A study of fuel substitution flexibility effects on economic impacts of carbon emission constraints using an energy-multi-sector-economy model

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Abstract

In this paper, we focus on how the economic activities in the stringent carbon mitigation policy are affected by the flexibility in substitution among end-use energies up to the middle of this century. This study compares the economic impacts of different levels of substitution flexibility of energy demands in the end-use sectors using an intertemporal energy-economic optimization model, namely, DEARS (Dynamic Energy-economic model with multi-Regions and multi-Sectors). The model has the input-output structures including non-energy inter-industry and energy inputs defined by the production function based on the assumption of the time-series input-output coefficients scenarios which take into account changes in technological structures. Simulation studies focus on atmospheric stabilization of carbon dioxide. The impacts on economic activities in the carbon stabilization cases are dependent on flexibility of energy inputs in the end-use sectors. The GDP losses in the S450 (CO2 only) case under the rigid substitution flexibility of energy inputs defined by the Leontief production functions are larger than those in the same case under the perfect substitutions of fuels in the end-use sectors. More energy switching to lower carbon energy is observed under the perfect substitutions of fuels in the end-use sectors. These indicate that the energy switching to lower carbon energy plays an important role in mitigation of decreases in activity of the world economic under stringent global carbon constraints when the substitution flexibility of energy inputs in the end-use sectors are allowed. Not only innovative technologies to reduce the CO2 emissions but also fuel substitution flexibility in the end-use sectors lead to alleviation of world GDP losses at a stringent CO2 emission constraints, 450 ppmv (CO2 only).

keywords: global warming, input-output table, energy systems model, industry structure changes

1. Introduction

A recent report of "IPCC Fourth Assessment Report Working Group III: Summary for Policymakers (IPCC, 2007)" summarized that "with current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades. In order to stabilize the concentration of GHGs in the atmosphere, emissions would need to peak and decline thereafter. In 2050 global average macro-economic costs for multi-gas mitigation towards stabilization between 710 and 445 ppmv CO2eq, are between a 1% gain to a 5.5% decrease of global GDP." Another report of "The Economics of Climate Change–Stern Review (Stern, 2007)" was released on October 2006. This report summarized that the annual costs of achieving stabilization between 500–550 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 rise 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 voluntarily 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. The importance of assessing the mitigation impacts is increasing in light of the international arguments on the next framework of emission reduction after 2013.

In order to assess global warming mitigation policies focusing a short- to middle-term analysis in consideration of inter-industry relations in an economy, Homma *et el*. (2006) 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 which take into account changes in technological structures under the rigid flexibility of fuels in the end-use demands 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. Compared with the GDP losses in past studies, DEARS results in the S650-S500 cases are very similar to them. On the other hand, considerable differences between DEARS results and past studies in the S450 case are observed. The solutions of past energy systems models and integrated assessment models do not show surprisingly large GDP losses even in the S450 case.

Homma *et el*. (2007) indicates that the differences in assumptions of substitution flexibility of the end-use fuels between models cause the large differences in the impacts on GDP losses under the stringent carbon emission constraints. The GDP losses are considerably influenced by the structures of substitutions of energy sources in the demand side. Consequently, the conventional energy systems models, often having 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 in general we do not assess which solutions are realistic and reasonable, we should interpret the solutions in consideration of their model structures. The evaluations by past energy systems might underestimate the GDP losses under the stringent CO_2 emissions constraints.

Homma *et el*. (2007) also summarized that the CO_2 emission improvements in "transport sector" result in the greatest improvements in GDP losses under the stringent CO2 mitigation constraints. The GDP loss of the 450 ppmv level comes to 11.3% while the same mitigation case with 50% CO2 emissions reduction by hypothetical technologies of the transport sector gives approximately 1.6% GDP loss. The transport sector is a bottleneck sector so as to cause the serious GDP losses in the S450 case. They suggest the importance of technology developments in the transport sector. IPCC Fourth Assessment Report also reported the importance of mitigation options in the transport sector to reduce CO2 emissions (IPCC, 2007).

As mentioned previously, Homma *et el*. (2007) suggests that the assumptions of the substitution flexibility of energy inputs in the end-use sectors have a great impact on evaluations of mitigation policies for global warming. However, they do not sufficiently discuss the quantitative analysis on fuel substitutions flexibility effects under carbon emission constraints. In this paper, we focus on how the economic activities in the stringent carbon mitigation policy are affected by the flexibility in substitution among end-use energies up to the middle of this century.

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 of 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 (Hertel, 1997) model which is a static multi-sectoral model. (Homma et *el*, 2006) 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 endogenously 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.

In DEARS, the energy demands in the industry and transport sectors are endogenously decided by the Leontief production functions using monetary input-output coefficients, while the energy demands in the residential sector are formulated by the GDP and price elasticities of the fuels.

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

3.1. Effect of reductions of CO_2 emissions on world GDP

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.

Table 1 shows the GDP losses 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 are required to meet the 450 ppmv (CO_2 only).

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 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.

3.2. Effects of flexibility among fuels in the end-use demands on world GDP in the stabilization cases

As for the flexibility in substitutions in the end-use energy demands in the stabilization cases, the following three simulation cases are conducted: (1) Case A (regular case) with the rigid flexibility of fuels in all end-use sectors, (2) Case B with perfect substitutions in non-electric fuels only in the non-energy 18 sectors, corresponding to 16 industry and two transport sectors, and (3) Case C with perfect substitutions in non-electric fuels only in the residential sector. It is noted that even in the perfect substitutions of fuels the sectors with no fuel consumptions in the base year are assumed to have no fuels demands in the future.

Figure 4 shows the world GDP losses on the assumptions of the three types of flexibility in substitutions in end-use sector energy demands, relative to GDP in the reference case with rigid flexibility in substitutions in end-use sector energy. The GDP losses in Cases B and C are smaller than those in Case A in almost all stabilization cases. The GDP loss of the 450 ppmv mitigation policy in the year 2047 comes to 11.8% while the same stabilization case with the perfect substitutions in non-electric fuels in Cases B and C give approximately 2.8% and 6.6% GDP losses, respectively. These indicate that the whole economic activity in the stringent CO2 reduction case are considerably affected by the assumptions of substitution in non-electric fuels in the end-use sectors.

Figure 5 and 6 show the world final energy consumptions and its composition ratios at different levels of flexibility in substitutions in S450 cases, respectively. Compared with Case A, the final energy consumptions of the gaseous fuel in Cases B and C increase while those of the solid fuel decrease. Especially in Case B, those trends are strong. These indicate that the energy switching to lower carbon energy–from coal to natural gas– plays an important role in mitigation of the world economic activity under stringent global carbon constraints when the flexibility of structures of energy inputs in the end-use sectors are allowed. The rigid flexibility of energy inputs in the end-use sectors leads to relatively large GDP losses in the stringent carbon constraints.

4. Conclusions

This study evaluates the economic impacts at different levels of flexibility in substitutions in fuels in end-use sectors under stabilizing atmospheric CO_2 concentration by an intertemporal energy-economic optimization model, DEARS. The concentration stabilization at 650–500 ppmv (CO_2 only) can be achieved by changes of energy demands accompanied with industry structure changes which are reasonably expected by DEARS and by adoption of technological measures of emission reductions. The serious GDP losses in the 450 ppmv (CO2 only) case are observed under the rigid structures of energy demands substitutions based on the assumptions of the Leontief production functions in the sectoral productions.

The GDP loss of the 450 ppmv mitigation policy in the year 2047 comes to 11.8% while the same stabilization case with the perfect substitutions in non-electric fuels in the industry and transport sectors, and the residential sector give approximately 2.8% and 6.6% GDP losses, respectively. The computational results indicate that the whole economic activities in the stringent CO2 reduction case are considerably affected by the assumptions of substitutions in fuels in the end-use sectors. The energy switching to the lower carbon energy under the perfect substitutions of fuels in the end-use sectors are observed. These indicate that the energy switching to lower carbon energy–from coal to natural gas– plays an important role in activity of the world economic mitigation under stringent global carbon constraints when the flexibility of structures of energy inputs in the end-use sectors are allowed. The rigid structures of energy inputs substitutions in the end-use sectors leads to relatively large GDP losses in the stringent carbon constraints. These indicate that not only the technology developments but also the changes in industry structures with enormous flexibility of energy demands in the end-use sectors play important roles in alleviating GDP losses in the stringent CO2 reduction policies.

References

[1] Hertel, T. W. (1997) **Global Trade Analysis: Modeling and Applications** (Cambridge University Press).

[2] Homma T, Mori S, Akimoto K, Tomoda T, and Murota Y. (2006) Evaluation of Global Warming Mitigation Policies with a Dynamic World Energy-economic

Model Considering Changes in Industrial Structures by IT Penetration, **Proceedings of 9th Annual Conference on Global Economic Analysis**, https://www.gtap.agecon.purdue.edu/resources/download/2544.pdf (accessed May 14, 2007)

[3] Homma T, Mori S, Akimoto K, Tomoda T, and Murota Y. (2007) Sectoral economic impacts of CO2 mitigation policies under different levels of stabilization targets: A study with the hybrid model DEARS, **Proceedings of 10th Annual Conference on Global Economic Analysis**, https://www.gtap.agecon.purdue.edu/resources/download/3246.pdf (accessed May 14, 2007)

[4] Intergovernmental Panel on Climate Change (2000) **Special report on emissions scenarios** (Cambridge University Press).

[5] Intergovernmental Panel on Climate Change (2001) **Mitigation: Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change**. Metz B, Davidson O, Swart R and Pan J (eds) (Cambridge University Press).

[6] Intergovernmental Panel on Climate Change (2007) **The AR4 Working Group III Report : Summary for Policymakers**, http://www.ipcc.ch/SPM040507.pdf (accessed May 14, 2007)

[7] Grubb, M., Carraro, C., Schellnhuber, J. (2006) Technological Changes For Atmospheric Stabilization: Introductory Overview to the Innovation Modeling Comparison Project, **The Energy Journal**, Special Issue: Endogenous technological change and the economics of atmospheric stabilization, pp.1-16.

[8] Ednhofer, O., Lessman, K., Kemfert, C., Grubb, M., Kohler, J.(2006) Induced Technological Change: Exploring its Implications for the Economics of Atmospheric Stabilization. Synthesis Report from the Innovation Modeling. Comparison Project, **The Energy Journal**, Special Issue: Endogenous technological change and the economics of atmospheric stabilization, pp.57-108.

[9] Stern, N. (2007) **The Economics of Climate Change: The Stern Review** (Cambridge University Press).

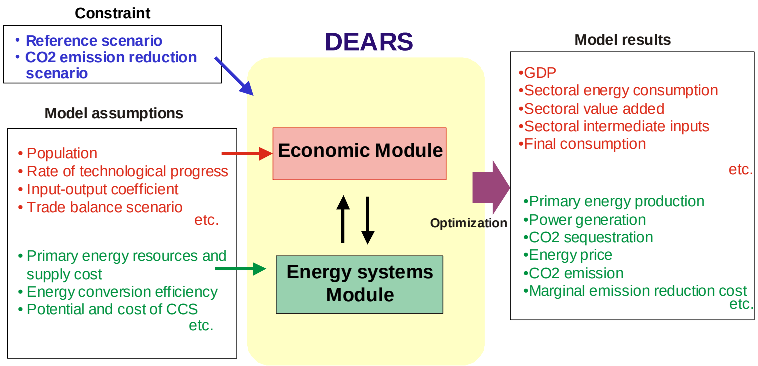

Figure 1：Inputs and outputs of DEARS

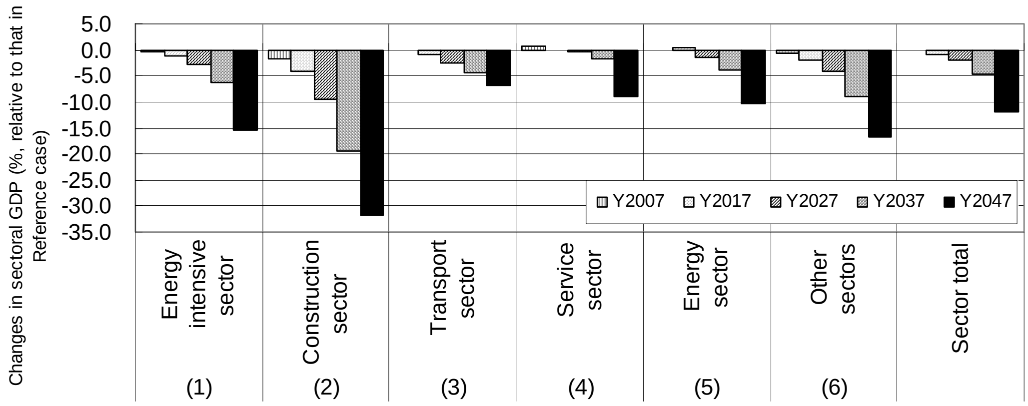

Figure 2: Changes in world sectoral GDP in the S450 cases

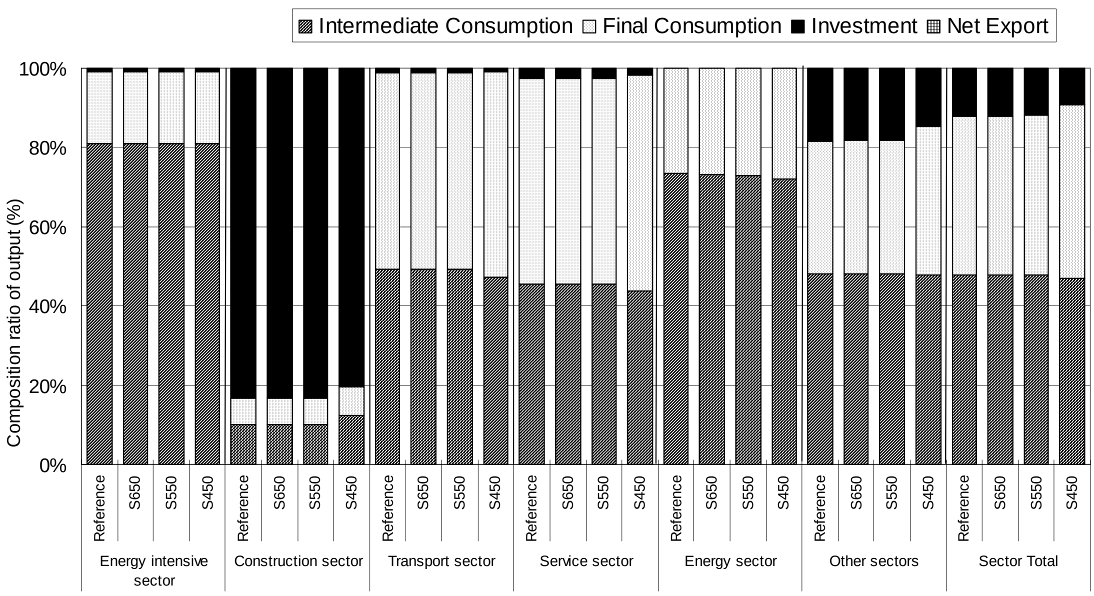

Figure 3: Composition ratio of world outputs in the aggregated sectors

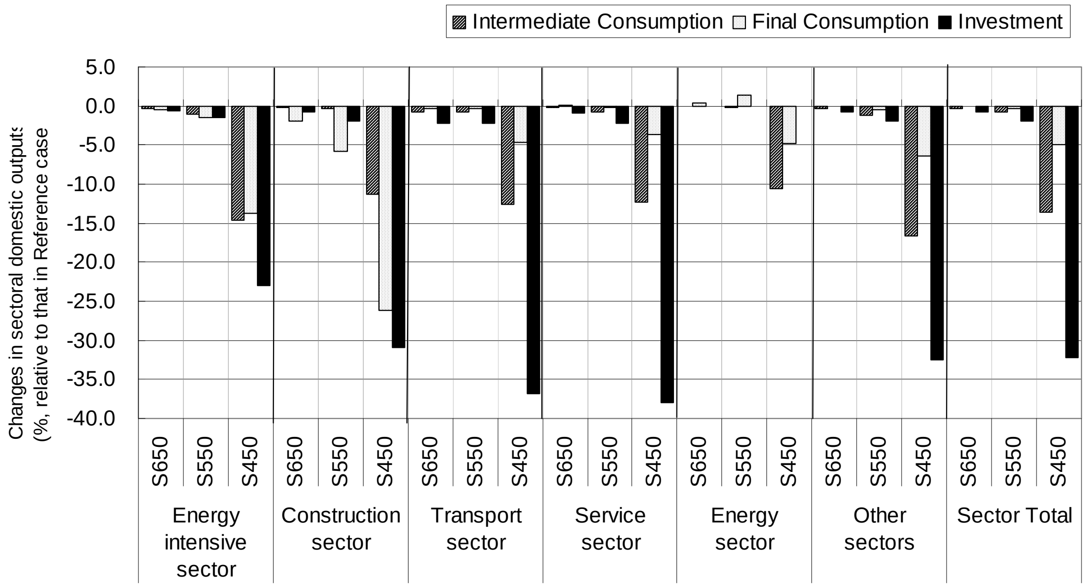

Figure 4: Changes in world outputs by demand in the year 2047

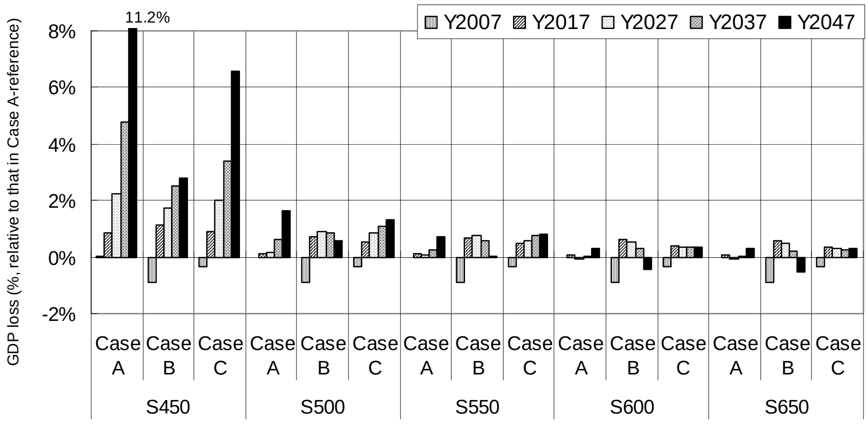

Figure 5: World GDP losses affected by the flexibility in substitutions in energy demand

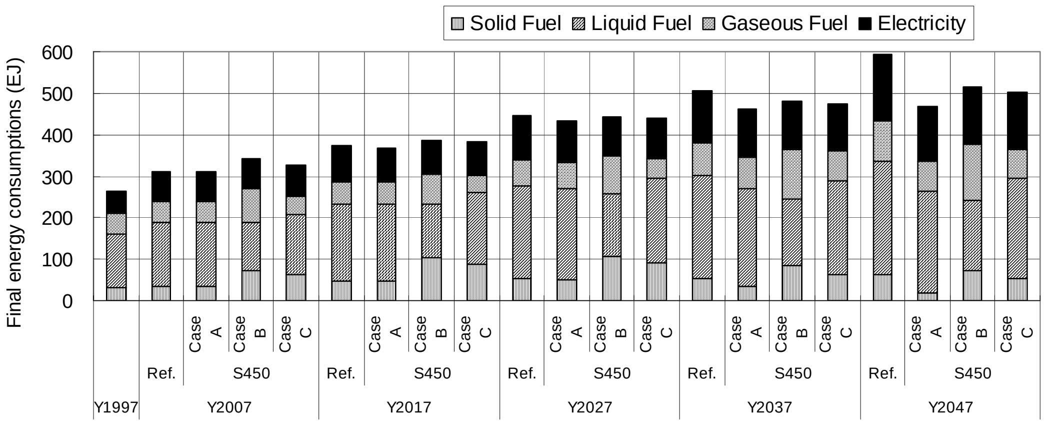

Figure 6: World final energy consumptions at different levels of flexibility in substitutions of fuels in S450 case

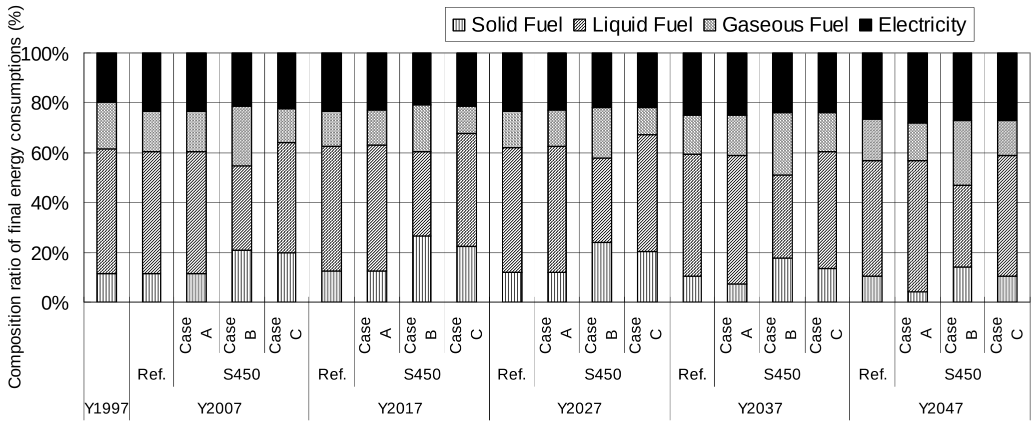

Figure 7: Composition ratios of world final energy consumptions at different levels of flexibility in substitutions of fuels in S450 case

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 (IPCC, 2000)	2.6%	—	0.6%	—	0.4%
2050 IMCP project (Grubb, 2006; Ednhofer, 2006)	-4% to 10% (450 ppmv Co2 only); 1% below in all but two models				
2050 Stern Review (Stern, 2007)	around 1% (500-550 CO2 eq)				