Sectoral economic impacts of CO2 mitigation policies under different levels of stabilization targets: A study with the hybrid model DEARS

Authors and their organizational affiliations
Takashi Homma (Research Institute of Innovative Technology for the Earth)
Shunsuke Mori (Tokyo University of Science)
Keigo Akimoto (Research Institute of Innovative Technology for the Earth)
Toshimasa Tomoda (Research Institute of Innovative Technology for the Earth)
Yasuhiro Murota (Shonan Econometrics Inc.)

Abstract

This study compares the economic impacts of different stabilizing levels of atmospheric CO2 concentration by a new intertemporal energy-economic optimization model, namely, DEARS (Dynamic Energy-economic model with multi-Regions and multi-Sectors. The model has the input-output structures defined by the Leontief production function based on the assumption of the time-series input-output coefficients scenarios with changes in technical structures. In this paper, we focus on how the sectoral economic activities are affected by the carbon mitigation policies up to the middle of this century. Simulation studies focus on atmospheric stabilization of carbon dioxide at levels of 450–650 ppm CO2 only. The impacts of sectoral productions on economic activities in the carbon stabilization cases are dependent on sectoral characteristics; the carbon emission reduction policies have less economic impacts on the sectors with less energy requirements like “service sector”, while they have more critical impacts on the sectors served as investment commodities like “construction sector,” and energy-intensive commodities like “iron and steel sector.” The GDP losses and shadow prices increase within the relatively small ranges in the S650-S500-CO2 only cases while the losses in the S450-CO2 only case increase rapidly and enormously. Innovative technologies in the “transport sector” into energy supply sectors are required in the stabilizations at 450 ppmv-CO2 only before 2030 under the assumption of the relatively rigid substitution of energy demands using the Leontief functions as in the DEARS model.

Title, address, telephone, Fax, and E-mail address of the lead author
Takashi Homma,
Researcher,
Research Institute of Innovative Technology for the Earth (RITE),
9-2 Kizugawa-dai, Kizugawa-shi, Kyoto 619-0292, Japan
Phone +81-774-75-2304, Fax +81-774-75-2317
homma@rite.or.jp

1. Introduction

The Kyoto Protocol, which came into force in February 2005, is the first step toward establishing an international treaty designed to limit greenhouse gas (GHG) emissions for Annex I countries for the period between 2008 and 2012. The importance of assessing the mitigation impacts is increasing in light of the international arguments on the next framework of emission reduction after 2013. A review of 'The Economics of Climate Change–Stern Review' by Sir Nicholas Stern was released on October, 2006. This report summarized that the annual costs of achieving stabilization between 500 and 550 ppmv-CO2eq. are around 1% of global GDP, and it would already be very difficult and costly to aim to stabilize at 450 ppmv-CO2eq. In January 2007, Commission of the European Communities asserted that the global mean temperature should not exceed 2 ºC compared to pre-industrial level. In order to achieve it, by 2050 global CO2 emissions must be reduced by up to 50% compared to 1990. The European Communities should take the lead by committing autonomously to reduce its own emissions by at least 20% by 2020 and a cut that should be increased to 30% as part of a satisfactory global agreement.

In order to carry out the economic evaluations of the mitigation policies on global warming, this study are discussed focusing a short- to middle- term analysis mainly focusing on the changes in industrial structures until the middle of this century. We can observe the solutions of the dynamic changes in the sectoral value-added under the CO_2 emissions mitigation policies. In this study, we focused on how the sectoral economic activities are affected by the carbon stabilization policies.

The following two main issues in the past model studies are identified. One is that most of the existing energy systems models, e.g., MERGE[1] and MESSAGE[2], fail to assess the dynamic structural changes in the explicit international reallocations of industry sectors and energy demands under CO_2 emission constraints although these models have provided dynamic analyses, focusing on the technological changes in energy systems and their mitigation costs. The other reason is that though the integration of energy systems model and CGE model with multi-sectors, e.g., AIM[3] and MIT-EPPA[4], have iterative procedures to run dynamic simulations, they could not obtain fully-optimized solutions for capital formation trajectories and economic growth paths because they require the aprioristic assumptions such as the fixed ratio of saving in total income not depending on the levels of the economic growths. Most of existing models do not have the disaggregation of industrial sectors to express the detailed industrial structures. They did not sufficiently evaluate the dynamic changes in industrial structures because they assumed the fixed input-output coefficients of the benchmark year even in the future although they were formulated by the CES functions and/or Leontief functions in the sectoral productions.

In order to assess global warming mitigation policies focusing a short- to middle- term analysis, we have developed an energy-economic model, DEARS (Dynamic Energy-economic Analysis model with multi-Regions and multi-Sectors), integrating a top-down economic module with multi-sectors and a bottom-up energy systems module. The model includes the time-series input-output structures with changes in technical structures defined by the use of the Leontief production function. This model enables the assessments of the global warming mitigation policies under the carbon mitigation policies in the context of changes in industrial structures.

The structure of the paper is as follows. Section 2 outlines the model structure of DEARS model; Section 3 presents the computational results and discussions in a simulation study. Finally, Section 4 presents the conclusions.

2. Overviews of DEARS

DEARS is an intertemporal non-linear optimization model, extending the formulation framework based on GTAP[5] model which is a static multi-sectoral model. (see [6]) The solutions of DEARS include comparatively sectoral productions, exports and imports, household consumptions, and cost-effective structures of energy supply required to perform their economic activities under maximization of the discounted total consumption utilities. In order to evaluate carbon policies until the middle of this century, the model time span is up to the year 2067 with a 10 years step; the base year of this model is the year 1997, dependent on the available database of world and regional economic input-output tables. The model includes 18 regions and 18 non-energy sectors and eleven energy sources with seven types of primary energy —coal, crude oil, natural gas, biomass, hydro power, wind power, and nuclear power— and four types of secondary powers —solid, liquid, and gaseous fuels and electricity. —

Figure 1 shows inputs and outputs of DEARS. The model structures include the economic module through input-output tables is integrated with the simplified energy system module based on the DNE21 model, where energy supply technology and CCS (carbon dioxide capture and storage) technology are considered. The model also assumes the time-series changes in input-output coefficients estimated by the econometric method. The model decides endogeounously the economic activities and the energy demands of the respective sectors. The model is suitable for analyzing a mid-term change in the energy system and the industrial structures under the carbon mitigation policies.

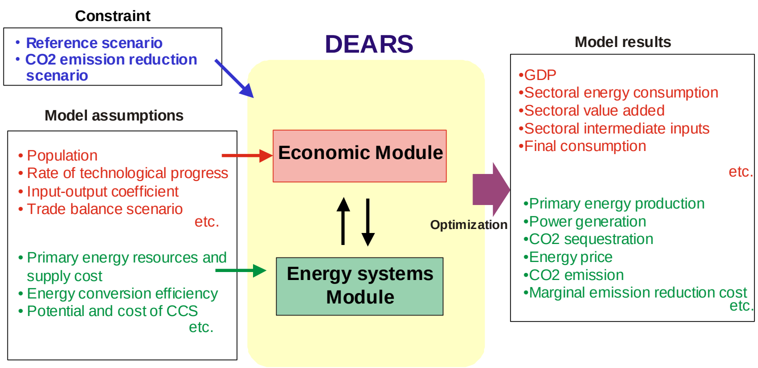

Figure 1：Inputs and outputs of DEARS

3. Middle-term evaluation of mitigation policies focusing on industrial structure changes

3.1. Effects of reductions of CO_2 emissions on industrial structures

In this paper, we focus on how the economic activities are affected by the carbon mitigation policies. We compare the sectoral economic impacts at the following different stabilizing levels of atmospheric CO2 concentration by using DEARS: reference case (without climate policy) and stabilization cases (S650, S600, S550, S500, and S450). Under the latter five cases, the global CO_2 emissions are constrained such that they do not exceed their IPCC WGI stabilization profiles with emission trading allowed.

The population scenario in this study is taken from SRES-B2. CO_2 emissions and GDP trajectories, which are determined endogenously in the model, are harmonized with the SRES-B2 marker scenario by adjusting parameters such as the regional annual rate of technical progress. We assumed that the parameters of both the annual discount and depreciation rates are 5% in all the regions. The intermediate coefficients of the input-output tables in the economic module are based on the time-series input-output coefficients estimated under the industrial structure changes scenario. The optimization software GAMS/CONOPT3 was used for the simulation study. As mentioned previously, it is important to note here that in order to avoid the "terminal effect," which influences the computational results around the end of time horizon, we accept the solutions only until the year 2047, although we solve our dynamic model through the time horizon until the year 2067. It should be noted that the lifespan of power plants and other plants was not explicitly considered.

Figures 2 shows the changes in sectoral value-added in the stabilization cases. 18 non-energy sectors and 11 energy sources are aggregated into six sectors in the figures. Figure 3 shows the composition ratio of world outputs in the aggregated six sectors. The more stringent reductions in CO_2 emissions, the larger losses of productions are observed in all the sectors. The sectoral losses in productions of "energy-intensive sector" and "construction sector" in the stabilization cases are higher because "energy intensive sector" such as "iron and steel sector", which serves as intermediate goods, has large energy-intensity, and "construction sector" is largest shares of total investments. In addition, "construction sector" is also a domestic demand-oriented industry so that the effect of international division of production is very small. The losses of "other sector" such as "other machinery sector" are also high because they serve as investment goods. On the other hand, losses of "transport sector" and "service sector" are low because these sectors have large shares of total consumptions and small shares of total investments. In particular, "service sector" has low energy-intensity.

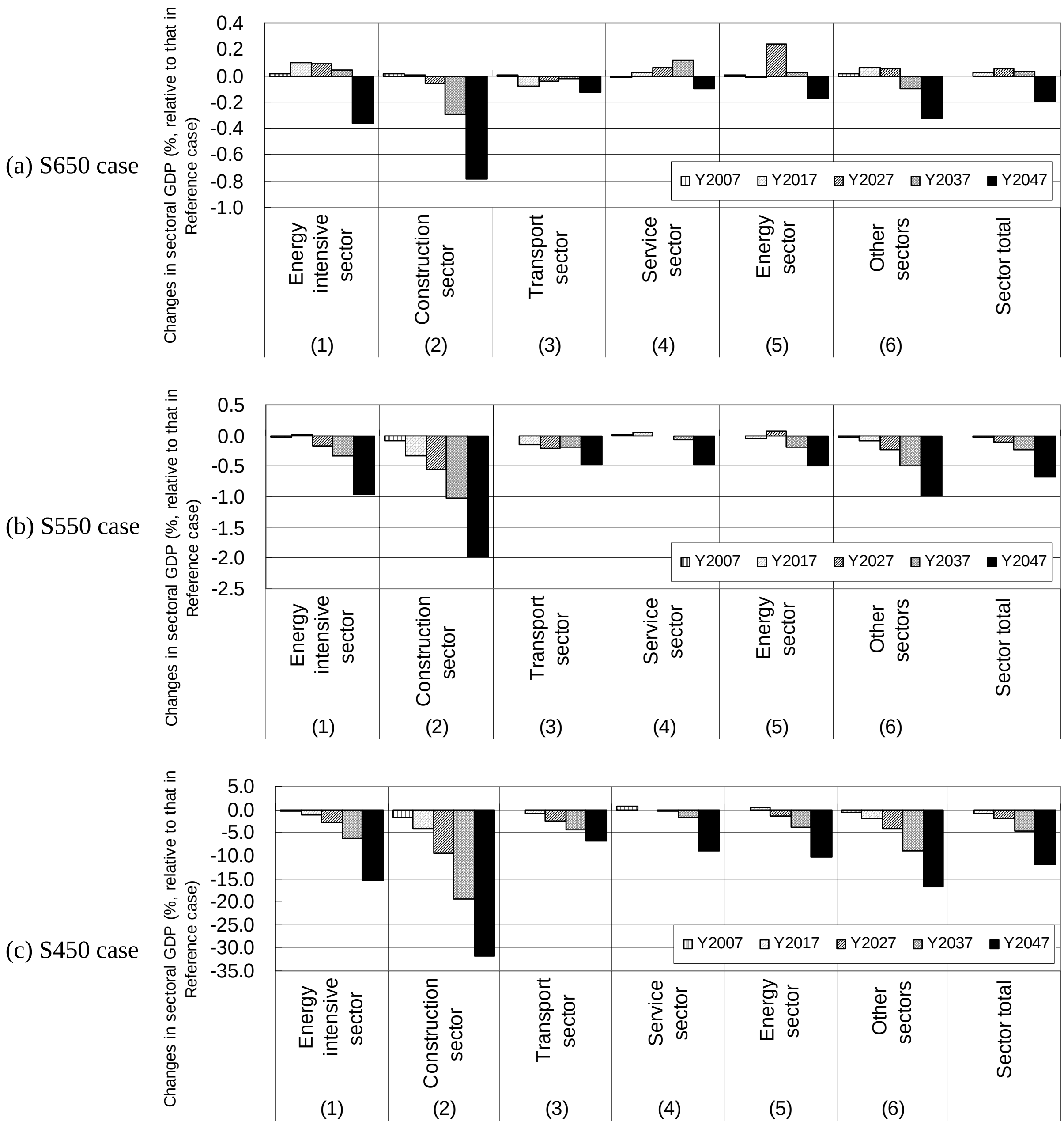

Figure 2: Changes in world sectoral GDP in the S650, S550 , and S450 cases

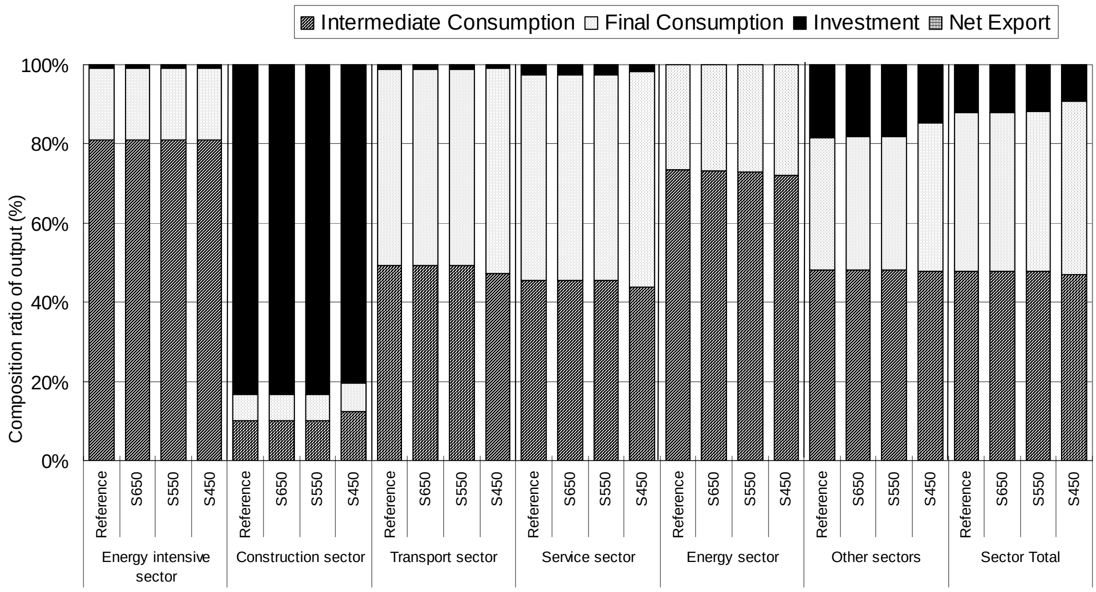

Figure 3: Composition ratio of world outputs in the aggregated sectors

Figure 4 shows the changes in sectoral outputs by demand in the stabilization cases. The decreases in the investment and intermediate consumption almost all the sectors are observed in the S450 case are relatively large, while the decreases in the final consumption are relatively small. In the service sector, the relatively small effects on the final consumption lead to the small changes in the valued-added. As mentioned previously, changes in production of a sector in the stabilization cases are greatly affected by types of serving roles in the economic flow.

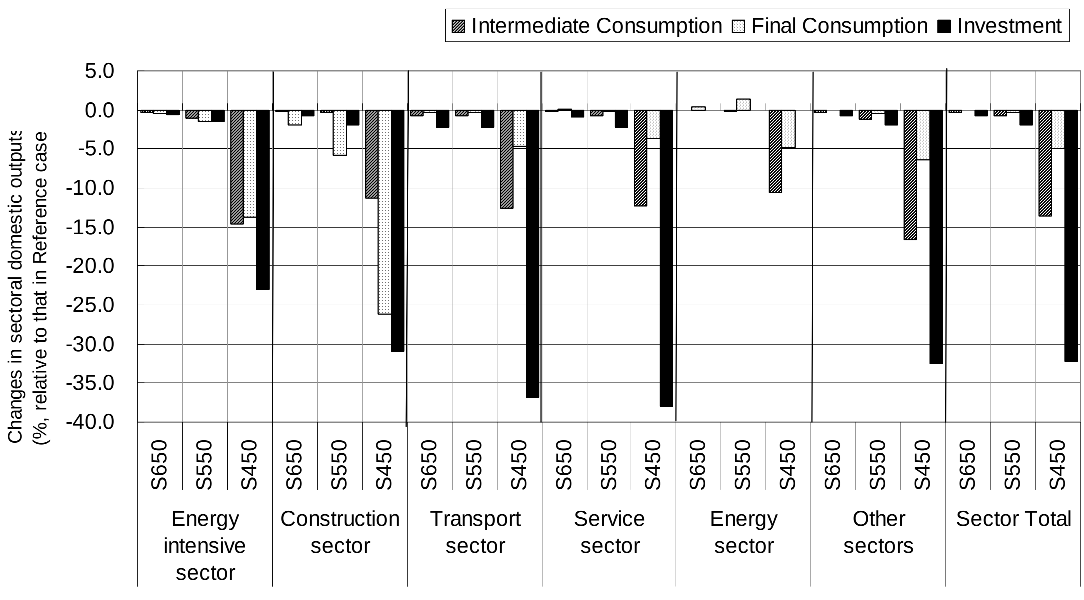

Figure 4: Changes in world outputs by demand in the year 2047

3.2. Effect of reductions of CO_2 emissions on GDP

Table 1 and Figure 5 show the GDP losses and CO_2 shadow prices under the CO_2 stabilization cases, respectively. Table 1 also includes the results of GDP losses from other models in the 450 ppmv (CO2 only) based SRES-B2 scenario in the year 2050. The GDP losses and shadow prices increase within the relatively small ranges in the S650-S500 cases while the losses in the S450 case increase rapidly and enormously. Under the assumptions of this model, the whole economic activities decrease so that large world GDP losses and high CO_2 shadow prices are required to meet the 450 ppmv (CO_2 only).

Table 1：World GDP losses under the CO_2 constraints (relative to that in reference case)

Year	S450	S500	S550	S600	S650
2007	0.01%	0.00%	0.00%	0.00%	0.00%
2017	0.79%	0.06%	0.02%	-0.02%	-0.03%
2027	2.08%	0.20%	0.10%	-0.05%	-0.05%
2037	4.74%	0.58%	0.24%	0.00%	-0.03%
2047	11.28%	1.67%	0.68%	0.32%	0.20%
2050 (DNE21)	1.33%	—	0.40%	—	0.32%
2050 (IPCC TAR[8])	2.6%	—	0.6%	—	0.4%
2050 (IMCP project[9][10])	-4% to 10% (450 ppmv Co2 only); 1% below in all but two models				
2050 (Stern Review[11])	around 1% (500-550 CO2 eq)				

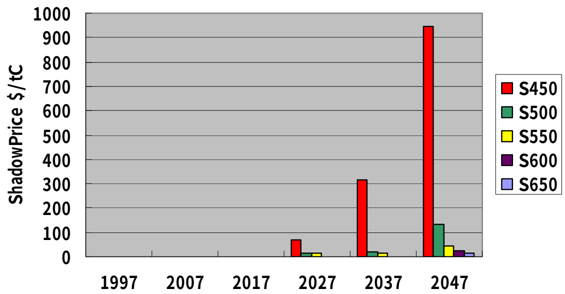

Figure 5：CO2 shadow prices in the stabilization cases

3.3. Why are large GDP losses observed in the S450 case?

Compared with the GDP losses in past studies, DEARS results in the S650-S500 cases are not significantly different from them. On the other hand, we see a considerable difference between DEARS results and past studies in the S450 case. The solutions of past energy systems models and integrated assessment models do not show surprisingly large GDP losses even in the S450 case. To explain the differences, the following two reasons are considered.

Firstly, the model structures of DEARS and past energy systems models are different. DEARS explicitly includes the industrial input-outputs defined by the Leontief function so that the substitutions of the energy inputs from energy sources to the respective industrial sectors are not flexible in order to incorporate price-induced energy saving with price elasticities. On the other hand, the conventional bottom-up type of energy systems models are based on the model structures consisting only one macro-economic sector to represent the whole economic activity so that they do not have the explicit linkages between industrial sectors. The representative energy systems models are assumed on the allowed flexibility of energy demands required in the industry with no constraints of the changes in industrial structures under the carbon mitigation policies. For example, DEN21 model represents whole energy demands by fuel source with no classification of industry, transport and residential sectors; the whole energy demands by fuel source are determined by using price elasticities as the top-down approach. The model also allows flexible substitutions of energy sources among or within sectors.

In addition, the profiles of the final energy consumptions by fuel source between DEARS and DNE21 in the reference scenario are different although the total CO_2 emission paths are based on the same profiles, SRES-B2 scenarios. Under the respective assumptions of substitutions of energy demand, the final energy demands of liquid fuels in DEARS are larger than that in DNE21, and the electrification in DEARS expands less than that in DNE21 so that the rigid structures of energy demands in DEARS at stabilizing 450 ppmv concentrations of CO2 cause larger GDP losses.

Secondly, the assumptions of energy technologies in both models are different. Compared with DNE21 model that focuses on the detailed energy systems, DEARS does not represent some energy technologies such as liquefaction of biomass. In order to evaluate effects of energy technologies, a sensitivity analysis was conducted; GDP losses with and without liquefaction of biomass by using DNE21 model in the S450 case are 1.3% and 1.8%, respectively. The result suggests that the detailed representation of energy technology does not explain the differences in GDP losses.

It follows from these arguments that the differences in assumptions of substitution flexibility of the end-use fuels between DEARS with multi-sectors and DNE21 with one-macro sector and detailed energy systems cause the large differences in the impacts on GDP losses under the stringent carbon emission constraint. The GDP losses are considerably influenced by the structures of substitutions of energy sources in the demand side. Consequently, the conventional energy systems models with one-macro economy sector that assumes the flexibility in substitution among end-use energies tend to result in the optimistic solutions, while DEARS tends to result in the pessimistic solutions. Although we do not assess in general which solutions are realistic and reasonable, we should interpret the solutions in consideration of their model structures. The evaluations by using past energy systems might underestimate the GDP losses under the CO_2 emissions constraints.

3.4. Bottleneck sectors in the S450 case

As mentioned previously, the GDP losses in the S450 are considerably large when DEARS is used, while those in the S500-S650 cases are not different from past studies. In order to search the bottleneck sectors causing the serious GDP losses in the S450 case under this model structures, we carried out the following sensitivity analysis on the hypothetical introductions of CO_2 emissions reductions technologies in the respective sectors. We compare the impacts on world GDP losses in the following two cases. (i) CO2 emissions improvement case when the CO2 emission coefficients of all the fuels in the respective sectors after the year 2027 are 50% of them, (ii) Energy intensity improvement case when the monetary input-output coefficients from the fuels in the respective sectors after the year 2027 are 50% of them. The technologies introduced in the sensitive analyses are assumed to be cost-free; the details of technologies are not explicitly considered in this study

Figure 6 shows the GDP losses under the hypothetical improvements of halving energy intensity in each sector in the S450 case; S450 regular case corresponds to the S450 case without the above hypothetical technologies. As shown in Figure 6, almost all the sectors have the small impacts on world GDP losses by the hypothetical improvements of energy intensity. The slight increases in GDP losses in the case of improvements of the transport sector are observed. This is because the model structure in which the energy consumptions in the transport sector are formulated by using GDP elasticities estimated from the historical data (see [6]). For this formulation, the reduction in the CO2 emissions in the transport sector directly lead to the reduction in GDP.

Figure 7 shows the GDP losses under the hypothetical improvements of halving CO_2 emissions in each sector in the S450 case. Figure 8 shows the CO_2 emission paths in the reference and S450 cases, respectively. As shown in Figure 7, the CO_2 emission improvements in “transport sector” result in the greatest improvements in GDP losses, while energy-intensive sectors like “iron and steel sector” have the small impacts. The GDP loss of the 450 ppmv level comes to 11.3 percent while the same mitigation case with 50% CO2 emissions reduction in the transport sector gives approximately 1.6 percent GDP loss. This indicates that “transport sector” is a bottleneck sector so as to cause the serious GDP losses in the S450 case. In this study, “transport sector” includes energy consumptions of own-vehicles in the household according to the classifications of IEA energy balances.

As shown in Figure 8, most of the sectoral shares of total CO_2 emissions remains unchanged, while the shares in the S450 case changes dynamically and the shares of “transport sector” gradually increase especially in the latter of this model time span. The improvements of CO_2 emissions in “transport sector” lead to the increases in productions of its own, and the positive effects of which through input-output tables lead to increases in production of other sectors. The emissions improvements of “transport sector” allow other sectors to increase the CO_2 emissions replacing the assignments of emissions of “transport sector” in the case of CO2 emissions improvements of “transport sector.” The production of other sectors, which decrease by decreases in the whole economic activities in the S450 regular case, increases and the world GDP losses declines in the case of CO2 emissions improvements of “transport sector.” Meanwhile, the “iron and steel sector”, which is one of the greatest carbon-intensities and energy-intensities, the decreases in GDP losses in the case of emissions improvement in “iron and steel sector” are small even in consideration of positive effects of increases in production of this sector.

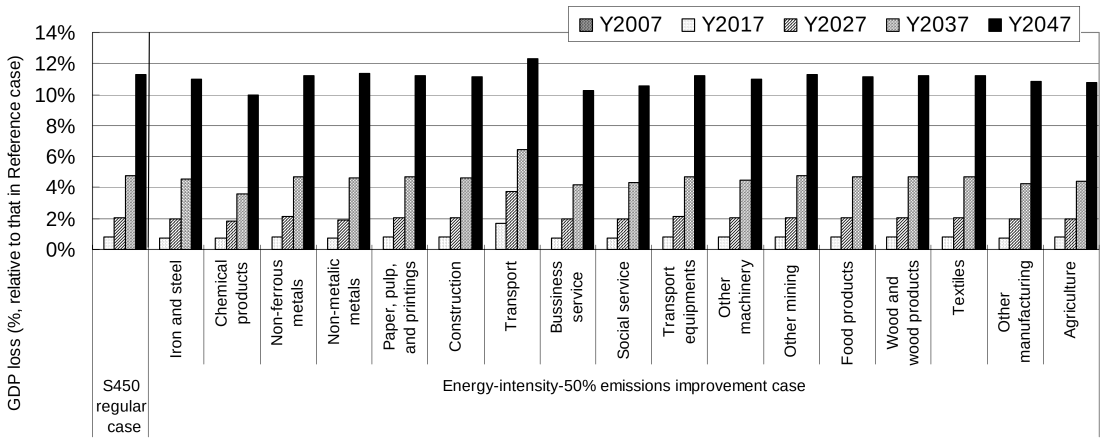

Figure 6: World GDP losses under the 50% hypothetical improvements of energy intensity of each sector in the S450 case (relative to that in reference case)

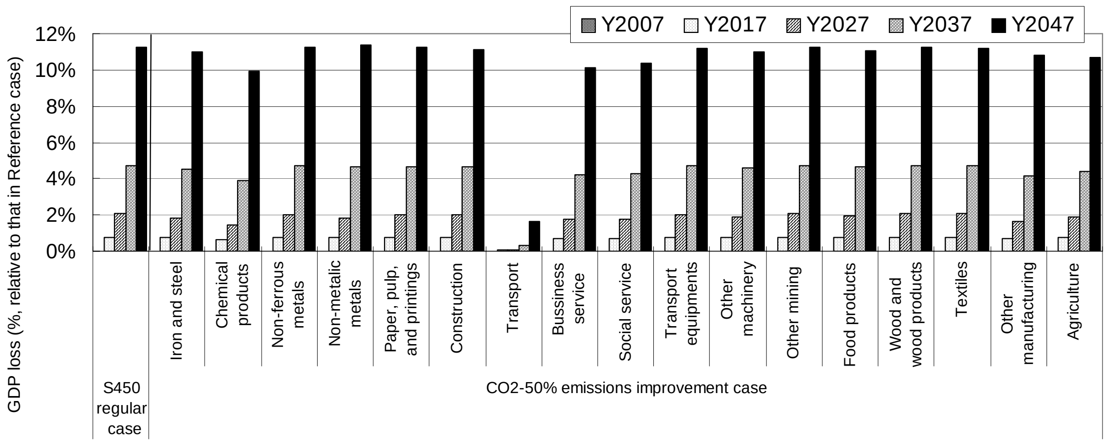

Figure 7: World GDP losses under the 50% hypothetical improvements of CO_2 emissions of each sector in the S450 case (relative to that in reference case)

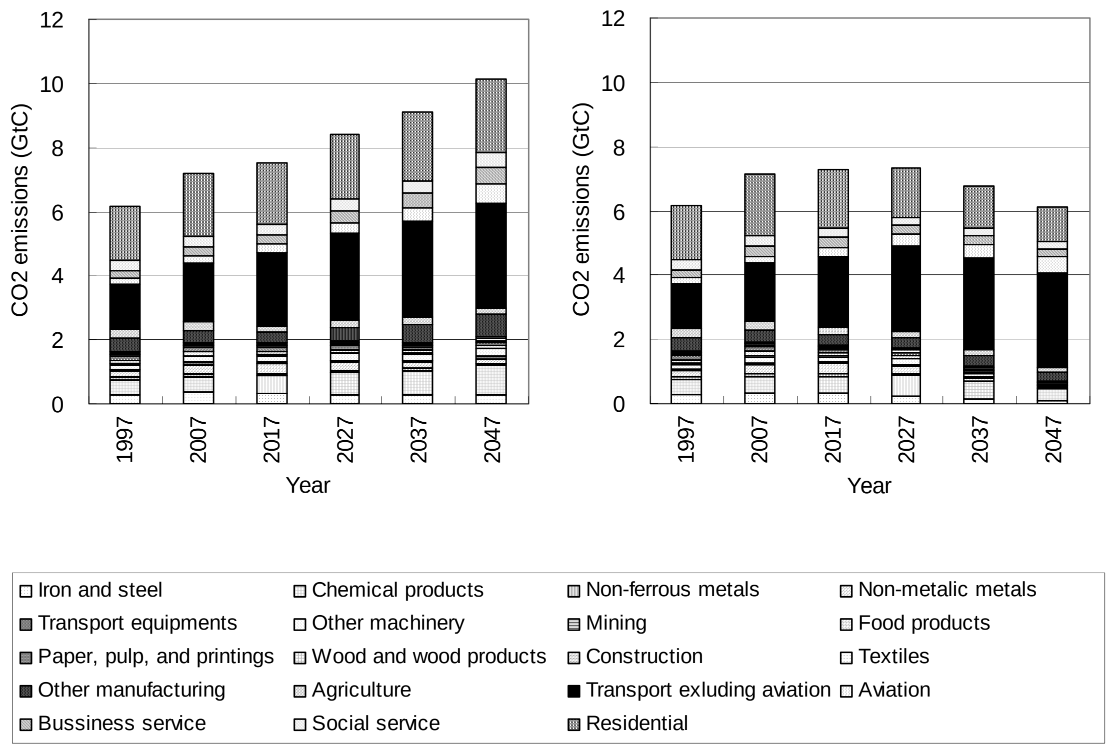

Figure 8: World CO2 emissions in Reference case (Left) and S450 case (Right)

4. Conclusions

This study evaluates the economic impacts of stabilizing atmospheric CO_2 concentration at different levels by an intertemporal energy-economic optimization model, DEARS. The sectoral losses of productions of "energy-intensive sector" and "construction sector" in the stabilization cases are higher because "energy intensive sector" has larger energy-intensity and also play a main role of intermediates goods and "construction sector" has the largest shares of total investments in the world and regions. On the other hand, losses of "transport sector" and "service sector" are lower because these sectors have large shares of total consumptions with small shares of total investments. In particular, "service sector" has a lowest energy-intensity.

The concentration stabilization at 650–500 ppmv-CO_2-only can be achieved by changes of energy demands accompanied with industrial structural changes which are reasonably expected by DEARS and by adoption of technological measures of emission reductions. The GDP losses in the 400 ppmv-CO2-only case increase rapidly and enormously under the rigid structures of energy demands based on the assumptions of the Leontief production functions in the sectoral productions. The sensitivity analysis indicates that the bottleneck sector at 450 ppmv-CO_2-only is "transport sector." However, the stabilizations at 450 ppmv-CO_2-only is possible only when innovative transportation technologies are installed before 2030 in addition to new technology installations into energy supply sectors if the assumption of the relatively rigid substitution of energy demands as in the DEARS model is accepted.

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