Development of multi-regional and multi-sectoral energy-economic model and the analysis of CO2 emission reduction

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Abstract

The KP (Kyoto Protocol) came into force in February 2005, which is an international treaty designed to limit GHG emission for Annex I for the period from 2008 to 2012. The international arguments on the framework of emission reduction after 2013 will also begin soon. Under these circumstances, the role and importance of the mitigation strategies of climate change is increasing. In order to assess the impacts on energy and economy by mitigation of climate change, we have developed a new dynamic optimization-type model, DEARS (Dynamic Energy-economic Analysis model with multi-Regions and multi-Sectors), to deal with the changes in both energy systems and industrial structure not only for the world but also detailed region up to the middle of this century.

This model is an intertemporal non-linear optimization type where the objective function of cumulative consumption utility is maximized. The model represents energy technology choice, sectoral energy consumption and economic growth by region for the middle term. This model consists of an energy systems module having about 15 energy technologies, e.g. coal power with and without CCS (Carbon Capture and Storage), nuclear power and biomass power and of an economic module having 18 economic sectors; the world is divided into 18 regions. Both energy and monetary flow systems module are consistent with each other. In the energy module, the supply side is formulated by bottom-up fashion, while the demand side is formulated by top-down fashion. The energy systems module covers various energy conversion processes (electricity generations and CCS, etc.). The assumptions for the bottom-up energy systems include the fossil fuel resource estimates by WEC (2000) and USGS (2000), and their cost-supply functions by Rogner (1997). The economic module is based on GTAP (Global Trade Analysis Project) model and its comprehensive world economic database, which has been widely used for economic analysis on the international trade and impacts across various sectors.

Thanks to the above model structure, the model enables to evaluate the costs and technologies to reduce CO2 emission for 18 regions under CO2 emission regulations. Dealing with the detailed regional division leads to observe the regional differences of both economic and energy systems. Therefore the model provides useful information about the quantitative and comprehensive assessments for the climate change mitigation policies.

A case study was carried out on the assumption under the reference case (No-CO2-regulation) and the CO2 emission constraint cases for IPCC-WGI 550 ppmv stabilization scenarios under SRES-B2 population scenario up to the middle of this century. Global warming mitigation strategies were evaluated for the multi-regions and multi-sectors up to the mid-century using the computational results of this model. Two cases for the CO2 emission constraint are assumed:(1) IPCC stabilization profile for the world, and (2) IPCC stabilization profile under the KP constraint to 2012 and the U.K. proposal constraint after 2013 for Annex I

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countries. In both of the constraint cases, the CO2 emission of the world is constrained to meet that of IPCC stabilization scenario. The U.K. proposal constraint means that the CO2 emission for Annex I countries will keep the U.K. proposed target after 2013, where the CO2 emission is reduced to about 40% in 2050 relative to that in 1990. In the stabilization case, a large CO2 emission reduction for Annex I countries causes the shift in the production of several energy-intensive industrial sectors from Annex I regions to Non-Annex I regions, so-called "carbon leakage." The changes in energy systems are also described. In both of the constraint cases, the share of the non-fossil energy increases, and it means that the renewable energy and nuclear power plays an important role in CO2 reduction for the middle term. The model analysis results show the optimized strategies differ by region and sector under CO2 emission reduction policy.

1. Introduction

The KP (Kyoto Protocol) legally entered into force on 16 February 2005. The protocol, designed to limit GHG emission for only Annex I regions for the period from 2008 to 2012, is an international biding treaty that starts the road to curbing greenhouse emissions into the atmosphere which cause global warming. The international arguments on the framework of emission reduction after 2013 will also begin soon. Under these circumstances, the role of the mitigation strategies of climate change is increasing. In order to assess the impacts on energy and economy by mitigation of climate change, we have developed DEARS (Dynamic Energy-economy Assessment model with multi-Regions and multi-Sectors) to deal with the changes in both energy systems and industrial structure not only for the world but also detailed region up to the middle of this century.

This study discusses a new dynamic multi-regional and multi-sectoral energy-economic model for the comprehensive assessment of the climate change mitigation policies. The model focuses on the assessment of the impacts on energy and economy by mitigation of climate change up to the middle of this century. The mid-term analysis for climate policies should be evaluated incorporating economy, energy, and technological issues. In particular, shifts in industrial structure have the critical influences on energy demands.

In the past studies, most of existing multi-sectoral economic models have mainly focused on the short-term analysis. The GTAP (Global Trade Analysis Project) model (Hertel 1997), applied widely for the economic analysis of the international trade impacts under various policies, is a multi-sectoral and multi-regional applied general equilibrium model. GTAP is mainly applied for the short-term. On the other hand, the existing long-term climate policy models, e.g., MESSAGE (Messner and Strubegger 1995) and MARIA (Mori 2000) utilized for IPCC-SRES (IPCC 2000), mainly address the long term up to 2100 and beyond, with disaggregated about 10 regions and one macro-economy sector. These models intrinsically fail to assess the economic and societal structural changes consistent with the trajectories of the future energy demand and GHG emissions.

A dynamic model with multi-sectors is required to evaluate the structural changes according to the future consumption pattern of commodities in the developing regions, the shift in share of the service industry in the whole economic activity etc. Although the stories on the future structure changes are widely discussed in the literature, these have not been well studied in the global environmental context.

It is one of important problems that the analysis focused on the middle of the 21st century were not discussed well. The previous model approaches for the climate policies in IPCC-TAR (IPCC 2001) have mainly dealt with the long term and the short term. Climate policies should be also evaluated incorporating economy, energy, and technological issues. Mid-term analysis of mitigation options for climate change is needed in consideration of their structural changes. It is necessary to incorporate the dynamic changes in industrial structure for multi-regions and multi-sectors in order to evaluate the longer term and global issue of carbon emission reduction potentials.

DEARS developed in this study deals with changes in both energy systems and industrial structure for world detailed regions. DEARS has 18 non-energy industrial sectors and 7 types of primary energy and 4 types of secondary energy, dividing the world into 18 regions. DEARS enables the assessment of global warming mitigation strategies for the multi-regions and multi-sectors up to the middle of this century. Thanks to the model structure by integrating a top-down economic multi-sectoral module and a bottom-up energy systems module, global warming mitigation strategies are evaluated for the multi-regions and multi-sectors. The model analysis results show that optimized strategies differ by region and sector, depending on the carbon emission reduction policy.

The structure of the paper is as follows. Section 2 describes the design of DEARS integrated with the economic module and the energy module, Section 3 presents the main computational results and discussion in a simulation study for limiting atmospheric CO2 concentrations, and Section 4 offers conclusions and future work.

2. Model structure

2.1. Framework of the model

DEARS is formulated as a multi-regional and multi-sectoral model. The whole world is geographically divided into 18 regions, while the whole macro-sector excluding energy sectors is economically divided into 18 non-energy sectors, as shown in Figure 1 and Table 1. The most of sectoral economic data for these sectors are based on GTAP database (ver.5). Dealing with the detailed regional and sectoral division causes the comprehensive global and regional analysis of the impact on both economic and energy systems.

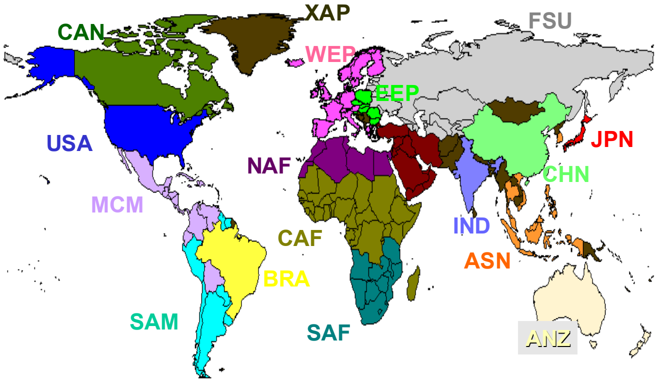

Figure 1: 18 Division of the world by regions

Table 1: Regions and non-energy sectors in DEARS

No.	Region Code	Description
1	USA	U.S.A
2	CAN	Canada
3	MCM	Central america
4	BRA	Brazil
5	SAM	South america
6	WEP	Western europe
7	EEP	Eastern europe
8	FSU	Fomer USSR
9	NAF	Nothern africa
10	CAF	Central africa
11	SAF	Southern africa
12	JPN	Japan
13	CHN	China
14	IND	India
15	ASN	Asian NIES
16	TME	Middel east
17	ANZ	Oceania
18	XAP	Rest of the world

No.	Sector Code	Description
1	I_S	Iron and steel
2	CRP	Chenical products
3	NFM	Non-ferrous metals
4	NMM	Non-metalic metals
5	TRN	Transport equipments
6	OME	Other machinery
7	OMN	Other minings
8	FPR	Food products
9	PPP	Paper, pulp and printings
10	LUM	Wood and wood products
11	CNS	Construction
12	TWL	Textiles
13	OMF	Other manufacturing
14	AGR	Agricultrue
15	T_T	Transportation
16	ATP	Aviation
17	BSR	Bussiness service
18	SSR	Social service

DEARS has the following characteristic features: (a) integration of a top-down economic model and a bottom-up energy technology assessment model such as DNE21 (Fujii and Yamaji 1998) and LDNE21 (Yamaji *et al*. 2000) (b) intertemporal optimization-type model by extension of the model with multi-sectors. This model is a dynamic multi-regional and multi-sectoral model developed for the analysis of the world economy under climate change policy. The time horizon of DEARS is between 1997 and 2047; the time intervals are 10 years. The dynamic framework of this model is shown in Figure 2. This model determines the sectoral production, the final consumption, investment, and international trade as the maximization of the total consumption utilities. Capital stock in time t+1 is decided by depletion of capital stock and investments in the immediate predecessor time t.

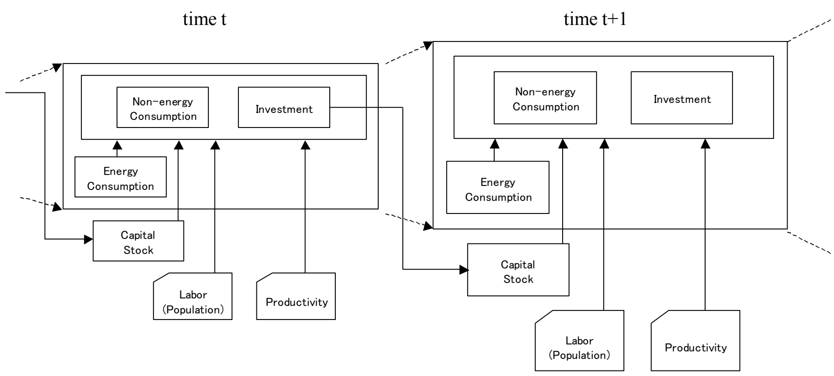

Figure 2: Dynamic structure in DEARS

In this model, Cobb-Douglass functions are utilized for the description of the whole production and the final consumption of non-energy sectors by region. Figure 3 provides a detailed structure between economic and energy moule in the model. The model consists of 18 regions, where the economic and energy systems are linked through international trade of non-energy industrial commodities and fossil fuels.

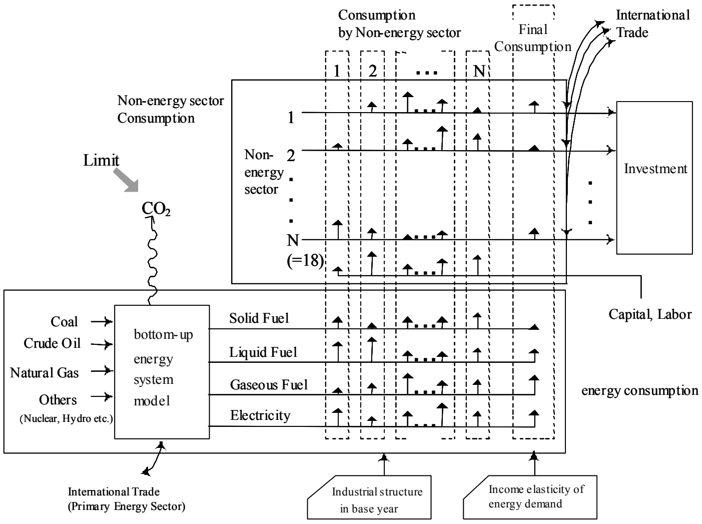

Figure 3: Integration of non-energy sectors and energy technologies in DEARS

In order to integrate a bottom-up energy systems module and a top-down economic systems module, the model has the relational equations as the input-output structure and energy supply-demand balances. In this model, the supply curve of the primary energy is characterized by the parameter regarding the supply curve of the primary energy. We utilize the approximate linear function of the supply price curve of exhaustive resources as crude oil, coal and natural gas explained by the amount of cumulative productions, respectively. Value added of the electricity sector equals the total fixed costs of all kinds of various power generation processes by generated energy of resource. On the energy demand side, the final energy consumption is decided by the growth of GDP per capita and its elasticity. Considering the relation between real and nominal values and the transport services as well as the original GTAP framework, our model has the following formulations available for relative price by industrial sector. The model deals with energy technology choice and economic growth by region. Both energy and monetary flow systems module are consistent with each other.

2.2. Energy systems module

DEARS consists of an energy systems module having 7 kinds of primary energy and 4 kinds of secondary energy, such as coal power, nuclear power and biomass power and of an economic module having 18 economic sectors. In the energy module, the supply side is formulated by bottom-up fashion, while the demand side is formulated by top-down fashion. The energy systems module covers various energy conversion processes such as electricity generations and CCS (Carbon Capture and Storage) as shown in Figure 4. These regional energy flows are linked to each other through interregionally traded items: coal, crude oil, and natural gas. The energy commodities are traded through their common international price, respectively.

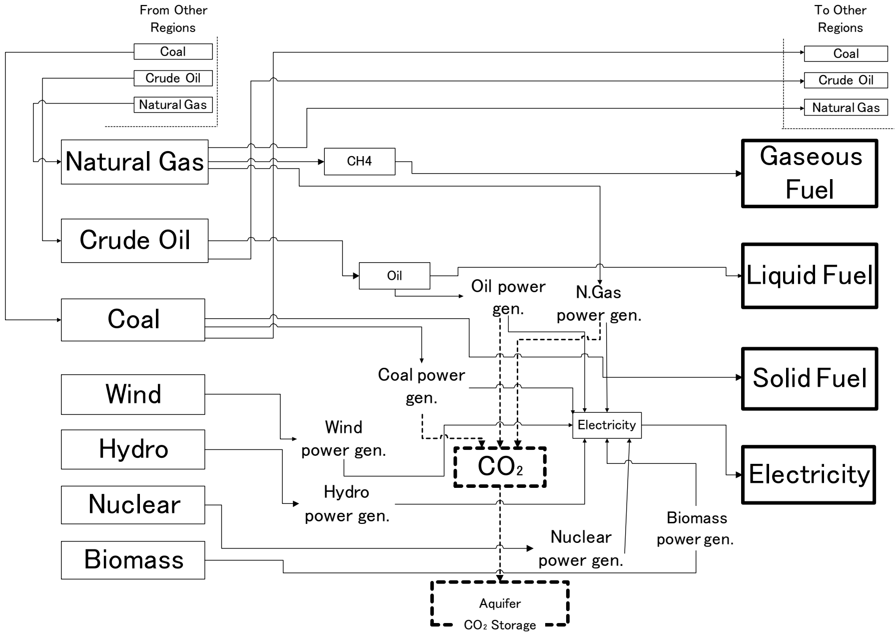

Figure 4: Assumed energy flow in DEARS for one region

DEARS enables the global and regional assessment of the costs and energy technologies to reduce CO2 emission for 18 regions under various CO2 emission regulations. The model deals with the regional and sectoral upper limit of carbon dioxide emission by the emission coefficient of fuel. The model enables the sectoral assessment of CO2 emission for the world and detailed regions. Therefore, the model provides useful information about the quantitative and comprehensive assessments for the climate change mitigation policies.

As mentioned previously, the developed model deals with 7 types of primary energy i.e., coal, crude oil, natural gas, biomass, wind power, hydro power and nuclear power, and 4 types of secondary energy i.e., solid fuel, liquid fuel, gaseous fuel and electricity. Energy balances in assumed conversion processes, such as crude oil to liquid fuel (petroleum), coal to solid fuel, natural gas to gaseous fuels and various fuels to electricity, are described with the use of their conversion efficiency. The model also copes with the conversion process of power generation including the transmission loss.

Assumed potentials of fossil fuels are derived from WEC (2000) and USGS (2000), and their linearlized cost-supply functions based on Rogner (1997). The regional potentials of fossil fuels are shown in Figure 5.

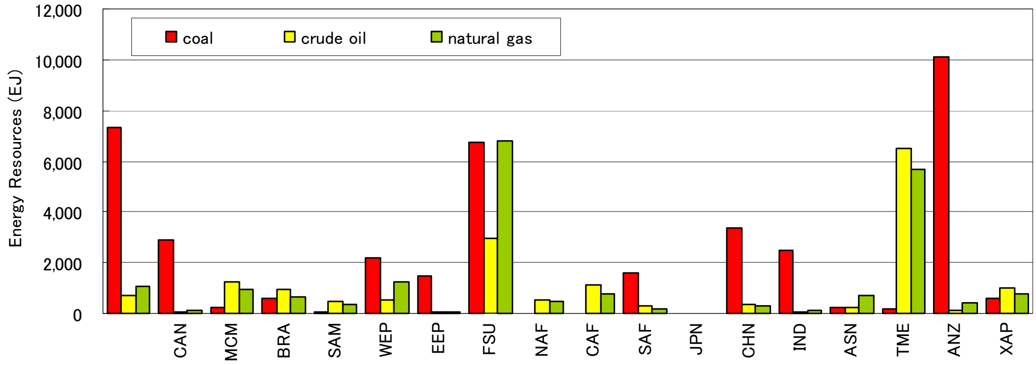

Figure 5: Assumed potentials of fossil fuels

Assumed costs and potentials of biomass energy are derived from Yamamoto *et al.*(2001). The regional potentials of biomass energy are shown in Figure 6. The facility cost of the power generation by biomass energy is 1970 $/KW, and the resource cost of biomass energy is 0-20 $/GJ.

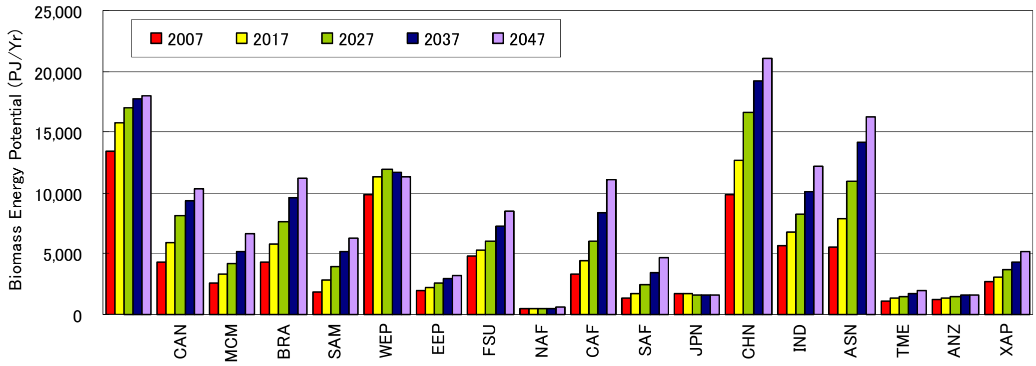

Figure 6: Assumed potentials of biomass energy

The potentials and costs of hydropower and wind power are derived from WEC(2000) and Akimoto *et al.*(2004). The cost of hydropower and wind power is 30-180 and 56-118 $/MWh, respectively. The cost reduction of wind power is assumed to be 1.0 % per year.

The model also takes into account the aquifer injection as the CO2 capture technology. The model enables the assessment of their regional future potentials. The operational cost using the CO2 capture technology is derived from Rubin *et al.*(2004). The cost for the transport and the geologic storage is 3.2 and 5.0 $/tCO2, respectively. In the model, the operational cost for the capture technology is incorporated in the fuel cost for the power generation with CCS. The fixed plant cost with CCS in the power generation sector is 1.75 or 2.12 time higher than that without CCS. The regional CO2 storage potential into aquifer is derived from Akimoto *et al.* (2004) shown in Figure 7.

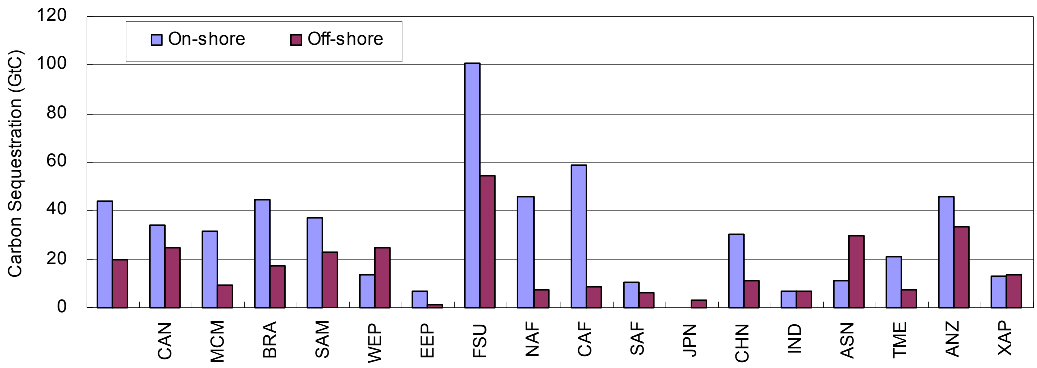

Figure 7: Assumed potentials of carbon storage into aquifer

2.3. Economic systems module

Table 2 describes the model structure for the variables, and the table of economic and energy flow in this model. The macro-production function of whole non-energy industrial sector is defined by capital stock and the total energy demand by non-energy sector. The value added of non-energy sector is described as follows:

$$V_{j,r,t} = \left(1 - \sum_{i} a_{i,j,r}\right) Q_{j,r,t} - \sum_{s} EC_{s,j,r,t} \tag{1}$$

Hence, the subscripts "i" and 'j" designate the non-energy sector, while the subscript "s" stands for the secondary energy sector. The subscript "t" and "r" designate the time and the region, respectively. Assumed that (2) equals the first term of the right hand in (1), the macro Cobb-Douglass function takes the form of the following equation for the whole sector.

$$\sum_{j} f(K_{j,r,t}, L_{j,r,t}, E_{j,r,t}, N_{s,j,r,t}) = a_r \cdot A_{r,t} \cdot K_{r,t}^{\alpha_r} \cdot L_{r,t}^{\beta_r} \cdot E_{s,j,r,t}^{\gamma_r} \cdot N_{s,j,r,t}^{1-\alpha_r-\beta_r-\gamma_r} \quad , \tag{2}$$

where $A_{r,t}$ is the rate of technical progress; $K_{r,t}$ is the total capital stock; $L_{r,t}$ is the population (labor). The parameters of a_r, α_r, β_r, and γ_r in (2) are obtained by GTAP benchmark data set in the base year. The sectoral capital stock is not explicitly dealt with as decision variables in this model.

The model requires to integrate the bottoming-up energy technology into GTAP economic framework in order to assess the certain technologies such as energy conversion technologies, carbon capture options, biomass production and utilization. Our optimization model uses the objective function that is represented as the world total discounted consumption utilities. The sectoral utility is defined as the sectoral consumption divided by regional labor (population).

Table 2 Input-output table and energy balances table

Monetary Flow

			Intermediate Demand													Final Demand				Output
			Non-Energy (j)			Energy										Consumption	Investment	Export	Import	
						Primary(p)					Secondary(s)									
											Non-ELE			ELE						
			j_1	...	j_N	COL	CRU	GAS	BIO	OTH	SLD	OIL	GDT							
Intermediate Input	Non-Energy(i)	i_1	$a_{i,j}Q_j$			$a_{i,p}EC_p$			0		$a_{i,s}EC_s$					C_i	I_i	X_i	M_i	Q_i
		...																		
		i_N																		
	Energy	Primary (p) COL	0			0					$EC_{COL,SLD}$	0	0	0	0	0	0	$EC_{p,X}$	$EC_{p,M}$	EC_p
		CRU									0	$EC_{CRU,OIL}$								
		GAS										0	$EC_{GAS,GDT}$	$EC_{GAS,ELE,NCS*(2)}$	$EC_{GAS,ELE,CS*(2)}$					
		BIO									0		0	$EC_{BIO,ELE,NCS}$	0			0	0	
		OTH*(1)									0			0	0					0
		Secondary (s) SLD	$EC_{s,j}$			0					0			$EC_{SLD,ELE,NCS}$	$EC_{SLD,ELE,CS}$	$EC_{s,C}$		0		EC_s
		OIL												$EC_{OIL,ELE,NCS}$	$EC_{OIL,ELE,CS}$					
		GDT												0	0					
		ELE																		
Value-added			V_j			VA_E_p				0	VA_E_s									
Output			Q_j			EC_p				0	EC_s									

Energy Flow

			Non-Energy (j)			Energy										Consumption	Investment	Export	Import	total	Price
						Primary(p)					Secondary(s)										
											Non-ELE			ELE							
			j_1	...	j_N	COL	CRU	GAS	BIO	OTH	SLD	OIL	GDT								
Energy	Primary (p)	COL	0			0					$E_{COL,SLD}$	0	0	0	0	0	0	$E_{p,X}$	$E_{p,M}$	E_p	P_p
		CRU									0	$E_{CRU,OIL}$									
		GAS										0	$E_{GAS,GDT}$	$E_{GAS,ELE,NCS}$	$E_{GAS,ELE,CS}$						
		BIO									0			$E_{BIO,ELE,NCS}$	0			0	0		
		OTH											0	$E_{OTH,ELE,NCS}$	0						
	Secondary (s)	SLD	$E_{s,j}$			0					0	0	0	$E_{SLD,ELE,NCS}$	$E_{SLD,ELE,CS}$	$E_{s,C}$		0		E_s	P_s
		OIL												$E_{OIL,ELE,NCS}$	$E_{OIL,ELE,CS}$						
		GDT												0	0						
		ELE																			

Note:
*(1):OTH(Others) sector includes all the non-fossil fuels excluding biomass for convenience
*(2):Sub-script CS and NCS mean the CCS and non-CCS technologis, respectively.

3. Simulation Study

3.1. Data assumptions

A simulation study was applied to DEARS by the use of the expanded data -18 non-energy sectors, and 7 kinds of primary energy and 4 kinds of secondary energy-combined IEA data(IEA 2002a, 2002b) and the aggregated GTAP-EG(Rutherford 2000) database which is based on the production statistics in 1997. A case study was carried out on the assumption under the reference case (No-CO2-regulation) and the CO2 emission constraint cases under SRES-B2 population scenario up to the middle of this century. In this case study, the regional and global population assumption is the same as the SRES-B2 scenario, and CO2 emissions and GDP trajectories, which are determined endogenously in the model, are harmonized with the SRES-B2 marker (MESSAGE model) scenario by adjusting the various parameters such as the regional annual rate of technical progress. The population of the 18 regions aggregated country-level population and downscaled projections for the SRES B2 Scenario 1990-2100 by TGCIA data (TGCIA); the historical regional population in 1997 was adjusted by WDI (World Bank 2002). The regional rate of technical progress is basically adjusted in accordance with the annual growth rate of GDP per capita of IPCC-SRES-B2 scenario.

Other assumptions were used for the simulation study as follows:

discount rate：5%/year,
depreciation rate：5%/year (Manne *et al.* 1995),

which were assumed as the same values in all the regions and sectors. Here, it is important to note that the procedure to avoid the end effect is left out of consideration, and the stock of power plant is not allowed in this current model. Furthermore, it is assumed that the input-output coefficients until 2047 are fixed in the benchmark year. The optimization software GAMS/CONOPT3 was used for the simulation study.

3.2. Simulation cases

Three simulation cases are assumed in order to examine the effect on economic and energy sectors for the multi-regions up to 2047. The first simulation case is the reference case (REF Case) under no carbon emission control policy up to 2047. The second case is IPCC-WGI 550 ppmv stabilization case (S550 Case). The final case is the 550ppmv stabilization case in the world plus the KP constraint to 2012 and the U.K. proposal constraint after 2013 for Annex I countries except for USA - CAN, WEP, EEP, FSU, JPN, and ANZ- without tradable emission permits (S550UK Case); the Kyoto protocol target for Annex I countries except for USA in 2012, and a target of 2%/yr reduction of CO2 intensity for USA until 2012. The future carbon emission after 2013 from all of the Annex I countries does not exceed U.K. proposal emission target of 60 % reduction for Annex I countries in 2050, while the CO2 emission of Non-Annex I countries is constrained to fill the gap between IPCC S550 stabilization scenario and the allowable maximum emission for Annex I. In this simulation case, the KP emission target is assumed to be kept in year 2007 for convenience. In this paper, we show only some of the representative computational results of both the future economic and energy systems.

3.3. Computational results and discussion

Figure 8 shows the simulation results for the world power generation in the three cases. Here, it is important to address carefully the computational results around the end of time horizon affected by the end effect. This figure suggests some prospects for global power generation in the future. The differences in the world power generation between the reference case and the carbon control cases reflect the effect of carbon control on power generation structure. The world total amount of power generation in the S550 Case and S550UK Case dropped to about 0.9 and 7.5 % less than that of the REF Case in the year 2027, respectively.

The CCS profiles in the world are also shown in Figure 8. The CCS technology for coal power generation is required from the year 2007 under these carbon reduction policies. The results suggest that the CCS for coal power generation from earlier period is one of the cost-effective technological options for the reduction of the carbon emission in both the carbon control cases. In the S550UK Case, the CCS for gas power generation also plays an important role in carbon reduction. In Figure 8, the share of power generation by fossil fuels in the carbon control cases is smaller than that of the REF Case.

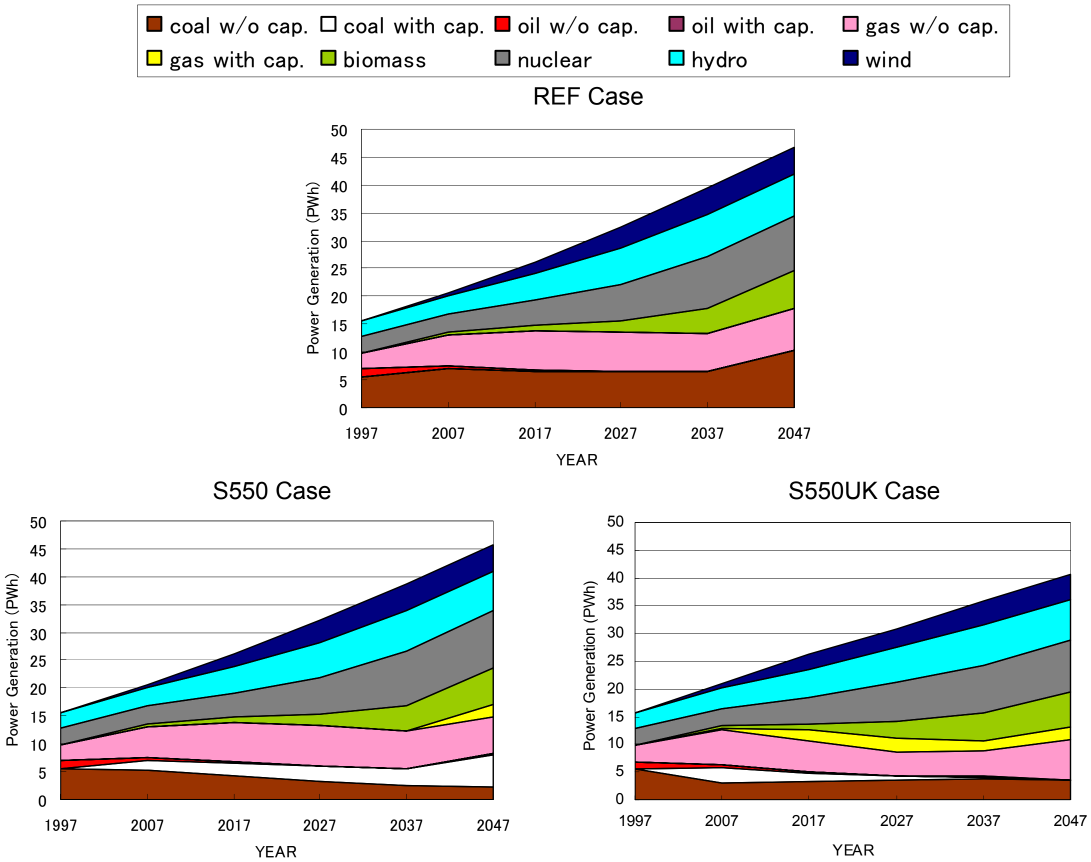

Figure 8: World power generation in the three cases

Figure 9 shows the simulation results for the world total primary energy consumption in the three simulation cases. The world total amount of primary energy consumption in the S550 Case and S550UK Case dropped to about 0.4 and 1.8 % less size than that of the REF Case in the year 2027, respectively. The observed fuel switching from coal to less carbon-intensive fuels in the carbon control cases results in the contribution to reduce the carbon emission. The share of non-fossil fuels in the carbon control cases is higher than that of REF Case. The share of total non-fossil fuels in the world primary energy consumption in the REF Case, the S550 Case and S550UK Case is about 21.3, 21.4 and 24.4 % in year 2027, respectively. The non-fossil fuels such as nuclear power and biomass power play an important role in CO2 reduction up to the middle of this century.

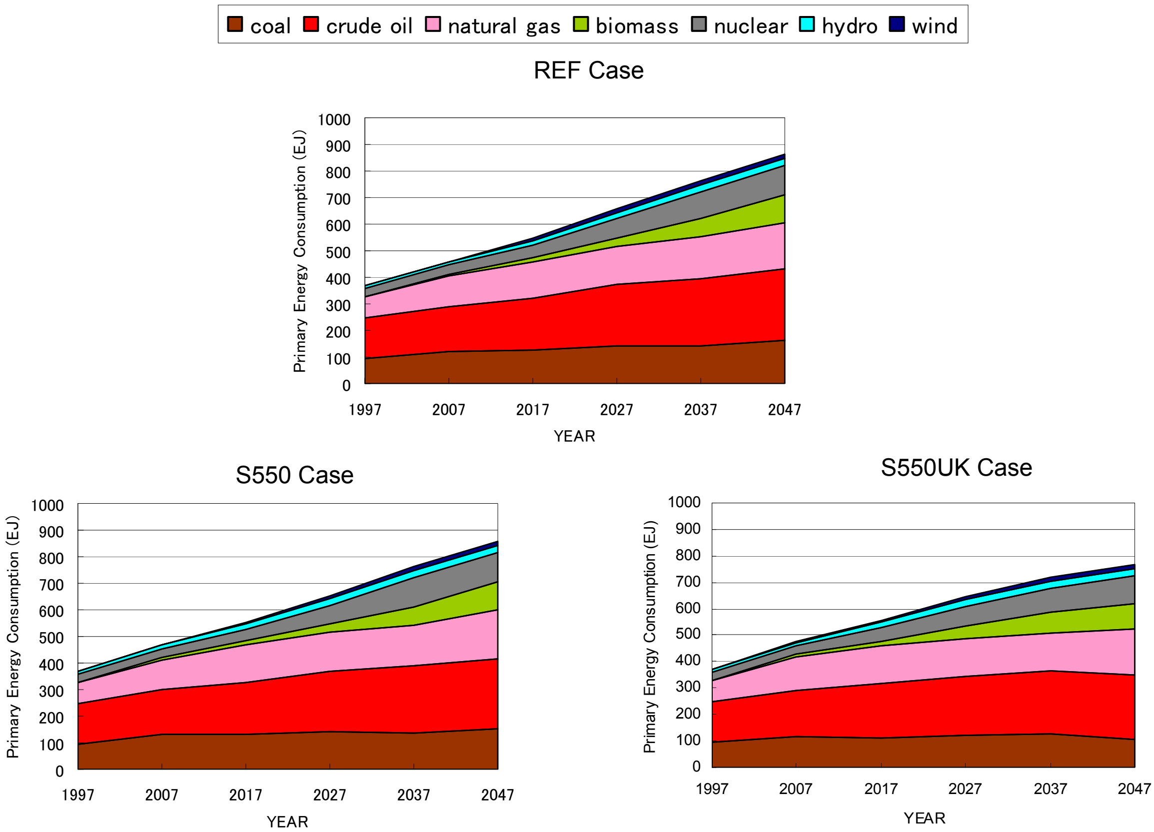

Figure 9: World primary energy consumption in the three cases

Figure 10 visually describes the simulation result for the sectoral losses of the value added in year 2027 relative to that of the REF Case, in the Annex I regions, Non-Annex I regions, and the world. These figures suggest some prospects for global industrial structure shift in the future for the carbon control policies. The world total losses of value added observed in the year 2027 in the S550 Case and the S550UK Case are 0.4 and 4.6 % relative to that of the REF Case, respectively. Here, the world total loss of value added equals to the world GDP loss. The differences in the value between the reference case and the carbon control case reflect the effect of carbon control on sectoral economic activities. For example, in the S550 case, the loss of value added of "Paper and pulp " sectors in Annex I parties, Non-Annex I parties and world total, which is one of the representative energy-intensive sectors, are about 4.1, -2.5, and 0.6 % relative to that of the REF Case in the year 2027, respectively. A negative value of the loss in a sector equals a positive value of the gain. The shifts in the several sectors such as " Paper and pulp " and "Transportation machinery" from Annex I regions to Non-Annex I regions, so called "carbon leakage", are observed in the S550 Case, while the shifts in the several sectors such as "Chemical products" are observed in the S550UK Case. The losses of value added in both Annex I regions and Non-Annex I regions in several sectors such as "Iron and steel" sector are also observed in the two stabilization cases. The decreases of their trade values in the world, mainly caused by the decreasing consumption in the developed countries, are observed under the carbon reduction policy. On the other hand, the carbon emission reduction policy have the less critical impacts on the sectors less-intensive in fossil fuels. For example, the losses of value added of "Business service" sector in Annex I regions, Non-Annex I regions and world total in the S550 case are about 0.2, 0.1, and 0.1 % relative to that of the REF Case in year 2027, respectively. The loss of most sectors in the S550UK Case is higher than that of the S550 Case. In the optimized result, the cost-effective carbon emission reduction in the carbon control case requires these changes in industrial structure.

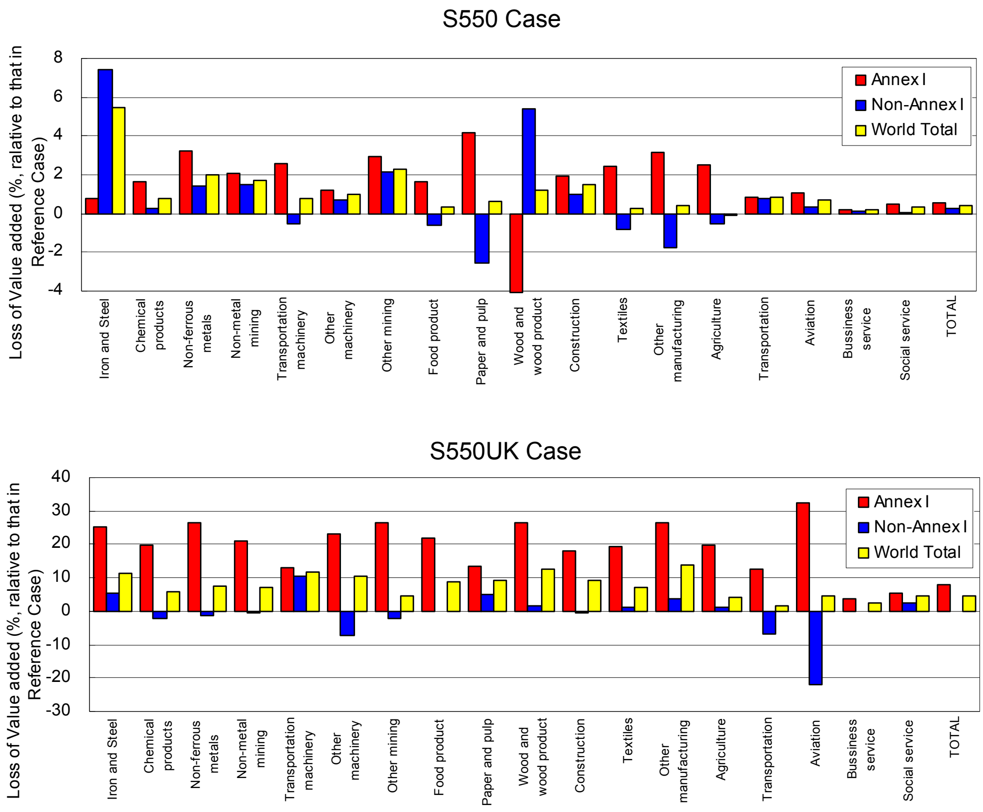

Figure 10: Loss of sectoral value added in the year 2027

4. Conclusion and future work

In order to assess the climate change policy up, we have presented the DEARS with multi-regions and multi-sectors by integrating energy conversion processes into economic framework The model has a multi-regional and multi-sectoral structure to evaluate the global warming mitigation strategies including the industrial structure change and the energy conversion technology change to the middle of this century. DEARS consists of 18 non-energy sectors, and 7 types of primary energy and 4 types of secondary energy, dividing the world into 18 regions. The model also covers CCS technologies. The simulation study is also described. A case study is conducted under the future carbon emission path constrained below :(1) IPCC stabilization profile for the world, and (2) IPCC stabilization profile plus the KP constraint to 2012 and the U.K. proposal constraint after 2013 for Annex I countries. The analysis results show regional and global structure changes in industry, which is consistent with the energy systems, under the carbon control emission policy. The share of the non-fossil energy in the two emission control case increases more than that of the reference case. The simulation results confirm the importance of CCS technology in CO2 reduction for power generation. The carbon leakage of the several energy-intensive production from Annex I regions to Non-Annex I regions was observed, while the less critical impacts on the sectors less-intensive in fossil fuels was observed. The resulting changes in the world total value added under the 550ppmv stabilization emission target are in about 0.4 to 4.6 % decreases relative to that of the reference case in the year 2027.

The following research subjects should be mentioned as the future works. These results should be interpreted carefully, depended on a number of important assumptions of the parameters. For instance, it is assumed that the input-output coefficients of the future are fixed in this simulation study. For a greater accuracy on the industrial structure changes for the future, the model requires applying to the sectoral and regional time-series input-output coefficients estimated by various methods. This study discussed a simulation study under the 550 ppmv stabilization scenario. Under the various plausible assumptions of the international industry allocation scenarios in the short- or middle-term, it is necessary that we analyze more detailed quantitative estimates.

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