving the United Nation's (UN) 2 °C global warming target for 2100. They show possible GHG emission pathways for achieving the target using both models. However, they focus on technological and economic perspectives, combining short- and long-term views. Research to integrate climate model studies and socioeconomic model studies has just begun, and consequently there is no documented information on the non-uniqueness of the climate models and their future projections from a socioeconomic perspective. If the spread among the climate models significantly affects economics and society, policymaking

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must follow a different path, including climate, energy, and socioeconomic policies.

In recent days, many climate models have been coupled with ecosystem and other models to consider biogeochemical processes, thus creating earth system models (ESMs). ESM (or climate model) uncertainties include physical uncertainties, such as climate sensitivity and oceanic heat uptake efficiency, and biogeochemical uncertainties, such as the sensitivity of carbon uptake capacity in increasing carbon dioxide (CO_2) concentration or temperature [13]. These factors, in combination, affect the amount of CO_2 that human society can emit for a given concentration pathway.

In the following sections, the uncertainty of ESMs and the allowable emission pathways for the given concentration pathway are defined as their spreads that are consistent within the range of existing ESMs and observational data (see Section 2.3 for detail). That is, the uncertainty is caused by our insufficient knowledge to formulate each process of the earth system and to constrain the parameters by using observational data.

The purpose of this study is to analyze the impact of ESM uncertainties on socioeconomics (including energy). It follows a climate mitigation scenario defined by an RF level using a computable general equilibrium (CGE) model based on multiple GHG emission pathways obtained from an ESM of intermediate complexity (EMIC) while considering the uncertainties in existing ESMs. This study significantly combines climatic model studies (climate aspects) and a CGE model (socioeconomic aspects) and clarifies the meaning of the uncertainties in existing ESMs in terms of the socioeconomic aspects. Here, we examine carbon price, gross domestic product (GDP), energy demand, and the Kaya identity for the socioeconomic aspects. In this study, we use emission pathways to achieve an RF of 4.5 W/m^2 in 2100 (called the “RF4.5 scenario”), which is a medium climate mitigation scenario and one of the four RF levels designed for the RCP scenarios [7].

Section 2 of the paper describes the model, scenarios, and emission pathways. In Section 3, we show the results of the analysis, focusing on GDP and energy demand. Finally, in Section 4, we draw conclusions.

2. Methods

2.1. Model

We use a CGE model to analyze the impact of ESM uncertainties on socioeconomics for achieving a RF of 4.5 W/m^2 in 2100. This model is based on Masui et al. [5], Matsumoto and Masui [14,15], and Okagawa et al. [16]. The CGE model is economic in nature, widely known as a top-down approach for analyzing the economic implications of climate change issues and the related policy designs [14,15,17–19].

The model used here is a multi-regional and multi-sectoral recursive dynamic CGE model on a global scale, with energy and environmental components. Though model details are included in Appendix A, an overview is provided here. The model, also referred to as an IAM, is disaggregated into 24 geographical regions, each producing 21 economic goods/services (Table 1) and having a final demand sector. Within the energy sector, electric power is disaggregated into detailed technologies, including thermal, hydro, nuclear, and renewables. Moreover, carbon capture and storage (CCS) technology can be selected as an advanced technology for power generation. Each industrial sector is represented by a nested constant elasticity of substitution (CES) production function (see Fig A1 in Appendix A).

Each industrial sector produces goods/services delivered for the international and/or domestic markets. In each domestic market, the supplied goods/services are consumed as final consumption, investment, and/or intermediate input for industrial sectors. For each period, the total investment demand is set exogenously to meet a prescribed future economic growth rate (see Section 2.2.1).

The final demand sector in each region owns all production factors (e.g., capital, labor, land, and resources) and supplies them to the industrial sectors to earn income for final consumption and savings. The final demand for each goods or service is determined to maximize the utility represented by a CES function.

The model endogenously handles the global emissions of 10 gases, including CO_2, and is run to follow the emission pathways described in Section 2.3 between the base year (2001) and 2100.

The model considers global GHG emissions trading, assigning emissions to regions in proportion to their projected population from the year 2050 onwards. Between the base year and 2050, regional GHG emission limits were set by linear interpolation of emissions (known as contraction and convergence).

The model is calibrated to reproduce economic activity and energy levels in the base year using the following data: the Global Trade Analysis Project (GTAP) 6 database [20] for economic activity levels; the Emission Database for Global Atmospheric Research (EDGAR) v4 database [21] for GHG emissions; and the International Energy Agency (IEA) energy balance tables [22,23] for energy.

2.2. Scenarios

2.2.1. Reference scenario

The RF4.5 scenario described in Section 2.2.2 is an emission reduction scenario achieved by introducing climate policies. It indicates that, without policy intervention, RF will exceed 4.5 W/m^2. Before analysis of the RF4.5, a business-as-usual scenario, or a reference scenario, was developed. The reference scenario assumes that no policies and measures are introduced solely aiming to control GHG emissions beyond those already in place; it also assumes that existing policies are not renewed when they expire.

The reference scenario is based on several assumptions. Demographic assumptions are based on a medium variant of the UN World Population Prospects [24]. Future economic growth assumptions are based on the Sustainability First scenario presented in the UN Environmental Programme [25]. Finally, technological improvement is based on the SRES B2 scenario, a moderate scenario in the SRES [1]. These assumptions are applied to both the reference and RF4.5 scenarios.

The following details summarize the reference scenario: The global population grows from 6.1 billion in the base year to 9.8 billion in 2100, with a peak between 2080 and 2090 (Fig. 1a). Global GDP reaches $230 trillion[1] in 2100 (Fig. 1b), and the global primary energy demand reaches 1178 EJ in 2100 (Fig. 1d–e). Globally, fossil fuel demand, particularly coal, will increase continuously during this century because of its relatively low cost. Consequently, total CO_2 emissions increase to 25.1 GtC/yr (Gigatons of carbon per year) in 2100 (Fig. 1c), and the total RF reaches 7.2 W/m^2 in 2100.

2.2.2. RF4.5 scenario

In this study, we use a scenario based on RCP4.5 (a medium climate mitigation scenario), originally developed by Thomson et al. [7], to investigate the socioeconomic impacts derived from

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[1] In this study, we use the price in the base year (2001). That is, $230 trillion means 230 trillion in 2001 constant US dollars.

Table 1
Region and commodities/sectors definitions.

Code	Region	Code	Commodities/sectors
AUS	Australia	[Energy]	
NZL	New Zealand	COA	Coal
JPN	Japan	OIL	Crude oil
CAN	Canada	GAS	Natural gas
USA	United States of America	P_C	Petroleum products
E15	15 Western EU countries	GDT	Gas manufacture and distribution
RUS	Russia	ELY	Electric power[a]
E10	10 Eastern EU countries		
XRE	Other Europe (e.g., Bulgaria)	[Non-energy]	
KOR	Korea	AGR	Agriculture (e.g., rice)
CHN	China and Hong Kong	LVK	Livestock (e.g., bovine cattle)
XRA	Other Asia-Pacific (e.g., Mongolia)	FRS	Forestry
IDN	Indonesia	FSH	Fishery
THA	Thailand	EIS	Energy-intensive industries (e.g., chemical products)
XSE	Other Southeast Asia (e.g., Malaysia)	OMN	Other mineral mining
IND	India	M_M	Metals and manufacturing (e.g., motor vehicles)
XSA	Other South Asia (e.g., Bangladesh)	FOD	Food processing (e.g., food products)
MEX	Mexico	OMF	Other manufacturing (e.g., textiles)
ARG	Argentina	CNS	Construction
BRA	Brazil	TRT	Transportation (e.g., air transportation)
XLM	Other Latin America (e.g., Chile)	CMN	Communication
XME	The Middle East (e.g., Saudi Arabia)	WTR	Water
ZAF	South Africa	OSG	Governmental services (e.g., education)
XAF	Other Africa (e.g., Egypt)	SER	Other services (e.g., insurance)

[a] The electric power sector consists of thermal power (i.e., coal-, oil-, and gas-fired), hydropower, nuclear power, solar power, wind power, geothermal power, biomass power, waste power, and other renewables. In addition, thermal power and biomass power with CCS technology are available.

uncertainties in the ESMs.[2] RCP4.5 is a scenario of long-term global GHG emissions, short-lived species, and land-use and land-cover that stabilize RF at 4.5 W/m^2 in 2100 without previously exceeding that value [7]. Moss et al. [2,3] describe the defining characteristics of this scenario.

Unlike previous IPCC scenarios [1] examining possible global futures and the associated GHG emissions in the absence of measures designed to limit anthropogenic climate change, RCP4.5 is a stabilization scenario and assumes that climate policies are introduced to achieve the RF level.

The emission pathways to achieve 4.5 W/m^2 in 2100 vary depending on how much carbon the ecosystems take up. In this study, we focus on the various emission pathways derived from an EMIC considering the uncertainty of the ESMs (see Section 2.3).

2.3. Emission pathways

The emission pathways used here are compatible (or allowable) emission pathways obtained by using an EMIC with the RCP4.5 concentration scenario [26,27]. Tachiiri et al. [27] examine the uncertainty in CO_2 emissions, while the other GHG emissions are fixed to the values of RCP4.5 [7,28]. Tachiiri et al. [27] perturbed 12 physical and biogeochemical parameters in an ESM emulator to represent the spread of the existing ESMs. Each ensemble member was then weighted by the extent to which it represented the present climate. The accumulated weight was calculated from the ensemble member of the smallest allowable emission, and the 5th (lower bound), 50th (mean), and 95th (upper bound) percentiles of the accumulated weight are analyzed. Henceforth, these percentiles are called the “lower bound” (90% confidence interval), the “mean,” and the “upper bound” (90% confidence interval). Fig. 2 shows the three global CO_2 emission pathways included in the RF4.5 scenario. We also analyzed the emission pathways between the upper bound and mean cases (with cumulative weight of 84%), and the mean and lower bound cases (with a cumulative weight of 16%). These results lie between each of the two cases; hence, we only show the three outlined results in this paper.

3. Results and discussion

In achieving the three emission pathways in the RF4.5 scenario, the model assumes emissions are reduced cost effectively through emissions trading on a global scale, as described in Section 2.1. Although the socioeconomic impacts that can be calculated by the CGE model encompass various aspects (e.g., GDP, welfare, trade, consumption, investment, and energy), this paper focuses primarily on changes in energy and GDP because they are suitable indicators to comprehensively understand the socioeconomic impacts of reducing emissions and are used often in this research area [5–9].

Fig. 3 shows the carbon prices, or marginal abatement cost curves, in the RF4.5 scenario. The prices tend to increase over time along with increases in emission reductions from the reference scenario, and the prices in the lower bound case are the highest. The carbon price rises gradually in the upper bound case, and sharply from 2070 to 2080 in the mean case and from 2060 to 2080 in the lower bound case. Such sharp increases in the carbon price are due to multiple factors, such as emissions, technological improvement, and prices of energy resources. However, emission reduction is the principal factor. In the corresponding periods, rapid emission reductions are observed (Fig. 2), while emissions continuously increase in the reference scenario. To implement such an emission reduction, sharp increases in price of carbon are required. By 2100, the carbon price is approximately three times higher in the lower bound case than in the upper bound case. The high carbon price induces a shift from carbon-intensive energy to less-carbon-intensive energy. Because the high energy costs arising from the high carbon price promote the introduction of CCS technology, global CO_2 emissions are very small in the lower bound case. The difference in the carbon price between the lower

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[2] We also analyzed the emission pathways based on RCP2.6 [8]. However, because the analysis for the lower bound allowable emission pathways to achieve 2.6 W/m^2 in 2100 by the CGE model was infeasible, we focused on the RF4.5 scenario in this paper.

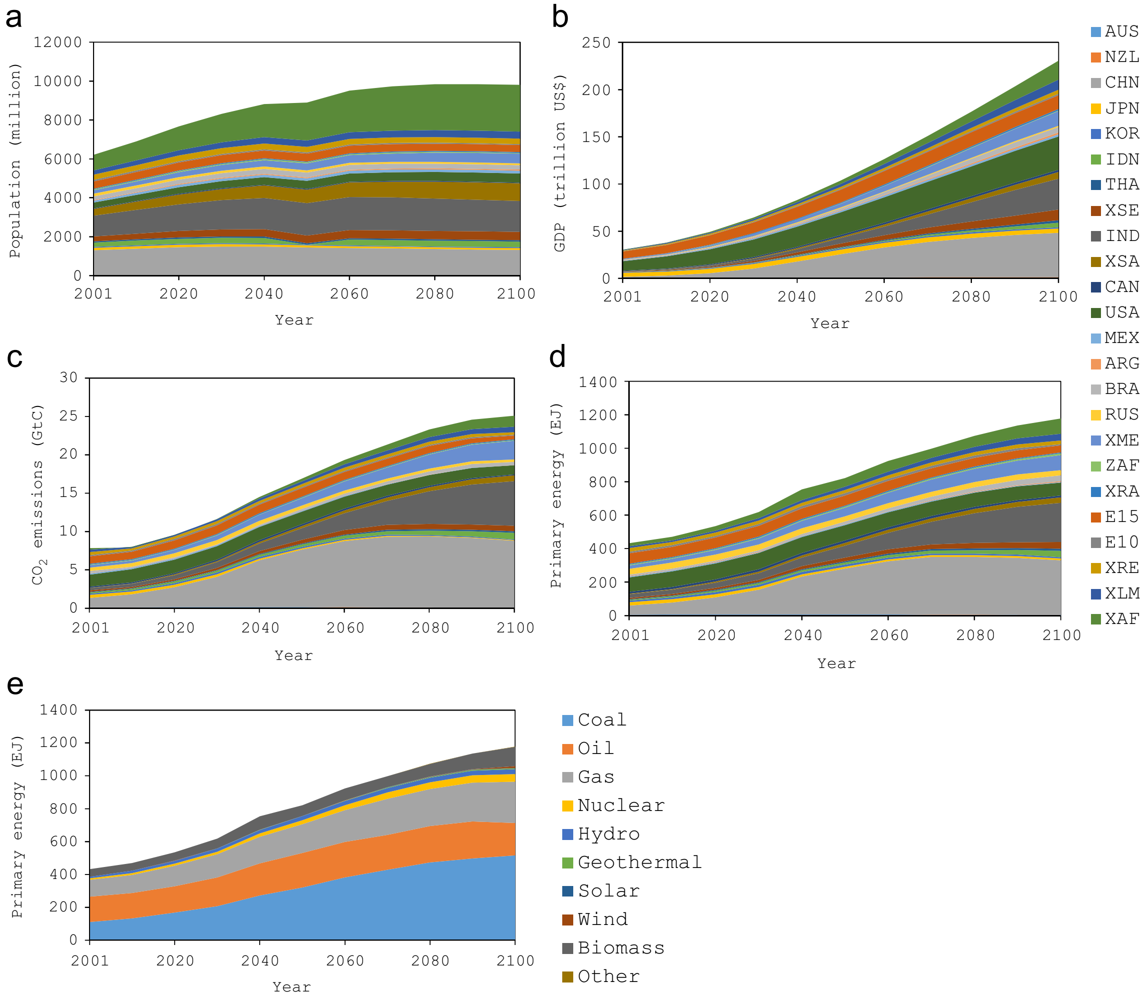

Fig. 1. Property of the reference scenario (a: Population; b: GDP; c: total CO_2 emissions; d–e: primary energy demand (by region and by fuel type)).

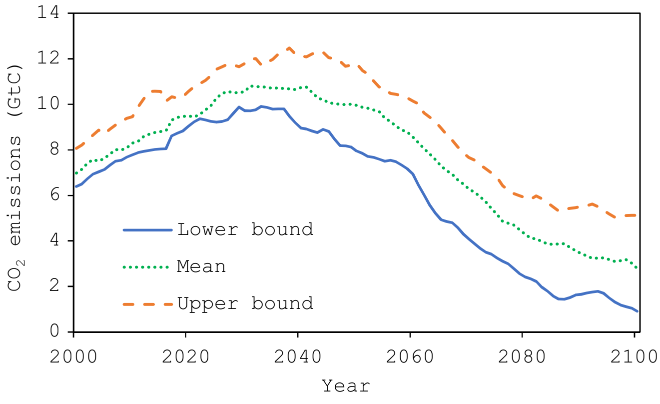

Fig. 2. Global CO_2 emissions of the RF4.5 scenario [27].

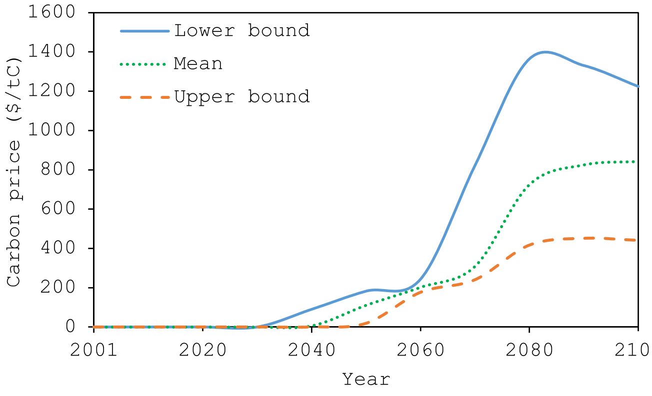

Fig. 3. Carbon prices (marginal abatement cost curves) in the RF4.5 scenario.

bound and upper bound cases in 2060 is less than that in 2050. This less difference is also due to emissions in these years. From 2050 to 2060, emissions are reduced from 7.9 GtC/yr to 6.9 GtC/yr in the lower bound case, while they are reduced from 11.8 GtC/yr to 10.1 GtC/yr in the upper bound case, indicating a larger emission reduction in the upper bound case during the corresponding periods. Thus, there is a greater increase in the carbon price in the upper bound case from 2050 to 2060.

The carbon price in the lower bound case declines after 2080. Because, in this case, emissions reductions after 2080 are more moderate than previous periods (the emissions are 4.1 GtC/yr in 2070, 2.4 GtC/yr in 2080, 1.7 GtC/yr in 2090, and 0.9 GtC/yr in 2100), carbon prices need not be increased.

These carbon prices affect energy demand and GDP (economic activities).

In the RF4.5 scenario, the global primary energy demand in 2100 for each emission pathway is 788 EJ (lower bound case), 782 EJ (mean case), and 810 EJ (upper bound case) (Fig. 4a). Beyond 2040 – 2060, the total primary energy demand growth slows (not shown). Coal and oil demand decreases, and natural gas demand

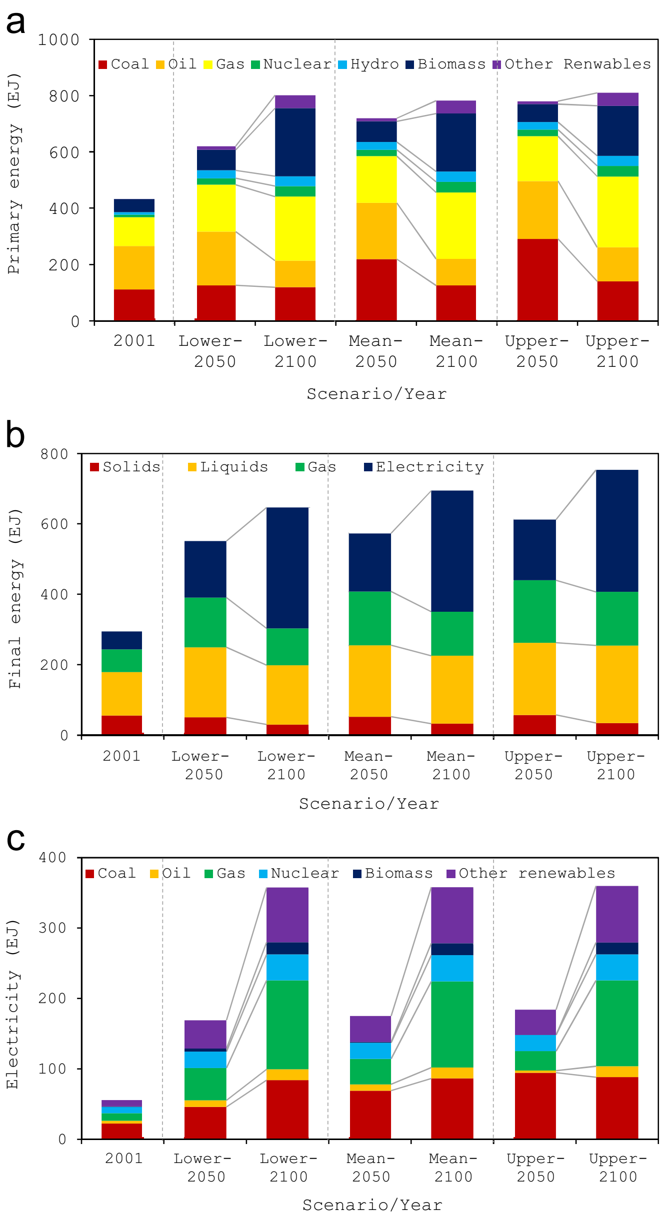

Fig. 4. Structure of energy in the RF4.5 scenario (a: primary energy; b: final energy; c: electric power generation). In each sub-figure, the left-hand bar shows the structure in the base year. The other bars show the structure of the lower bound, mean, and upper bound cases in 2050 and 2100.

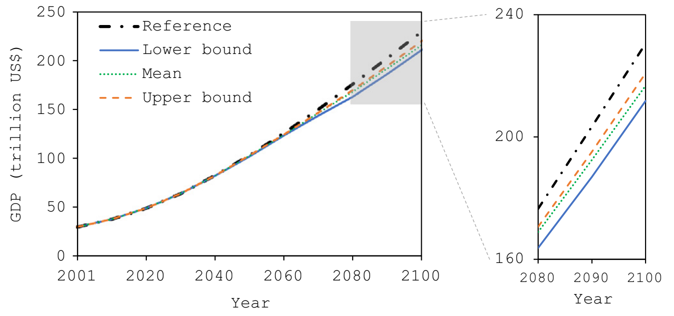

Fig. 5. Global GDP in the RF4.5 scenario. The right-hand figure shows an enlarged figure of the left-hand figure from 2080 to 2100.

increases, growing to 2.2–2.5 times the base year levels by 2100. The proportion of renewables rises from 13% in the base year to 32–40% in 2100, being higher in the lower bound case. It may seem counterintuitive that global primary energy demand in 2100 in the lower bound case is slightly larger than in the mean case[3]; however, to achieve the 2100 very low emissions in the lower bound case, it is necessary to increase the use of biomass energy with CCS technology, the only power source in this model that can offset CO_2 emissions from other sources. The biomass energy percentages increase from 11% in the base year to 30% (lower bound case), 26% (mean case), and 22% (upper bound case) in 2100. Before 2100, primary energy demand in the mean case is higher than in the lower bound case. Since biomass energy with CCS technology requires an additional energy input for capturing and storing CO_2, such inversion between the cases occurs. As indicated below, the final energy demand in the lower bound case is less than that in the mean case (see also Fig. 4b).

The global final energy demand increases from 295 EJ in the base year to 646 EJ (lower bound case), 695 EJ (mean case), and 753 EJ (upper bound case) in 2100 (Fig. 4b), significantly lower than the demand shown in the reference scenario (956 EJ). The proportion of electricity increases rapidly and reaches 46–53% in 2100, higher than the 41% in the reference scenario. This increase is due to the rising percentage of renewables in primary energy demand to reduce GHG emissions. The lower bound case leads to the highest proportion of electricity. The proportions of other fuels decline during this century, particularly coal ("Solids" in Fig. 4b).

Furthermore, in the RF4.5 scenario, the electric power sector shifts away from coal-fired power generation towards gas-fired power generation (Fig. 4c), while renewables exceed 25%. Hydropower decreases from 16% in the base year to 10% in 2100, while solar, wind, and biomass power each increase to approximately 5–7% in 2100. Higher percentages are seen in the lower bound case. Consequently, CO_2 emissions from electric power generation peak around 2030–2050 and become negative around 2060–2070. The peak and negative periods come earlier in the lower bound case in the RF4.5 scenario because of increased use of renewables and CCS technology. CCS technology is installed on over 90% of thermal power plants, representing about 50–60% of the global electric power generation in 2100. Such advanced technology plays a significant role in the RF4.5 scenario, particularly when human society is allowed to emit less CO_2.

In 2100, the global GDP for each emission pathway of the RF4.5 scenario is $212 trillion (lower bound), $217 trillion (mean), and $221 trillion (upper bound) (Fig. 5). The GDP increases continuously during this century for all the cases in the RF4.5 scenario, although the GDP levels in 2100 are 4.2–8.1% smaller than that of the reference scenario. A comparison of the GDP levels among the three cases shows that the GDP in the lower bound case is 4.1% smaller than that in the upper bound case (equivalent to a 0.042% decrease in the annual GDP growth rate in the 21st century). This gap, roughly equal to the level of China's GDP in recent years, is not insignificant, but it is smaller than the difference between the upper and lower bound cases of the global CO_2 emissions themselves. 2100 global CO_2 emissions in the upper bound case are 5.1 GtC/yr, while those in the lower bound case are 0.91 GtC/yr. In addition, the cumulative CO_2 emissions in this century are 619.7 GtC in the lower bound case, which is approximately two-thirds of those in the upper bound case (917.6 GtC; cf., the cumulative emissions in the mean case are 764.9 GtC). These emission differences are much larger than the differences seen in GDP.

Higher carbon prices drive energy prices up, particularly higher carbon-intensive energy; thus, energy demand declines. However,

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[3] Generally, current economic activities highly depend on fossil fuels. Hence, primary energy consumption inevitably results in high CO_2 emissions.

there are substitution effects in the economy (and in the model, which is composed of CES production functions) among production factors and intermediate inputs. This situation means that relatively-low-price production factors and intermediate inputs are used in the range of elasticity of substitution for economic activities. In addition, the revenue from emissions trading is used in each region's final demand sector. Therefore, the increase in carbon prices does not directly contribute to the decline in GDP; rather, the increase is reduced by such mechanisms, and as a result, the differences in GDP become smaller than those seen in the carbon prices.

The GDP structure shows that increasing the carbon price also drives a shift from industry towards the service sector in the RF4.5 scenario. The proportion of GDP based on industry is 31.3% and that of the service sector is 64.4% in the base year; in 2100, these percentages become 27.8% and 69.2% in the reference scenario and 25.3 – 26.1% and 71.0 – 71.9% in the RF4.5 scenario. The service sector represents a higher percentage in the lower bound case than in the other two cases in the RF4.5 scenario. Similarly, the industry represents a lower percentage in the lower bound case than in the other two. This phenomenon is also a factor in mitigating CO_2 emissions.

Finally, to understand the mechanism by which emissions are reduced, the CO_2 emissions are decomposed into four factors by the Kaya Identity [29]:

$$CO_2 = \frac{CO_2}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P \tag{1}$$

where CO_2: CO_2 emissions; E: primary energy use; GDP: GDP; and P: population.

The ratio CO_2/E represents the CO_2 emission (or carbon) intensity of energy, E/GDP is the economy's energy intensity, and GDP/P is the global per-capita GDP.

The instantaneous CO_2 emission growth rate can be expressed as the sum of the instantaneous growth rates of the four factors identified in Eq. (1). The difference among the scenarios and the emission pathways in the RF4.5 scenario is the difference in the growth rates for the four factors.

Because in the RF4.5 scenario, global CO_2 emissions peak around 2050 and then decrease through the rest of the century, we focus on the behavior of the three cases in the RF4.5 scenario relative to the reference scenario before and after 2050. Fig. 6 illustrates the annual percentage changes in the Kaya Identity factors.

As described in Section 2.2.1, all of the scenarios/cases are assumed to share a common population scenario. Annual global GDP increases throughout the century; changes in annual global per-capita GDP remain similar in both the reference and RF4.5 scenarios from 2001 – 2050, but clearly smaller in the lower emission cases in the RF4.5 scenario from 2050 – 2100.

The annual change in energy intensity decreases in both scenarios, including the three emission pathways of the RF4.5 scenario. The energy intensity improvement rates are higher in the lower emission cases before 2050. After 2050, however, the rate in the lower bound case is lower than those in the mean and upper bound cases. As described previously, this change might be due to the introduction of large biomass energy with CCS technology in the lower bound case, realizing very low CO_2 emissions at the end of this century.

Regarding the carbon intensity change rates, the positive values indicate the increasing carbon intensity of energy, reflecting a shift towards higher carbon-intensive energy, particularly before 2050. In the reference scenario, the increase results from the increased demand for cheap coal because no climate policies are introduced; in the RF4.5 scenario, the demand for coal and other fossil fuels is still large enough to increase the carbon intensity because of low carbon prices (Fig. 3). Within the RF4.5 scenario, changes in carbon intensity are lower in the lower bound case than the other two cases. Energy use continues to be more carbon intensive in the reference scenario, but drops in the RF4.5 scenario after 2050. This decline indicates the need for a rapid shift to low-carbon-intensive energy at least during the latter half of this century in order to achieve 4.5 W/m^2 by 2100. Notably, if the allowable CO_2 emissions are low, the intensity should be decreased greatly.

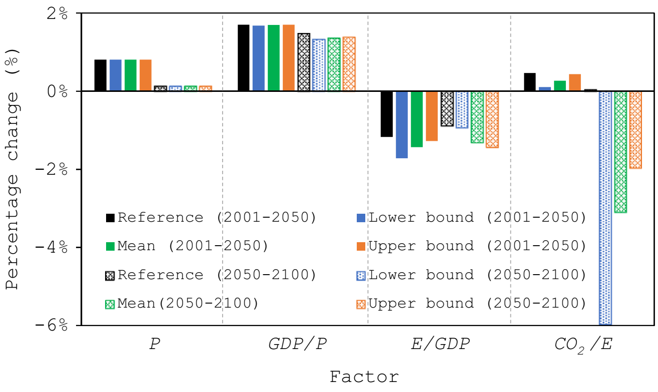

Fig. 6. Annual percentage changes of the factors in the Kaya Identity.

Among the four factors, carbon intensity is the principal factor lowering emissions in the RF4.5 scenario. In particular, an annual reduction of 6.0% is required in the lower bound case during the latter half of this century, which is larger than the mean (3.1%) and upper bound (2.0%) cases. This finding indicates that economic growth is realizable even if human society only is allowed to emit low amounts of CO_2 as in the lower bound case; however, efforts are required to use less-carbon-intensive energy in the latter half of this century, including a rapid shift in the energy structure towards renewables.

We are aware that some assumptions could affect the results, such as emission reductions under optimal conditions, the influence of CCS technology and nuclear power generation, the future economic structure in the CGE model, and the linkage between the models. In the CGE model used in this study, emissions are reduced cost-efficiently by introducing emissions trading on a global scale, which equalizes marginal abatement costs (carbon price) among the regions. Although this assumption is theoretically sound, it is not likely to occur even if global emissions trading is realized because of factors like transaction costs, imperfect information, and imperfect competition [30–34]. In addition, it is uncertain whether such a global emissions trading market will become established in the future, although regional and national emissions trading markets do already exist.

This study assumes that CCS technology will be available within the 21st century and will become an important technology in reducing CO_2 emissions to achieve 4.5 W/m^2 by 2100, particularly because there will then be further restrictions on CO_2 emissions. Currently, however, CCS technology remains in the experimental phase, making the extent to which CCS technology will be used in the future unclear.

In terms of nuclear power, some countries, such as Germany and Switzerland, have declared a nuclear power phase-out after the Fukushima Daiichi nuclear disaster. Some other countries, such as France, Russia, and China, continue to use nuclear power generation. Others, including Japan, still have not taken a position on its future.

From these points of view, difficulty in predicting the future use of CCS technology and nuclear power continues. In this study, however, we simply assume that the future application of such technologies will be determined by the relative prices in the model; the suitability of this assumption should be confirmed continuously with great care.[4]

Also, in the CGE model, future changes in economic structure (e.g., major technological innovation and appearance of unrealized technology, products, and industries that do not currently exist) are not considered since it is impossible to estimate such changes with certainty. However, since the model considers substitution effects in the economy by using CES functions in production and utility functions, the model can capture the shift in production (and consumption) among industrial sectors (see above) by reducing emissions. Furthermore, the model involves advanced technologies and energy efficiency improvement in power generation to capture possible future situations.

Finally, this study combines climate and socioeconomic aspects by applying the emission pathways obtained from the EMIC experiments [27] to the CGE model. This application does not mean that the two models are coupled; only one side of the interaction between the two is considered. The study does not consider the impact of changes in socioeconomic conditions due to emission reduction on the climate system.

Here, however, the socioeconomic impact of the three emission reduction pathways in the RF4.5 scenario was analyzed and compared based on the same assumptions mentioned above. Thus, the qualitative interpretation of this study is not affected by the above points.

4. Concluding remarks

In this study, we analyzed the impact of ESM (or climate model) uncertainties on socioeconomics under a medium climate mitigation scenario, which achieves a RF of 4.5 W/m^2 in 2100, using the CGE model. The emission pathways analyzed here are the 5th (lower bound), 50th (mean), and 95th (upper bound) percentiles of the weighted ensemble members in a parameter perturbation experiment using an EMIC [27]. Different pathways are derived from various physical and biogeochemical properties. The results for the three emission pathways suggested that the economic (GDP) and energy impacts were significantly larger in the lower bound case, although the economy and energy demand continuously increased during the century. However, global primary energy demand in 2100 in the lower bound case was slightly larger than in the mean case because of the use of biomass energy with CCS, the key technology for reducing future emissions. It was enhanced to achieve very low CO_2 emissions in 2100.

Comparing the upper bound case and the lower bound case, there were significant differences in the impacts. For example, the carbon price became approximately three times higher, the global primary energy demand was 1.0% lower, and the global final energy demand was 14% less in the lower bound than in the upper bound case for 2100. As a result, the GDP in the lower bound case was 4.1% smaller than that of the upper bound case in 2100. This gap, roughly equal to the level of China's GDP in recent years, is not insignificant, but it is equivalent to a mere 0.042% decrease in the annual GDP growth rate during the century. In addition, the gap in GDP between the two emission pathways was smaller than the differences (width of the 90% confidence interval) in annual and cumulative emissions. Furthermore, the differences seen in the GDP are smaller than those in the carbon prices among the emission pathways in the RF scenario. This finding results from the substitution effect in the economy and the use of revenue from emissions trading.

As seen in the primary energy demand in this study, the largest/smallest socioeconomic impacts obtained from the CGE analysis do not necessarily correspond to the lower/upper bounds of the emission pathways. However, Metz et al. [36], model comparison studies [9], and RCP studies [5–8] generally recognize that a larger/smaller socioeconomic impact is observed when the emissions are lower/higher. This study captures such features.

There are several policy implications of this study. Because of the imperfect understanding and representation of the climate system, human society does not know the exact emission pathway for achieving a certain RF (or concentration) level in the future; this relates to temperature change. Hence, we may follow an emission pathway to achieve a certain RF level and then realize that the emission pathway is inappropriate for achieving the target when the inconsistency between the assumed (or modeled) and the actual response by the earth system becomes significant. Such circumstances will necessitate shifting to another pathway. Should this result in a transition from a lower emission pathway to a higher emission pathway (e.g., from the lower bound case to the mean or upper bound case in this study), the change will be relatively easy because it will be a return to the traditional system. If the lower emission pathway is more appropriate from a socio-economic perspective, this transition will not be necessary, and the lower emission pathway is also appropriate from the climate change aspect. However, transitioning from a higher emission pathway to a lower emission pathway requires a large and rapid shift in the energy use and composition of industrial sectors (higher growth of less energy/carbon intensive sectors), as demonstrated by the results in Section 3. This transition is something that has never been experienced in human history. In such cases, appropriate policy measures must be developed to induce society to follow a new pathway.

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Appendix A

This appendix provides further details of the CGE model used in the analysis.

A.1 CGE models in general

A CGE model is an economic model that uses actual economic data, such as Input-Output Tables and national economic accounting to estimate how the economy might react to changes in certain factors. These factors include policy and technology, where price is an important signal driving economic agents and balancing supply and demand of each goods/service and each production factor in the economy. The model can be used on a global or individual country basis. A CGE model consists of equations describing model variables and a database consistent with the equations. The equations generally are based on neo-classical economic theory, often assuming industrial sectors (producers) cost minimization, average-cost pricing, and final demands based on optimization behavior. The model also is widely regarded as a top-down approach to analyzing the economic implications of climate change [17,19]. Carbon pricing policies, such as carbon taxes and emissions trading, change the relative prices from the baseline condition according to the GHG intensity of the goods. This change means that energy-intensive industries, such as the steel industry,

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[4] There exist studies analyzing the socioeconomic impacts of either CCS technology or nuclear power is unavailable [16,35].

tend to experience a larger negative effect from such policies. Many climate policy designs have been evaluated quantitatively with various CGE models [14,15,18,37–39].

A.2 CGE model in this study

A.2.1 model structure

The model used in this study is a multi-regional and multi-sectoral recursive dynamic CGE model on a global scale, incorporating energy and environmental components, based on the work of Masui et al. [5], Matsumoto and Masui [14,15], and Okagawa et al. [16]. The model is disaggregated into 24 geographical regions and 21 types of economic goods and services (Table 1). Each region includes the production sectors in the table. One sector produces one type of goods/service, and we assume perfect competition in all markets. We also assume that production is subject to constant returns to scale technology. The electric power sector (the ELY sector in Table 1) is disaggregated into detailed technologies, including thermal power (coal-, oil-, and gas-fired), hydropower, nuclear power, solar power, wind power, geothermal power, biomass power, waste power, and other renewable forms of power generation. Advanced thermal power plants, such as the integrated gasification combined cycle, are assumed to be available in the future. In addition, CCS technology can be selected as an advanced technology by thermal power and biomass power generation. These new technologies also are modeled as the production functions of the ELY sector.

Each industrial sector in the economy is represented by a nested CES production function (including the Leontief production function if the value of elasticity of substitution is zero, and the Cobb – Douglas production function if the value is one). Although all of the production structures are based on nested CES functions, we assume several different production structures by sector. The most basic structure is illustrated in Fig. A1 where goods/services are produced as a CES aggregate of a value-added composite, intermediate inputs, and an energy input composite. It is applied to several of the defined sectors (energy-intensive industries (EIS), metals and manufacturing (M_M), other manufacturing (OMF), food processing (FOD), construction (CNS), transportation (TRT), communication (CMN), water (WTR), governmental services (OSG), and other services (SER)). The value-added composite is a CES aggregate of labor and capital. The energy composite is a CES aggregate of a fossil fuels composite and ELY. The fossil fuels composite is a CES aggregate of coal (COA), a liquid energy composite, and a gas energy composite. The liquid energy composite and the gas energy composite are CES aggregates of crude oil (OIL) and petroleum products (P_C), as well as natural gas (GAS) and gas manufacture and distribution (GDT), respectively. During production, GHGs are emitted from fossil fuels and industrial processes. In the production structure, emissions from fossil fuels are considered as Leontief aggregates (aggregation using the Leontief production function) at the bottom-level nests, while emissions from industrial process are considered as the Leontief aggregate at the top-level nest. GHG emissions are treated the same for the other sectors. With respect to the fishery (FSH) and other mineral mining (OMN) sectors, resources (natural resources) are treated as a component of the value-added composite in contrast to Fig. A1. Similarly, in the agriculture (AGR), livestock (LVK), and forestry (FRS) sectors, land is treated as a component of the value-added composite.

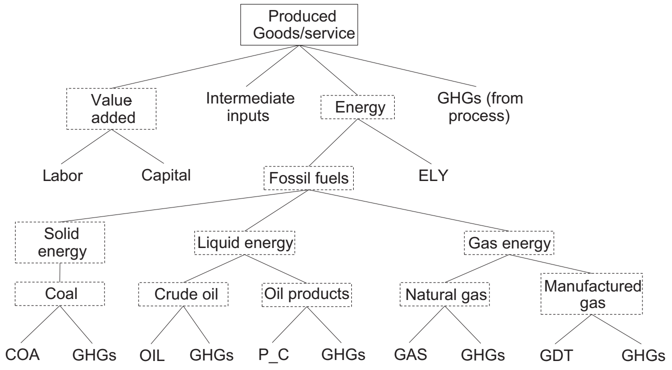

Fig. A1. Production structure for the manufacture and service sectors (EIS, M_M, OMF, FOD, CNS, TRT, CMN, WTR, OSG, and SER). This figure shows the most basic structure in the model. In each nest, corresponding factors are aggregated by a CES function, the elasticity parameters of which are obtained from the GTAP6 database [20] (as is the case for the other sectors).

In the production structure for the fossil fuels extraction sectors (the COA, OIL, and GAS sectors), natural resources are considered to be aggregated at the top-level nest. The magnitude of the resource limits and associated extraction costs are obtained from Rogner [40].

With respect to the P_C sector, crude oil is considered to be aggregated at the top-level nest (and not treated as energy) because most crude oil is used as feedstock in this sector. Similarly, in the GDT sector, natural gas is considered to be aggregated at the top-level nest to treat it as feedstock in this sector.

Finally, there is a slightly different structure in the ELY sector. The thermal power sectors use corresponding fossil fuels as an input (e.g., COA is used for coal power generation), while the renewables sectors do not. However, the biomass power sector uses land as an input, and the other renewables sectors use the input of their corresponding renewable sources. This structure is similar to the Emissions Prediction and Policy Analysis (EPPA) model [41]. In the model, the elasticity parameters are taken from the GTAP6 database [20], as it is also used for economic data.

Each industrial sector produces goods/services that are delivered for the international market and/or the domestic market by using inputs of production factors, raw materials, and energy. The Armington assumption [42] is applied for international trade (goods/services produced in different regions are imperfect substitutes). In the model, goods/services from different regions are aggregated through a two-stage CES function; first, imports from different regions are aggregated into a composite import, and then composite imports and domestic goods/services are aggregated.

In each domestic market, the supplied goods/services are consumed as final consumption, investment, and/or intermediate input for industrial sectors. The total investment demand in each period is set exogenously to meet a prescribed future economic growth rate (see Section A.2.4 below). The model uses a putty-clay approach for forming capital. It includes two types of capital, old (or existing) capital and new capital. Old capital cannot be moved among sectors, while new capital can be installed in any sector. When new capital is installed in a certain sector, it is subsequently handled as old capital. Technological improvements, such as energy efficiency improvement, are applied only to new capital. Thus, the productivity of aggregated (old and new) capital is the weighted average of the technology levels in old and new capital. This factor suggests that the more new capital is installed, the more rapid the efficiency change will be. Industrial sectors without new investment do not realize technological improvement.

Each region has one final demand sector consisting of the household sector and government. The final demand sector in each region is assumed to own all production factors (i.e., capital, labor, land, and resources), supplying them to the industrial sectors through the economy's factor markets. The final demand sector income is derived from the sale of the production factors. The final demand sector distributes income between final consumption (of goods/services) and savings. Savings rates are identical to investment, which is exogenously determined. The final demand for each goods/service is determined to maximize the utility represented by a Cobb–Douglas function subject to an unsaved income constraint in each period. GHGs are emitted when the final demand sector consumes fossil fuels.

A.2.2 GHG emissions

The model is run to follow the global GHG emission pathways with constraints including the following: CO_2; methane; nitrous oxide; carbon monoxide; nitrogen oxides; sulfur oxides; non-methane volatile organic compounds; black carbon; organic carbon; and ammonia. Because the model cannot handle fluorinated gas (hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) emissions endogenously, the emissions of these gases are given exogenously.

A.2.3 Baseline data

The CGE model is calibrated to reproduce economic activity and energy levels in the base year (2001) using the following data sources: the GTAP6 database [20] for economic activity levels; the EDGAR v4 database [21] for GHG emissions; and the IEA energy balance tables [22,23] for energy.

A.2.4 Future scenario

The simulation periods for this study include those between the base year (2001) and 2100 (i.e., 2001, 2005, 2010, and every 10 years thereafter until 2100).

Several assumptions are included to expand the model to a dynamic structure. Demographic assumptions are based on the medium variant of the UN World Population Prospects [24]. Future economic growth assumptions determining the amount of investment are based on the Sustainability First scenario in the Global Environment Outlook 4 [25]. Finally, technological improvement is based on the SRES B2 scenario [1]. These assumptions are applied to both the reference scenario and the RF4.5 scenario.

The model includes several types of renewables. It is expected that the role of renewables will increase, thus reducing future GHG emissions; however, this increase is not infinite. Therefore, the future potential of each renewable energy is set in the model. The survey and calculations of Masui et al. [43] are applied in this study.

In the emission reduction cases, the global GHG emissions (emission permits) are assigned to regions in proportion to their population in 2050 and after. Between the base year and 2050, regional GHG emission limits are set by linear interpolation of the emissions in the base year and the limits in 2050. The model also incorporates GHG emissions trading on a global scale.

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