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Long-term Analysis of Global CO_2 Emission Reduction by Efficient Technologies

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Abstract

This study analyzed the role of efficient energy technologies and the achievable solution of reducing and/or offsetting CO_2 emission globally considering the supply constraint of fossil fuels towards 2030. The Multi-regional Energy TEchnology Optimization (METEO) model was developed for this study. The result shows that the introduction of clean-coal technologies (CCTs) is especially important for reducing CO_2 emission in Japan and other countries. The amount of installed CCTs will change greatly according to the emission trading scenarios and the theoretical cost of emission trading in 2030 is estimated to be \$36-\$145 per ton-CO_2.

1. Introduction

Effectuation of the Kyoto Protocol on February 2005 put the ratified countries an obligation to reduce their emissions of green house gases (GHGs). Among GHGs, CO_2 from fuel combustion dominates other gases in most of the countries, and energy conservation and fuel switching should be applied to reduce CO_2 emissions. Government of Japan has revised the plan to achieve the Kyoto Protocol in April 2005. According to it, CO_2 from fuel combustion will be reduced from the BAU (business-as-usual) case; however, it remains 0.6% greater in 2010 than the level in 1990. To achieve 6% reduction in GHGs as a whole, various measures of other GHGs (CH_4 and N_2O) reduction, CO_2 absorption by forests, and utilization of the flexible mechanisms (emission permit trading, JI, and CDM) will be taken in parallel.

Efficient technologies are the key to reduce CO_2 emissions drastically. However, the potential reduction of CO_2 is quite limited in Japan. On the other hand, huge reduction could be expected by assisting the diffusion of them all over the world. This study analyzed the effect of efficient technologies for reducing CO_2 emission quantitatively by the Multi-regional Energy Technology Optimization (METEO) model.

Another purpose of this study is to analyze the relationship between the flexible mechanisms and efficient technologies. If the flexible mechanisms are fully utilized, efficient technologies will be exported to developing countries and their costs will be shared as a form of CO_2 emission trading. The theoretical cost of emission trading based on various scenarios of emission trading is calculated.

2. Model Structure

The structure of the METEO model is shown in Figure 1. This model covers all over the world and divides it into 26 regions (Figure 2). Final energy demand except for road transportation and road transportation demand in each region are exogenously given. Energy technologies (fuel conversion, power generation, and efficient vehicles) will be selected to minimize the discounted total cost for energy supply by using linear programming technique. The amounts of ten kinds of primary energy and CO_2 emission will be calculated simultaneously (Table 1). Energy prices are endogenously determined according to the production cost curves of resources and energy consumption in each year, and transportation costs that depend on mode of transportation and length. Moreover, energy conservation by price rise will be included. The amount of conserved energy is calculated by using reverse demand function (Figure 3). Price elasticity is set to be -0.3 for all kinds of energy [1].

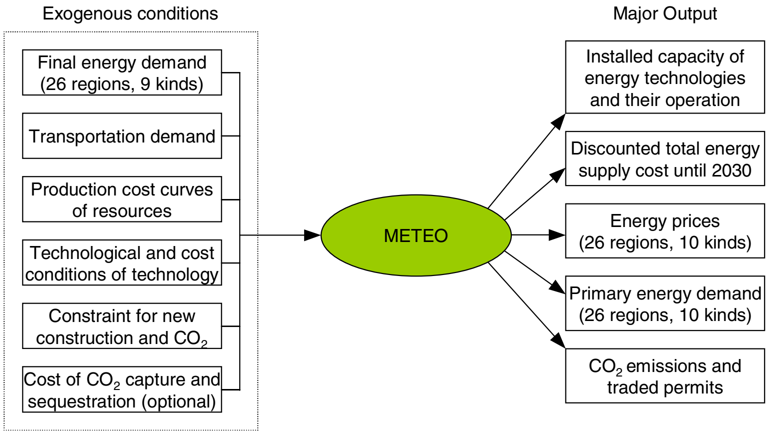

Figure 1: Structure of the METEO model

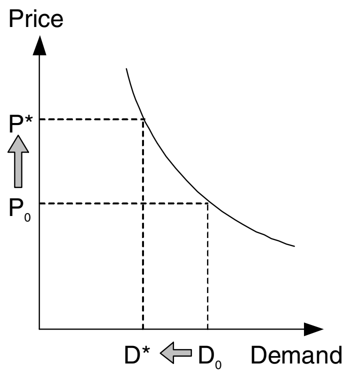

Figure 3: Treatment of price-induced energy conservation

Figure 2: Regional division of the METEO model

Table 1: Scope of the METEO model

Item	Scope
Region	Worldwide, multi-regional (26 regions)
Time range	2000-2030, 7 points (every 5 years)
Primary energy type	10 kinds (2 coal, oil, gas, biomass, nuclear, geothermal, hydro, PV, wind
Final energy type	9 kinds (2 coal, gasoline, diesel, naphtha, LPG, other oil, gas, electricity
Fuel conversion technologies	oil refinery, GTL, DME, natural gas liquefying, coal liquefying, coal gasification, steel making (by-product gases)
Efficient vehicle technologies	hybrid car, alternative fuel vehicles (CNG, DME)
Power generation technologies	Pulverized Coal-Fired (PCF), Ultra Super-Critical (USC) PCF, Conventional gas Combined Cycle (CC), Advanced CC (ACC), Most Advanced CC (MACC), Integrated Gasification Combined Cycle (IGCC), Integrated Gasification Fuel Cell (IGFC)
Energy transportation	considered (depends on mode and length)
Energy prices / resource reserves	considered (cost function in ten steps of supply curve)
Energy conservation	considered (reverse function of energy demand)

There are various models to analyze CO_2 emission reduction by technology substitution explicitly. Typical ones are NE21 [2] and GRAPE [3] (reformed version of NE21). The METEO model is similar to them in the points of dynamic optimization, cost function of resource reserves, and price induced energy conservation. The characteristics of the METEO model are detailed division of regions (especially Asia), considering transportation of energy between regions, and more detailed treatment for load curve of electricity. Load curve is divided into three time patterns (peak, middle, and base) and the capability of each power generating technology for each load is considered beforehand. For example, technologies whose loads are difficult to be changed in short time are not operated in peak load time.

The reason why the METEO model treats Asian countries in detail is for scenario case settings. Rapid economic growth is expected for Asian countries and the importance of reducing CO_2 emission in this region will rise in future. Japan should behave as a leader of a country releasing less CO_2 and promote energy efficiency improvement in this region.

Technological changes will occur in three ways in the METEO model; (1) mixture of power generation, (2) fuel conversion, and (3) alternative fuel vehicles. For example, a GTL (gas to liquid) technology and DME (Dimethyl Ether) production from natural gas will be installed in place of oil refinery, if future oil price will rise or CO_2 emission constraint will become severer.

CO_2 capture and sequestration technology can be included optionally. However, great uncertainty exists in its cost. In this study, optimal solutions were obtained without it even in CO_2 constraint cases.

3. Presuppositions and case settings

3.1 Presuppositions

Technological and cost assumptions of energy technologies are shown in Table 2, 3, and 4. These costs are unified in all regions. The reason why many types of topper are assumed is to avoid an infeasible solution.

The assumption of final energy demand is based on recent outlook by the Japanese government and IEA [9, 10]. However, electrification is ongoing all over the world and this trend is also assumed in this study. Average growth rates of final energy demand are shown in Table 5. Final energy demand of world total in 2030 will increase by 70% from the level in 2000 (1.8% per year) on this assumption.

Table 2: Technological and cost assumptions for power generation

	Efficiency	O&M cost ($/kW)	Construction Cost ($/kW)	Max. capacity factor	Available year	Lifetime (year)	Depreciation period	Operational load		
								peak	middle	base
USC	0.41	41	2,600	0.9	2005	40	15		x	x
IGCC	0.48	45	2,828	0.9	2015	40	15		x	x
IGFC	0.55	50	3,030	0.9	2020	40	15		x	x
Oil	0.39	35	800	0.9	2005	40	15	x	x	x
Gas-CC	0.43	24	720	0.9	2005	40	15	x	x	x
ACC	0.49	26	1,800	0.9	2005	40	15	x	x	x
MACC	0.53	29	2,000	0.9	2010	40	15	x	x	x
Biomass	0.2	12	2,400	0.5	2005	40	15		x	x
Nuclear	0.33	98	2,700	0.9	2000	50	16			x
Hydro	1	40	9,000	0.24	2000	70	40	x	x	x
Geothermal	0.1	30	1,500	0.6	2000	30	15		x	x
PV	1	14.9	5,500	0.25	2000	20	15	x	x	
Wind	1	15	1,000	0.3	2000	20	15		x	x

Source: [4, 5, 6, 7, 8]

Table 3: Technological and cost assumptions for oil refinery

	Kind of petroleum product					O&M Cost ($/TOE)	Construction cost ($/TOE)	Max. capacity factor	Lifetime (Year)
	LPG	Naphtha	Gasoline	Diesel	Others				
Topper 1	0.022	0.041	0.252	0.264	0.360	25	78	0.9	40
Topper 2	0.027	0.047	0.254	0.277	0.329	25	78	0.9	40
Topper 3	0.031	0.054	0.249	0.291	0.311	25	78	0.9	40
Topper 4	0.9					94	294	0.9	40
Topper 5		0.95				94	294	0.9	40
Topper 6			0.95			94	294	0.9	40
Topper 7				0.95		90	281	0.9	40
Topper 8					0.95	66	206	0.9	40

Source: Personal assumption.

Table 4: Technological and cost assumptions for fuel conversion

Technology	Product	Efficiency	O&M Cost ($/TOE)	Construction cost ($/TOE)	Max. capacity factor	Available year	Lifetime (Year)
Coal Liquefying	LPG	0.45	110	10,000	0.9	2020	40
	Naphtha	0.45	120	10,000	0.9	2020	40
	Gasoline	0.45	120	10,000	0.9	2020	40
	Diesel	0.45	120	10,000	0.9	2020	40
	Others	0.45	120	10,000	0.9	2020	40
Coal Gasification		0.5	170	8,000	0.7	2020	40
Natural gas liquefying		0.95	18.8	188	0.9	2000	40
Vaporization of LNG		0.95	2	20	0.9	2000	40

Source: Personal assumption.

Table 5: Assumptions of growth rates of future energy demand

Region	Total final demand	Increase in electrification rate	Region	Total final demand	Increase in electrification rate
China	2.7%	0.8%	Other Asia	3.0%	0.8%
Hong Kong	2.7%	0.5%	Australia	0.7%	0.5%
Taiwan	3.0%	0.5%	New Zealand	0.7%	0.5%
Japan	0.1%	*	OECD Europe	1.1%	0.5%
Korea	2.2%	0.8%	Non-OECD Europe	1.1%	0.5%
Singapore	3.0%	0.8%	Russia	1.3%	0.5%
Malaysia	3.0%	0.8%	Former Soviet Republics	1.3%	0.8%
Indonesia	3.2%	0.8%	Middle East	3.0%	0.8%
Philippine	3.0%	0.8%	Africa	3.0%	0.8%
Thailand	3.0%	0.8%	Canada	1.1%	0.5%
Brunei	3.0%	0.5%	USA	1.1%	0.5%
Vietnam	3.0%	0.8%	Mexico	3.0%	0.8%
India	3.5%	0.8%	Latin America	3.0%	0.8%

** Electricity Demand in Japan is assumed to grow by an average of 0.9% per year.*

Source: [9, 10, 11, 12]

The assumption of production cost curve is shown in Figure 4. For example, total reserve of general coal in China is 64,120 MTOE and the amount of GRADE1 equals to 64120X0.167 MTOE. Production cost of GRADE1 is $50 per TOE. If it will be mined and entered into GRADE6 in future, marginal production cost is determined to be $50 X 2 per TOE. Actual cost for each consuming region is the sum of production cost and transportation cost. Transportation cost by kind of energy and by mode of transport is assumed to be proportional to the length of transport in this study (Table 6).

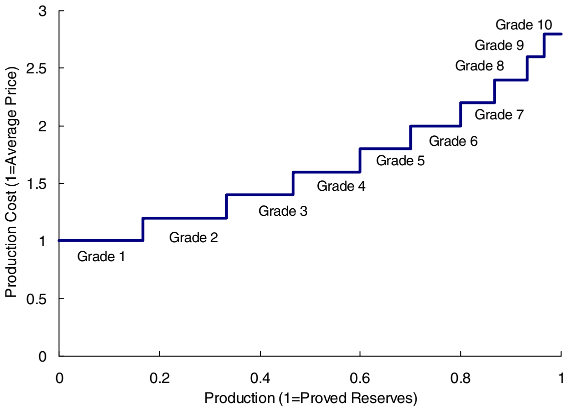

Figure 4: Assumptions of production cost curve for fossil fuels

Table 6: Assumption of freight cost of energy resources

	Coal	Crude Oil	Petroleum products	LPG	Natural gas (pipeline)	LNG	Nuclear	Electricity (grid)
Cost* ($/TOE/1000km)	1.2	0.6	0.7	1.0	2.5	2.5	0.1	1.0

** Ship is assumed to be the mode of international transportation except for natural gas and electricity.*

Source: Personal assumption.

3.2 Case settings

Nine cases are set in total (Table 7). First case is BAU (business-as-usual) where CO_2 constraint is not imposed. Then, eight cases of CO_2 constraint cases (2 cases of constraint targets multiplied by 4 cases of emission trading scenarios) are set.

The SR cases mean “separate reduction” where emission trading is not allowed. Annex-I countries that ratified the Kyoto Protocol (Japan, Canada, New Zealand, OECD Europe, Russia, other republics of former Soviet Union, and Non-OECD Europe) will reduce their CO_2 emission separately. Constraint of CO_2 emissions after 2015 is set to be (A) unchanged from the level in 2010 (“Kyoto forever”) and (B) reduced by 4% in every 5 years since 2010. In the latter case, “hot air” of Russia, other republics of former Soviet Union, and Non-OECD Europe will disappear in 2030. In the JC(A) and JC(B) cases, emission trading will be allowed between Japan and China. Constraint of CO_2 emissions (total of Japan and China) is equal to the total emissions of Japan in constraint cases and of China in the BAU case. In the Annex(A) and Annex(B) cases, emission trading will be allowed among Annex-I countries that ratified the Kyoto Protocol in the METEO model.

Table 7: Case settings

	BAU	SR(A)	JC(A)	Annex(A)	World(A)	SR(B)	JC(B)	Annex(B)	World(B)
CO_2 constraint after 2015	No	Kyoto forever				Reduced by 4% in every 5 years since 2010			
Emission trading region	-	No trading	Japan and China	Annex-I (ratified)	World-wide	No trading	Japan and China	Annex-I (ratified)	World-wide

4. Results

4.1 CO_2 emission

Figure 5 shows CO_2 emission by region in 2030 and Figure 6 shows the differences between each emission trading case and the separate reduction case. On account of price rise in oil and natural gas by moving to higher grades (Figure 7), coal power plant will increase in most of the countries (Figure 8). Average growth rate of CO_2 is 2.3% per year between 2000 and 2030 and it will be doubled in 2030 from the 1990 level in the BAU case. Although clean-coal technologies (CCTs, IGCC and IGFC in this study) will be installed after 2015 in Japan, Singapore, Thailand, and Latin America, CO_2 emission in 2030 will be extremely greater than the level in 1990 and serious reduction should be done to achieve the targets in CO_2 constraint cases.

In CO_2 constraint cases, regions that trade CO_2 credits depend on the scenario of emission trading. In the JC case, Japan will import credits from China. Its amount in 2010 is 61 Mt-C, about 20% of total emission in 1990. Traded amounts will increase according to the range of emission trading. If trading will be enlarged to Annex I countries that ratified the Kyoto Protocol, traded amount in 2030 will be quadrupled. Similarly, if trading will be enlarged to the whole world, traded amount in 2030 will be doubled furthermore. The biggest difference in these emission trading cases is countries exporting CO_2 credits. China and USA are the largest in the JC and world cases respectively, but Russia is in the Annex case.

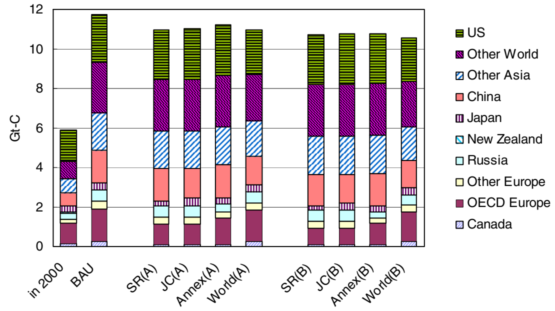

Figure 5: Regional CO_2 emission in 2030

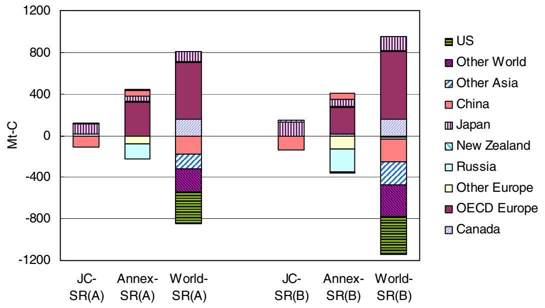

Figure 6: Differences in CO_2 emission in 2030

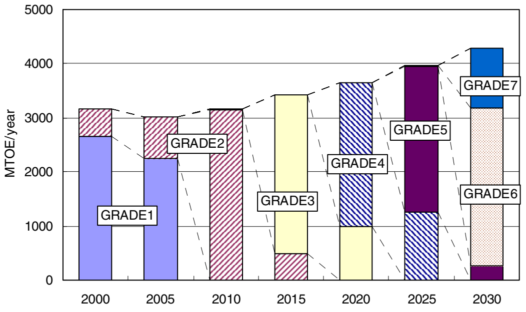

Figure 7: Production of crude oil (BAU case)

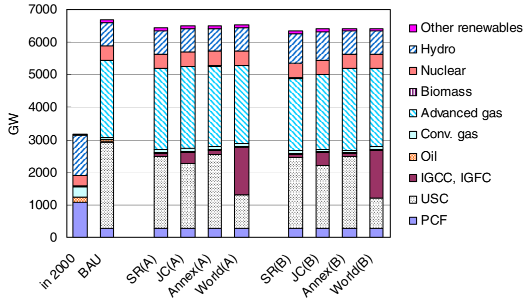

Figure 8: Capacity of power plants (world, in 2030)

Total CO_2 emission also depends on the scenario of emission trading in CO_2 constraint cases. Especially, emission in the Annex-I trading case is the largest among them. The reason of this is “hot air” in (A) constraint scenario and the behavior of China. In (A) constraint scenario, CO_2 emission in emission trading cases is larger than that of the SR case, because hot air will still remain in 2030 and they will be traded in emission trading cases. In the Annex cases, China cannot sell CO_2 credits in this case and CO_2 emission will increase than the SR cases seriously. It means it is quite important to integrate China into the framework of CO_2 reduction in the long term, even if China will not be obliged to reduce its CO_2 emission from the baseline emission scenario.

4.2 Technological change caused by CO_2 constraint

Figure 9 and Figure 10 show the generated electricity by plant type in 2030 in Japan and China respectively. A cheap measure to reduce CO_2 emission in power generation is switching conventional coal to advanced coal in these countries. USC and CCTs will be installed even in China in the JC cases and the world cases to supply CO_2 credits to other countries. Installed capacity of CCTs in the world in 2030 will reach 1,466GW, about 4 times higher than that in the JC cases (Figure 8).

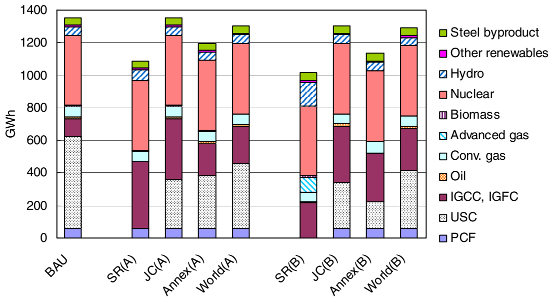

Figure 9: Electricity generation (Japan, in 2030)

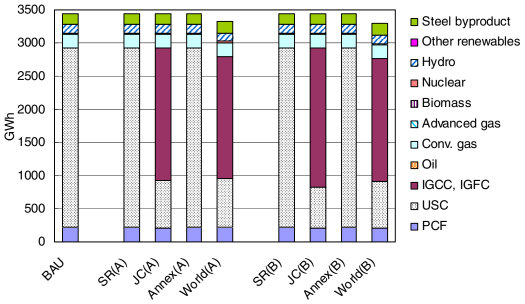

Figure 10: Electricity generation (China, in 2030)

On the other hand, almost all coal power plants will be switched to conventional CC and MACC in Russia in the Annex case (especially (B) constraint scenario) in 2030. This is because Russia has a lot of natural gas resources, and switching to gas-base technologies is cheaper than to CCTs. Thus, the amount of installed CCTs will change greatly according to the emission trading scenarios.

Energy consumption by fuel conversion technologies and automobiles in 2030 is shown in Table 8.

As for fuel conversion technologies, the location of GTL and DME will change by CO_2 constraints. These technologies will be introduced irrelevant to CO_2 constraints, but since CO_2 is emitted during the process, they will not be installed at the regions where CO_2 constraints will be applied. For example, GTL will be installed in China and Middle East but not in Russia in the Annex case. It means Russia will stop to produce diesel oil by GTL to sell more CO_2 credits in this case.

Hybrid vehicles will take place of gasoline vehicles after 2015 in Japan and OECD Europe where gasoline tax is relatively high. However, gasoline vehicles will still occupy 75-80% in number globally in 2030. As for diesel vehicles, diesel fuel will be replaced by GTL and DME by 27-35% in 2030. CO_2 constraints will have a minus effect on hybrid vehicles, GTL, and DME, because prices of fossil fuels will fall and the cost advantage of them will be weakened.

Table 8: Energy consumption by technologies in 2030 (world total, MTOE)

	BAU	SR(A)	JC(A)	Annex(A)	World(A)	SR(B)	JC(B)	Annex(B)	World(B)
Fossil fuel conversion technologies									
Oil Refinery	4296.1	4201.7	4222.9	4221.2	4296.1	4015.4	4033.3	4168.0	4276.4
Coal Liquefaction	0	0	0	0	0	0	0	0	0
Coal Gasification	0	0	0	0	0	0	0	0	0
NG Liquefaction	390.3	350.9	371.6	380.4	384.8	370.7	374.4	360.5	383.0
LNG Vaporization	370.8	333.4	353.1	361.4	365.5	352.2	355.7	342.4	363.9
GTL	508.6	414.9	424.5	481.0	508.6	418.1	428.2	443.8	506.0
DME	234.9	271.4	264.7	247.9	235.2	377.9	382.3	234.2	164.4
Alternative fuel vehicles									
Gasoline	1056.5	1056.5	1056.5	1053.9	1056.5	1056.5	1056.5	1003.8	1017.9
Hybrid*	156.2	144.5	146.6	150.2	156.2	131.3	134.3	168.0	175.5
Diesel	1106.2	1074.7	1081.9	1077.7	1106.0	946.8	949.6	1072.1	1105.9
GTL	289.9	236.5	242.0	274.2	289.9	238.3	244.1	253.0	288.4
DME	162.1	187.3	182.7	171.0	162.3	260.7	263.8	161.6	113.4

** The share of hybrid vehicles in number is twice because the efficiency of them is twice of gasoline vehicles.*

Price induced energy conservation also plays an important role for CO_2 reduction. For example, in the (B) constraint scenario, 14-30% of final energy consumption (different by kind of energy, excluding naphtha) will be conserved in Japan in 2030.

4.3 Emission trading cost

Theoretical cost of emission trading is calculated according to next equation:

$$\text{Emission trading cost (\$/ton-CO}_2\text{)} = \frac{\text{Differences in total cost between each case and the SR cases}}{\text{Total amount of excess (insufficient) emissions by region (ton-CO}_2\text{)}}$$

For example, the upper limit of "willingness to pay" for Japan should be equal to the differences in total cost of energy supply in the JC cases and in the SR cases. So, the emission trading cost per ton-CO_2 is obtained by dividing the differences in total cost by total amount of purchased credits. Figure 11 shows the cost of emission trading in CO_2 constraint cases. The reason why some of the values are minus is because optimization is done dynamically: some efficient but expensive energy technologies will be introduced in the early period to achieve future CO_2 constraints. For the same reason, the values in 2010 for (B) constraints are larger than those for (A) constraints, although the constraints are same in 2010. The values will rise gradually in the long run and if the ranges of emission trading will become narrower. The theoretical cost of emission trading in 2030 will reach $36-145 per ton-$CO_2$ in this study and it is extremely high compared with the current price of EU Allowance (€15-20 per ton-CO_2 [13]).

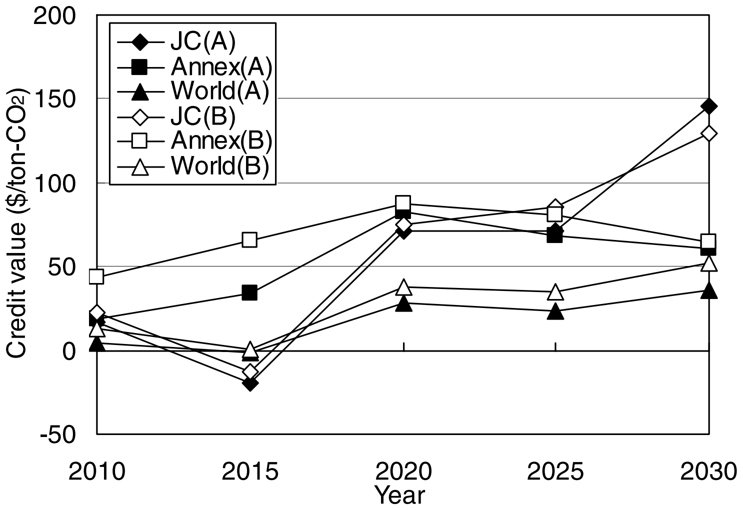

Figure 11: Cost of emission trading

5. Conclusions

This study analyzed the effect of efficient technologies for reducing CO_2 emission quantitatively and the theoretical cost of emission trading by the Multi-regional Energy TEchnology Optimization (METEO) model. The results are summarized as follows:

- In the BAU case, global CO_2 emission will be doubled in 2030 from the 1990 level. Main reason is the increase in final energy demand. Moreover, dependence on CO_2-intensive energy (namely coal) will rise on account of price increase in oil and natural gas by moving to more expensive resource grades. This is another reason for the increase in CO_2 emission.

- The introduction of clean-coal technologies (CCTs) is especially important for reducing CO_2 emission in Japan and other countries. The amount of installed CCTs will change greatly according to the emission trading scenarios.

- Advanced fuel conversion technologies (GTL and DME) and alternative fuel vehicles will be introduced irrelevant to CO_2 constraints. CO_2 constraints will have a minus effect on the diffusion of these technologies, because prices of fossil fuels will fall and the cost advantage of them will be weakened.

- The theoretical cost of emission trading in 2030 will be \$36-\$145 per ton-CO_2.

The discussion about the Second Commitment Period of the Kyoto Protocol has been just started in May 2005. Like in other studies, this study found the importance to integrate developing countries, especially China, into the framework of CO_2 reduction in the long term. The mechanism of CDM and technological assistance in promoting clean-coal technologies are the key to achieve it. Japan should supply energy efficient technologies to Asian developing countries as the only country that has an obligation to mitigate green house gases in this region.

Keywords: CO_2 emission, energy model, efficient energy technology

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