Analysis of Technological Portfolios for CO_2 Stabilizations and Effects of Technological Changes

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In this study, cost-effective technological options to stabilize CO_2 concentrations at 550, 500, and 450 ppmv are evaluated using a world energy systems model of linear programming with a high regional resolution. This model treats technological change endogenously for wind power, photovoltaics, and fuel-cell vehicles, which are technologies of mass production and are considered to follow the "learning by doing" process. Technological changes induced by climate policies are evaluated by maintaining the technological changes at the levels of the base case wherein there is no climate policy. The results achieved through model analyses ixnclude 1) cost-effective technological portfolios, including carbon capture and storage, marginal CO_2 reduction costs, and increases in energy system cost for three levels of stabilization and 2) the effect of the induced technological change on the above mentioned factors. A sensitivity analysis is conducted with respect to the learning rate.

1. INTRODUCTION

It is important to consider technological change endogenously when evaluating strategies for long-term global warming mitigation. This is because it is often observed that the practical application of new technologies in the initial stages usually involves very high costs; however, their adoption is accelerated once their costs decrease below certain thresholds on account of appropriate subsidies, etc. Optimization models that consider endogenous technological changes intrinsically have a nonconvex character. Multiple optima may exist because of that character and the conventional non-linear programming solvers cannot identify a global optimal solution. Therefore, endogenous technological changes cannot be easily evaluated using optimization models. In order to solve

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optimization models of this type, Messner (1997) and Kypreos et al. (2000) used the mixed integer formulation; Manne and Barreto (2004) solved using the Baron algorithm. However, these approaches are not practical for large-scale models because huge amounts of computation are required.

We developed a world energy systems model—DNE21+ (Akimoto et al., 2004; 2005)—that considers the technological change endogenously for three technologies, namely, wind power, photovoltaics (PV), and fuel-cell vehicles (FCVs). These are technologies of mass production and are considered to follow the typical learning-by-doing which is a function of cumulative installation with a constant learning rate (Grubler et al, 2002); they should thus be treated endogenously. On the other hand, the technological changes in other large-scale technologies such as nuclear and carbon capture and storage (CCS) can not be represented only by the cumulative installation. They are affected rather by R&D investment. R&D investment costs cannot be treated explicitly in our model. Therefore, their technological changes are treated exogenously in this paper. The DNE21+ is a linear programming model that employs a bottom–up approach for the technologies at the energy supply side and minimizes the total cost of world energy systems. Its high regional resolution enables a detailed analysis of the relatively high cost of energy transportation, regional differences in energy systems, technology levels, and potential of renewable energies such as wind power. Our model size is huge and the above mentioned approaches for solving models with endogenous technological changes cannot be practically applied to our model. Therefore, model-run iteration, described in Section 3.4.1, is used to solve endogenous technological changes.

Model analyses were conducted for the base case (no climate policy) and three levels of CO_2 concentration stabilization. For each stabilization level, two cases—one with and the other without induced technological change (ITC)—were studied in order to quantitatively analyze the effect of ITC. In addition, a sensitivity study was conducted with respect to the learning rate.

2. THE MODEL

2.1 Model Framework

The DNE21+ model was originally developed for the analysis of the post Kyoto regimes which requires to treat major countries separately and was extended to be used also for the study of the ITC effect. It considers a time range that covers the entire 21st century with the representative time points of 2000, 2005, 2010, 2015, 2020, 2025, 2030, 2040, 2050, 2075 and 2100. The model disaggregates the whole world into 77 regions: US, Canada, UK, France, Japan, Australia, China, India, Russia, etc. To take intoconsidering consideration the transportations of energy and CO_2 in more detail, large countries, such as US, China, and Russia are further disaggregated into several regions. The model represents the energy supply sectors in the bottom-up fashion and the end-use energy sectors in the top-down fashion similar to DNE21 (Fujii and Yamaji, 1998) and LDNE21 (Yamaji et al., 2000) models, which are forerunners of this model. The further details of modeling are described in the next section. The total cost of energy systems between 2000 and 2100 is minimized.

2.2 Energy System Modeling

Primary energy sources of eight types are explicitly modeled: natural gas, oil, coal, biomass, hydro & geothermal, PV, wind and nuclear power. Coal, oil, natural gas, methanol, hydrogen and biomass fueled power plants, hydro & geothermal, wind, PV and nuclear power plants are explicitly taken into account for electricity generation, and integrated coal gasification combined cycle (IGCC) with CO_2 recovery is also formulated. In addition, various types of energy conversion technologies, such as oil refinery, liquefaction of natural gas, coal gasification, etc., are explicitly modeled as technological options. The model also has the historical vintages of these technology facilities. As for CO_2 recovery, both of chemical absorption from flue gas of thermal power plants and physical absorption from outlet gas of fossil fuel gasification plants are explicitly modeled. In connection with CO_2 recovery, two major CO_2 sequestration measures, ocean sequestration and underground sequestration, are explicitly formulated. Underground CO_2 sequestration is further divided into four types: injection into oil wells for enhanced oil recovery (EOR) operation, storage in depleted natural gas wells, injection into coal-beds for enhanced coal-bed methane recovery (ECBM) operation and sequestration in aquifers.

The end-use energy sector of the model is disaggregated into four types of secondary energy carriers: solid fuel, liquid fuel, gaseous fuel and electricity. The liquid fuel demand is further decomposed into three types of oil products: gasoline, light fuel oil and heavy fuel oil. Electricity demand is expressed by load duration curves having four kinds of time periods: instantaneous peak, peak, intermediate and off-peak periods. The future energy demand in case of no climate policy is exogenously provided by energy type, region and year. Energy savings in end-use sectors are modeled in the top-down fashion using the long-term price elasticity and transportation technologies in end-use sectors, for example, are not explicitly formulated. However, hydrogen energy economy is attracting great attention recently. Therefore, we tried a simplified modeling of FCVs as one of the greatest hydrogen consumers. For this evaluation, it is assumed that the gasoline demand is partly substituted for by hydrogen which is to be used for FCVs. While the production costs of both gasoline and hydrogen are endogenously determined inside the model, the direct comparison between their costs does not give the answer because of the cost difference in the two kinds of vehicles; we impose the cost penalty on the hydrogen due to the higher cost of FCVs. This modeling is the first step for the evaluation of FCVs and further extension, e.g., modeling of infrastructure for supply of hydrogen, will be required.

The world disaggregated regions in the model are linked to each other by interregional trading of eight items: coal, crude oil, synthetic oil, methane, methanol, hydrogen, electricity and CO_2. The way of transportation, e.g., tanker, pipeline, is selected under the criteria of the least cost inside the model.

3. MODEL ASSUMPTIONS

3.1 Primary Energy Potentials and Costs

The potentials and costs of the eight types of primary energy are assumed as follows. Most of the assumed potentials are based on geographic information systems (the GIS) data, which are easily processed to provide each region with its corresponding potential.

3.1.1 Fossil fuel

Assumed potentials of conventional oil and natural gas are derived from USGS GIS data (USGS, 2000) and those of unconventional oil and gas by country are estimated using the data of Rogner (1997). The potential of coal is assumed using the country data of WEC (World Energy Council, 2001). Table 1 summarizes the assumed world fossil fuel potentials. The production costs of the fossil fuels are assumed based on the study mainly by Rogner.

Table 1. Assumed Fossil Fuel Potentials in the World

	Anthracite and Bituminous	**Sub-bituminous**		**Lignite**
Coal [Gtoe]	424	208		253
		Conventional		Unconventional
	Remaining Reserves	Undiscovered (Onshore)	Undiscovered (Offshore)	
Oil [Gtoe]	137	60	44	2,342
Natural gas [Gtoe]	132	59	52	19,594

3.1.2 Renewable energy

The world potential of hydropower is derived from WEC (2001) and assumed to be 14,400 TWh/yr. The world potential of potential of wind power, PV and biomass is assumed to be about 12,000 TWh/yr, 1,271,000 TWh/yr and 3,960 Mtoe/yr respectively. These latter three types of energy potentials are estimated combining some GIS data, such as wind-speed, solar radiation power, land use, etc. The potentials of all the four kinds of renewables are classified into five cost grades. The costs by grade in the year 2000 are summarized in Table 2.

Table 2. Cost of Renewables by Grade in the Year 2000

Grade	Hydropower [$/MWh]	Wind power [$/MWh]	PV [$/MWh]	Biomass [$/toe]
1	20	56	209	171
2	30 / 60	60	272	185
3	120	71	352	227
4	150	87	487	454
5	180	118	720	1000

3.2 Assumptions about Technologies

The technologies that are considered in this model are almost identical to those in DNE21 (Fujii and Yamaji, 1998). This section explains the assumptions about main technologies and a location factor that is a parameter for considering regional differences in facility costs.

3.2.1 Power generation

The assumed parameters of electricity generation such as unit facility costs and generation efficiencies are shown in Table 3 (OECD/IEA, 2000). With respect to conventional technologies such as fossil-fuel power generation, costs are assumed as being fixed over a century; however, the improvements in the generation efficiency are assumed to occur with time. Further, in the case of IGCC and biomass-fueled power generation that are relatively new technologies, both cost reductions and efficiency improvements with time are assumed. Here, the costs given in Table 3 are the standard costs considered in this study. The assumed regional cost at each time point is calculated based on these standard costs and the location factor that is explained in Section 3.2.3.

3.2.2 CO_2 Capture and storage

Table 4 shows the assumed facility costs and energy requirements for CO_2-capture technologies. The cost reduction and energy efficiency improvement of CO_2-capture technologies are exogenously assumed to occur with time; this assumption is based on several sources (David et al., 2000; Fujii et al., 1998). In this model, the cost of electricity generation is endogenously determined based on the region, time point, and kind of time period within the model. Therefore, although the energy requirements are exogenous, the costs per ton of avoided CO_2 emissions are also determined within the model. Table 5 summarizes the assumptions about the potentials and costs of CO_2 sequestration. The details of the procedures used for estimation are presented in Akimoto et al. (2004).

Table 3. Assumed Facility Costs and Generation Efficiency for Electric Power Plants

		Facility costs [US$/kW]	Generation efficiency [LHV %]
Coal-fueled power	High	1,200	42.0–52.0
	Middle	900	36.0–46.0
	Low	700	22.0–27.0
Oil-fueled power	High	450	50.0–60.0
	Middle	300	37.0–47.0
	Low	200	20.0–25.0
N. gas-fueled power	High	450	52.0–62.0
	Middle	300	38.0–48.0
	Low	200	24.0–29.0
IGCC with CO_2 recovery		1,700–1,450	34.0–49.0
Biomass-fueled power	High	1,800–1,200	36.0–46.0
	Low	1,300–700	18.0–28.0
Nuclear power		1,900	
Methanol-fueled power		450	52.0–62.0
Hydrogen-fueled power		450	52.0–64.5

Note: Generation efficiency improvements are assumed to occur with time.

Table 4. Assumed Facility Costs and Required Energy for CO_2 Capture

	Facility cost [US$/(tC/day)]	Energy requirement [MWh/tC]
CO_2 chemical recovery from coal-fueled power	59,100–52,000	0.792–0.350
CO_2 chemical recovery from gas-fueled power	112,500–100,000	0.927–0.719
CO_2 physical recovery from gasification plants	14,500	0.902–0.496

Note: Cost reduction and energy efficiency improvement are assumed to occur with time.
Source: David et al. (2000); Fujii et al. (1998)

Table 5 . Globally Assumed CO_2 Sequestration Potentials and Costs

	Sequestration potential [GtC]	Sequestration cost† [$/tC]
Oil well (EOR)	30.7	81–118‡
Depleted gas well	40.2–241.5††	34–215
Coal bed (ECBM)	40.4	113–447‡‡
Aquifer	856.4*	18–143
Ocean	–	36**

† Costs of CO_2 capture are excluded.
‡ The proceeds from recovered oil are excluded.
†† 40.2 is the initial value in 2000, and the capacity increases with natural gas production.
‡‡ The proceeds from recovered gas are excluded.
* The potential is the "practical" one, which is 10% and 20% of the "ideal" potentials for onshore and offshore, respectively.
** The cost includes that of CO_2 liquefaction.

3.2.3 Location factor

The facility cost can be divided into several components such as material and equipment costs, construction labor cost, etc. Regional differences in these components have been reported in several literatures (e.g., Saito, 2000). Based on these literatures, a location factor that is expressed by Eq. (1) is assumed for the construction labor cost. $LF_{r,y}$ denotes the location factor at region r and year y. Table 6 shows the location factor at each representative time point. The facility cost for each region and time point is adjusted by multiplying this factor by the construction labor cost. The shares of the construction cost in the facility cost are assumed to be 17.3 % for electric power plants, whereas they are 30.4 % for other plants. The material and equipment costs were assumed to be constant for all the regions.

$$LF_{r,y} = 0.151\text{n}(GDP / capita) - 0.54 \quad (1)$$

Table 6. Assumed Location Factor

	2000	2005	2010	2015	2020	2025	2030	2040	2050	2075	2100
$LF_{r,y}$	0.27–1.05	0.28–1.07	0.28–01.08	0.30–1.09	0.31–1.10	0.34–1.11	0.36–1.14	0.42–1.18	0.47–1.22	0.55–1.29	0.60–1.34

Note: The share of the construction cost in the facility cost: Electric power plants = 17.3%; Others = 30.4%

3.3 Population, GDP and Final Energy Demands

Future scenarios of population, reference GDP and reference final energy demands are derived from B2 Marker Scenario of IPCC SRES (Nakicenovic et al., 2000; TGCIA, 2000). We made, however, some modifications on the original scenario data so as to keep consistency with the historical data (IEA, 2002; World Bank, 2002; OECD/IEA, 2000) and with the region division of this model. Energy savings in end-use sectors are modeled using the long-term price elasticity. Based on several data (e.g., IEA, 1999), the elasticitiy of electricity and non-electricity is originally assumed to be –0.3 and –0.4, respectively. The model finds the least cost energy systems which meet the final energy demands in Reference case, and also does so in emission reduction cases assuming that energy saving takes place based on the price elasticity.

3.4 Endogenous Technology Learning

3.4.1 Methodology

The technological change is treated endogenously for wind power, PV and FCVs as described before. In this paper, the typical learning curve as expressed by Eq. (2) is assumed for these technologies. C_y, FC, LR and CI_y denote Cost at year y, Floor cost, Learning rate and cumulative installation at year y, respectively. The learning rate is the cost reduction ratio for doubling of the cumulative installation. FC and LR are exogenously provided and C_y and CI_y are endogenously determined according to Eq. (2).

$$C_y = (C_{2000} - FC)\,(1 - LR)^{\log(CI_y/CI_{2000})/\log 2} + FC \qquad (2)$$

The determination of C_y and CI_y is carried out through iterative model runs. For the first model run, time series values of initial guess are used for C_y, and time series values of CI_y are obtained by the model run. New time series values of C_y are determined by Eq. (2) using the obtained time series values of CI_y. The new time series values determined for C_y in this way are used for the second model run. This operation is iterated until the variations of time series values of C_y between the two successive model runs become acceptably small (below 0.5 %) for all the three technologies. Although the required times of model-run iterations vary depending on the circumstances, a good convergence was achieved by conducting several times of iterations (five to ten times).

As mentioned above, optimization models addressing endogenous technological changes have a nonconvex character and multiple local optima may exist. Therefore, we attempted the calculation using another set of initial values which are the floor costs of the three technologies as an optimality check. The achieved total system cost was higher than that obtained with the original initial values. Although this check does not guarantee the solution with the original initial values to be global optimal, the obtained solution is considered acceptable; it can be attained in practical time.

3.4.2 Wind power and PV

Wind power and PV have mature technology components whose cost portions are regarded to be fixed and only the remaining portions undergo the cost reduction according to learning rates. The assumed parameters are shown in Table 7. In this study, these technologies are regarded as products that are traded freely among the world and these parameters assumed to be common among the regions.

The initial values of time series costs for the first model-run were set based on the costs in the year 2000 shown in Table 2 and the annual cost reduction rates. The annual reduction rates were assumed to be 1.0 %/yr for wind power and 3.4 %/yr for PV, which were determined based on EPRI/DOE (1997). Figure 1 shows the convergence of the time series cost for the base case without CO_2 constraint.

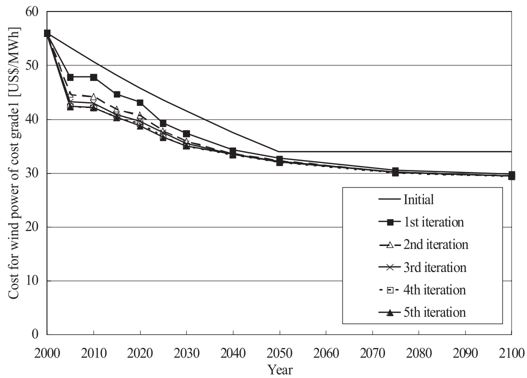
Table 7. Assumed Cost Reduction for Wind Power and PV

	Floor cost ratio in 2000 [%]	Ratio of cost for learning in 2000 [%]	Learning rate*** [% for doubling]
Wind power	36*	64	15
PV	13**	87	25

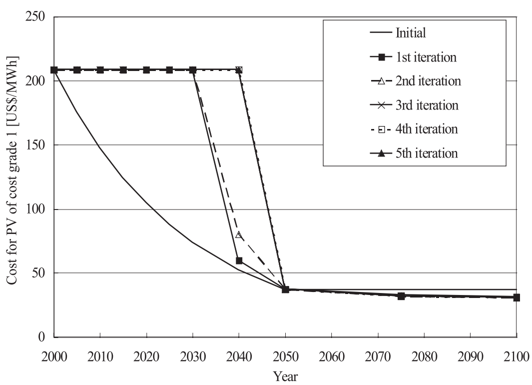
* Cost for construction, electric facilities, road for access, etc.
** Cost for power conditioner Source: Yamada and Komiyama (2002)
*** Source: A. Grubler et al (2002).

Figure 1. Convergence of Time Series Cost for Base Case

a. Wind power



b. PV



3.4.3 FCVs

The assumed cost reduction for FCVs is shown in Table 8. FCV technology was divided into four components. The initial values of cost for the first model-run were set based on the study of Tsuchiya (IAE/NEDO, 2003). The cost difference between FCV and gasoline vehicle is imposed as a cost penalty on the cost of hydrogen which substitutes for gasoline.

Table 8. Assumed Cost Reduction for FCVs

	Cost in the year 2000 [US$/vehicle]	Floor cost [US$/vehicle]	Learning rate [% for doubling]
Fuel cell	149,000	2,500	20
Hydrogen tank	3,300	420	10
Motor, battery controller	8,750	1,250	10

Note: Cost for gasoline vehicle and component common to that are 12,500 and 8,400 US$/vehicle, respectively.

The energy efficiency of FCVs at wheel is 3.1 times of that of gasoline vehicles.

4. MODEL ANALYSIS RESULTS

4.1 Simulation Cases

In this work, three CO_2 stabilization cases were studied with and without ITC besides Base case of no CO_2 constraint. The CO_2 emissions paths for stabilizations were determined based on TAR WGIII (IPCC, 2001) Chapter 2 diagrams. However, DNE21+ model is an energy system model and does not explicitly treat the land use change or CO_2-emitting industries like cement. Therefore, the emissions from land use and cement production were determined exogenously based on SRES B2 and they were subtracted from the above determined CO_2 emissions paths to obtain the path of CO_2 emissions only from energy systems. For the cases with ITC, the technological changes of wind power, PV and FCVs were treated endogenously in the same way as for Base case using the same parameters as shown in Table 7 and 8. However, we shall obtain different time series costs, that is, different cost reduction rates among the three constraint cases and Base case because the constraint cases demand more low-carbon technologies and consequently accelerate their cost reductions according to the learning curves, and the more stringent the constraint is, the faster the cost reduction proceeds. Thus, ITC is considered as the acceleration of "learning by doing process" in this study. On the other hand, for the cases without ITC, the time series costs of the three technologies that were obtained for Base case were kept fixed even for the emission constraint cases. A discount rate of 5 % was adopted throughout the study. The treatment of other technologies excepting the three endogenous technologies is fixed all through the cases.

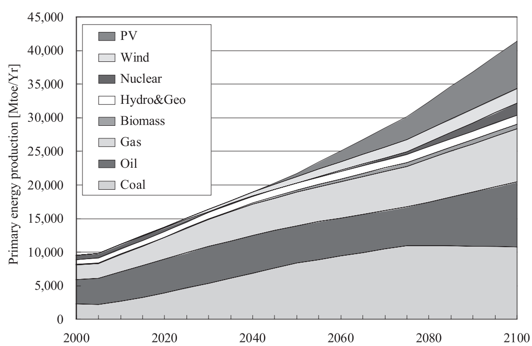
4.2 Model Results and Discussions

Figure 2 shows the world primary energy productions for Base case and ITC cases. Nuclear and renewables are expressed in primary equivalent by using a conversion factor of 0.33. The utilization of Non-fossil fuels, such as nuclear power, wind power, PV, biomass, increase in CO_2 concentration stabilization cases. Figure 3 shows the CO_2 emission and sequestration. Sequestration in aquifers and ocean sequestration play an important role for the stabilization of CO_2 concentration, and the lower stabilizations require the earlier utilization of CO_2 sequestration. Figure 4 shows the world final energy consumption. Gasoline is substituted for by hydrogen for FCV use and the trend is especially clear in 450 ppmv-ITC case.

Next discussed is the effects of ITC. Figure 5 shows the achieved time series costs for the three technologies with endogenous learning for Base case and cases with ITC. For wind power and PV, only the costs of grade 1 are shown. Although the cost for wind power for Base case is lower than that for 550 ppmv-ITC and 500 ppmv-ITC in some time points because of the competition among the technologies for mitigating global warming, the lower stabilization cases induce the early introduction of the three technologies, and as a result, the cost reductions in the early time period are observed. The differences in cost between Base case and cases with ITC are mainly observed during the short time period when substantial technology introduction is implemented, and they are small after a certain number of installations; this means that the effect of the ITC manifests

Figure 2. World Primary Energy Production for Base Case and ITC Cases

a. Base Case



b. Comparison

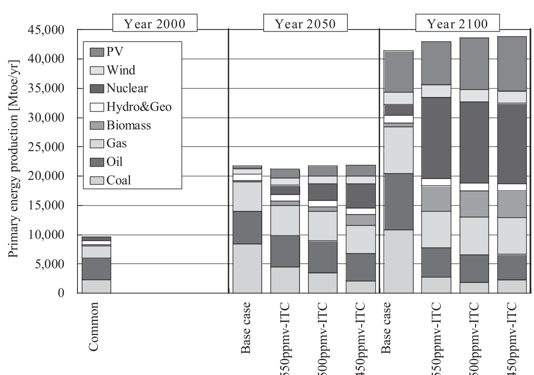
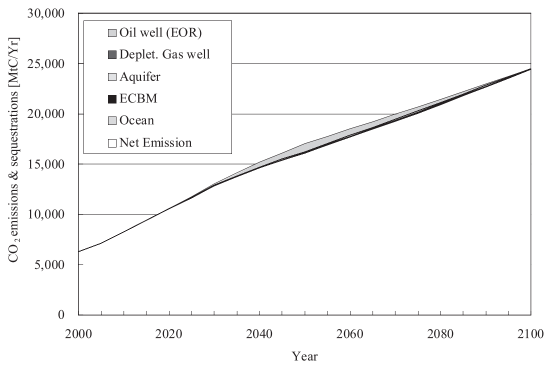
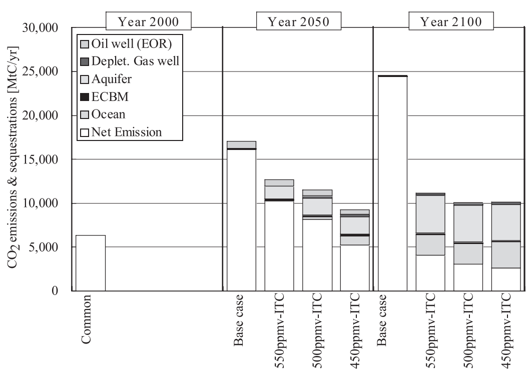


Figure 3. World CO_2 Emission and Sequestration for Base Case and ITC Cases

a. Base case



b. Comparison

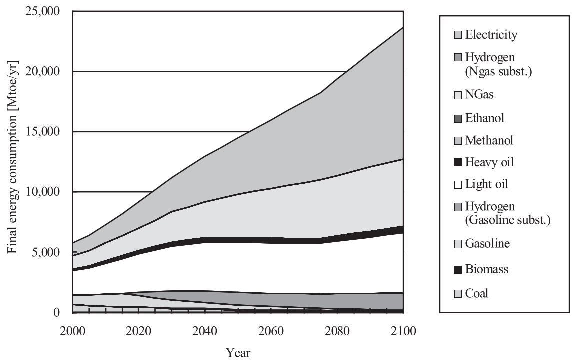


during a time period of a substantial initial introduction. For example, the largest difference in cost of PV between Base case and 450 ppmv-ITC case is observed in 2040. The costs in 2040 and the averaged annual cost reduction rates between 2000 and 2040 are 208 US$/MWh and 0 %/yr for Base case and 34 US$/MWh and 4.4 %/yr for 450 ppmv-ITC, respectively.

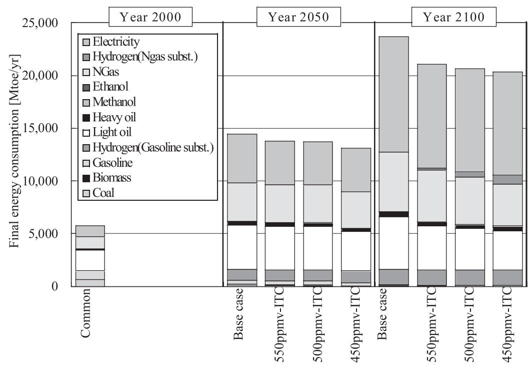
Figure 6 shows relative changes in primary energy production by source, in CO_2 sequestration and in hydrogen consumption for FCV use that substitutes for gasoline that are cumulatively caused during the 100 years by the ITC of the three technologies. In the figure, positive values mean increases for ITC cases as compared to without-ITC cases and negative values mean decreases for ITC cases. The CO_2 sequestration represents the sum of the five types as shown in Figure 3. The effects of the ITC on wind power and PV production are observed to increase when the stabilization level becomes lower. For 450 ppmv stabilization, the cumulative increases for the 100 years are 6.7 and 12.0 % for wind power and PV, respectively. For the hydrogen that substitutes for gasoline, the increase in consumption by the ITC is conspicuous for 450 ppmv but is small for 550 and 500

Figure 4. World Final Energy Consumption for Base Case and ITC Cases

a. Base case



b. Comparison



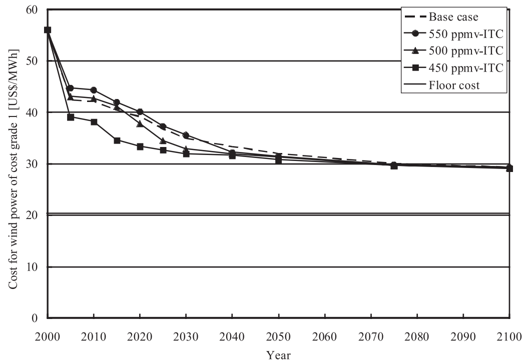
ppmv stabilization, because the hydrogen consumption in Base case is almost the same as that in 550 ppmv-ITC and 500 ppmv-ITC as shown in Figure 4.

Contrary to the acceleration of these three technology utilization, the other technologies of exogenous learning are less utilized by the ITC and the decrease ratios of nuclear energy production and CO_2 sequestration are relatively large among these technologies. It is considered that mainly the above two technologies are replaced by the technologies of endogenous learning due to the ITC.

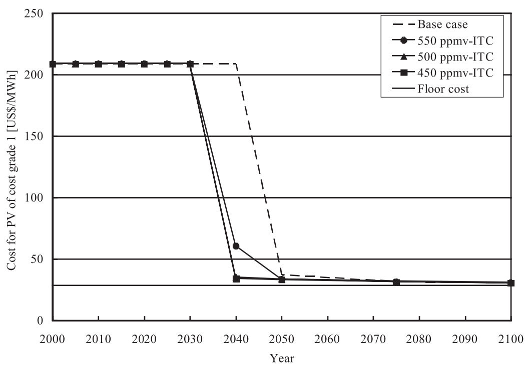
Figure 7 shows the changes caused by the ITC by time series. For the technologies of exogenous learning, nuclear energy production and CO_2 sequestration are shown as examples. The lower the stabilization level is, the earlier the effect of the ITC on wind power and PV production are observed. For 450 ppmv stabilization, the largest increases are approximately 240 (in the year 2025) and 1,400 (in the year 2040) Mtoe/yr for wind power and PV, respectively. For the hydrogen substituting for gasoline, the increase in consumption and the ratio of increase are largest in 2015 for 450 ppmv stabilization and they become smaller with time.

Figure 5. Time Series Costs for the Three Technologies With Endogenous Technology Learning

a. Wind power



b. PV



c. FCVs

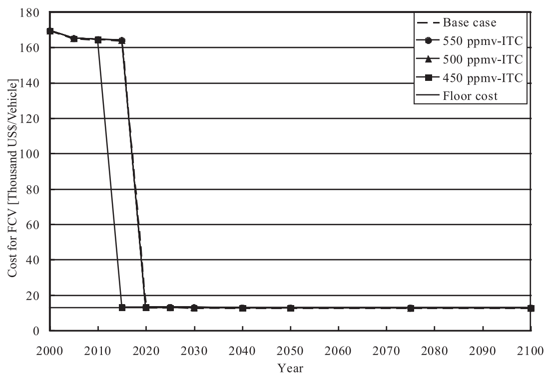
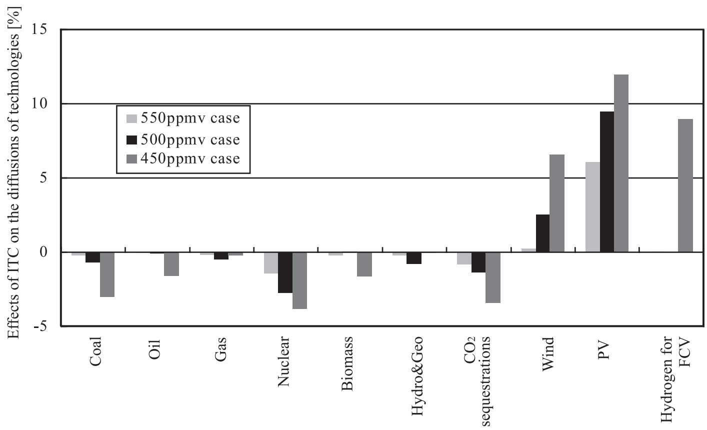


Figure 6. Effects of ITC on the Diffusions of Technologies Accumulated for the 100 years (Change for ITC Cases Relative to Without-ITC Cases for the Three CO_2 Stabilization Levels)



The utilizations of nuclear power and CO_2 sequestration decrease especially around the middle of the century according to the accelerated utilization of the three technologies with endogenous technological changes. The largest decrease of nuclear production and their ratio relative to that of without-ITC cases is approximately 150 Mtoe/yr (10%) in 2050 for 550 ppmv, 440 Mtoe/yr (48%) in 2040 for 500 ppmv, 540 Mtoe/yr (20%) in 2040 for 450 ppmv. For CO_2 sequestration, it is 160 MtC/yr (6%) in 2050 for 550 ppmv, 200 MtC/yr (11 %) in 2040 for 500 ppmv, 500 MtC/yr (14 %) in 2040 for 450 ppmv.

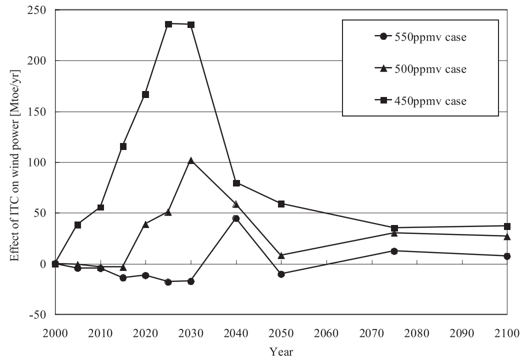
Figure 8 shows the marginal CO_2 reduction costs and the increases in discounted total system cost relative to that for Base case. The marginal reduction costs increase with the lower concentration level. On the other hand, the increases in marginal CO_2 reduction cost by the ITC suspension are much smaller than those by the CO_2 stabilization level difference. The increase in total system cost becomes larger non-linearly as the stabilization level lowers, and the increase by lowering the stabilization level is larger than that by the ITC suspension as shown in the right figure.

The above small effects of the ITC suspension on the marginal CO_2 reduction cost and total system cost are considered to be caused by the small portion of endogenously treated technologies in all the technologies considered in the model. If the technological change of new technologies such as CO_2 capture will be able to be treated endogenously, the effect of ITC will become more conspicuous even in the marginal cost and the total system cost.

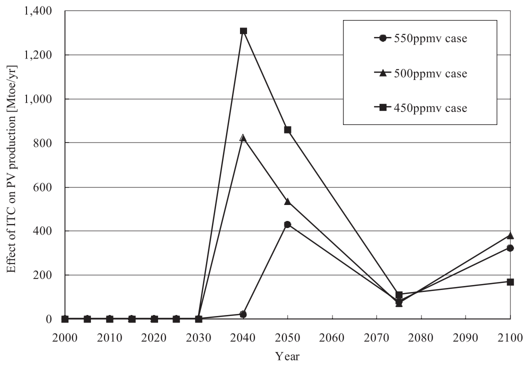
A sensitivity analysis with respect to the learning rate was conducted; the learning rates of the three technologies were changed by 5 percentage points at the same time for the three CO_2 stabilization cases. Figure 9 shows the obtained time series costs for the two sets of learning rates and for the three stabilization cases.

Figure 7. Effects of ITC by Time Series (Changes for ITC Cases Relative to Without-ITC Cases for the Three CO_2 Stabilization Levels)

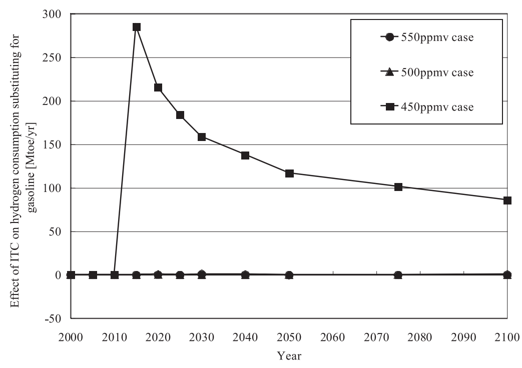
a. Power generation by Wind power



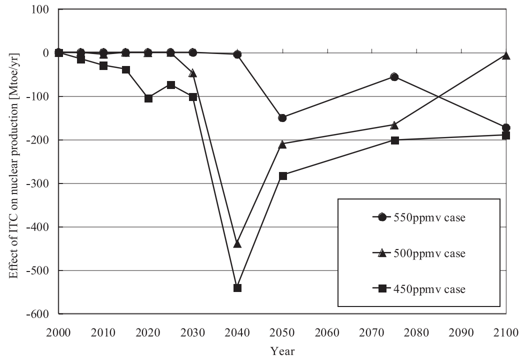
b. Power generation by PV



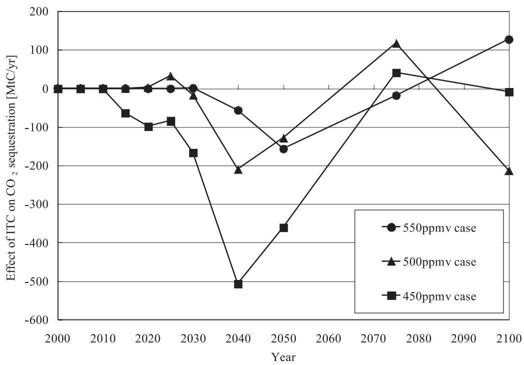
c. Hydrogen consumption substituting for gasoline



d. Nuclear



e. CO_2 sequestrations



For wind power, the effects of the learning rate change are conspicuous throughout the time span. The differences in cost due to the CO_2 stabilization level are observed mainly between 2000 and 2040, which is the same as the results of the original learning rate shown in Figure 5.

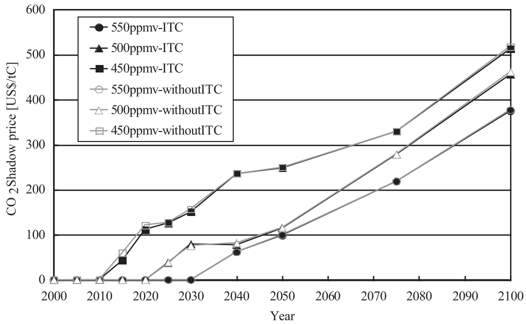
On the other hand, the differences in cost of PV due to the CO_2 stabilization level are very small and almost indiscernible. Only the changes due to the learning rate are observed. This implies that the timing of initial introduction of PV depends principally on the learning rate and not on the stabilization level. The initial cost of PV in 2000 is considerably higher than that of wind power and the utilization in 2000 is very small. In general, the cost reduction which takes place according to the learning curve in the early period is relatively large for the same ratio of increase in cumulative production.

For FCVs, a higher learning rate does not lead to a significant change in the utilization as compared to the original learning rate. The original learning rate seems to be so large that the higher learning rate does not bring about any more acceleration of utilization of FCVs further. For the cases of the lower learning rate, the delayed cost reduction of FCVs is observed for the higher CO_2 stabilization levels.

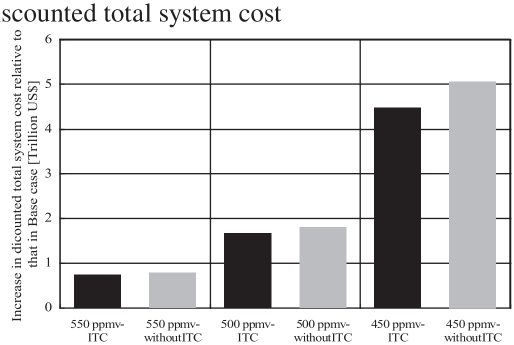
The impacts of the learning rate are relatively large, especially for immature technologies which have high cost and small utilization at the initial time point.

Figure 8. Marginal CO_2 Reduction Costs and Increase in Discounted Total System Cost Relative to that for Base Case

a. Marginal CO_2 reduction costs



b. Increase in discounted total system cost

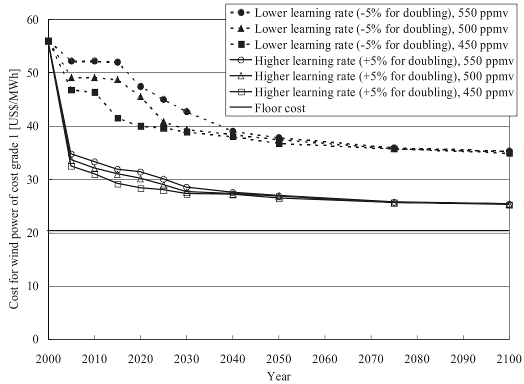


5. CONCLUSION

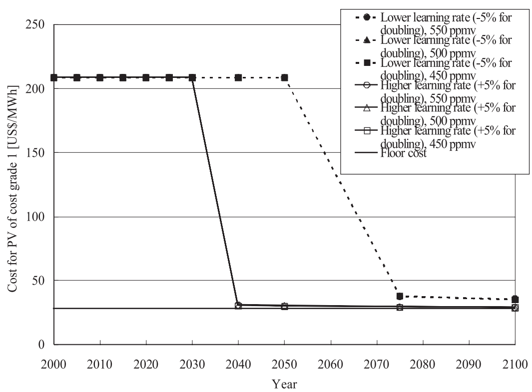
A world energy systems model was developed to explore cost effective measures for CO_2 stabilization of different levels and impacts of induced technological changes on them. The model treats technological changes endogenously only for wind power, PV and FCVs, which are mass production technologies and are expected to follow the typical learning curve with a constant learning rate. For all the other technologies, technological changes are exogenously determined. Despite the difficulties in solving the optimization model with endogenous technological changes, an acceptable solution is achieved

Figure 9. Sensitivity to the Learning Rate

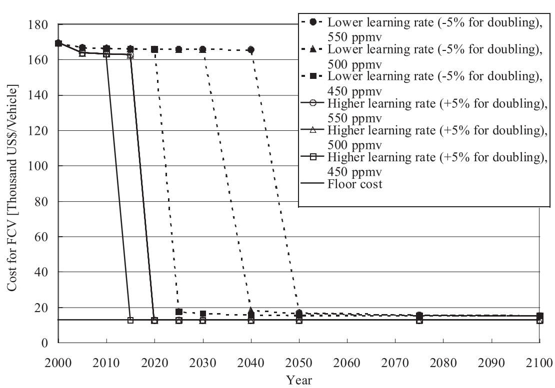
a. Wind power



b. PV



c. FCVs



with practical time through iterative model runs. Thanks to its high regional resolution, the model considers in detail, the transportation cost of energies and also regional differences in energy systems and technology level in exploration of cost effective energy systems for both non-policy case and stabilization cases of 550, 500 and 450 ppmv. The final remarks are as follows:

1) Endogenous technology learning is solved successfully through iterative model runs.
2) More nuclear and renewables, less fossil fuels and more CCS are to be used for lower levels of stabilization. The total system cost becomes larger non-linearly as the stabilization level becomes lower.
3) The effect of induced technological change is significant in terms of the amount of technology utilization, only during a time period of initial substantial introduction of technology.
4) The marginal CO_2 reduction cost or the total system cost is not influenced substantially by the ITC because the portion of endogenously treated technologies is not large in this study.
5) The determination of learning rate values should be careful because their impacts may be relatively large.

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