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# Analysis of energy strategies to halve $CO_2$ emissions by the year 2050 with a regionally disaggregated world energy model

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## Abstract

There is growing attention to the regulation of greenhouse gas (GHG) emissions to mitigate the global warming, and the target of 50% reduction of GHG emissions by the year 2050 has been discussed in concrete as a long-term goal. The authors have been revising the regionally disaggregated world energy model which is formulated as a large scale linear optimization model from the aspect of nuclear and photovoltaic power generation technologies and calculate the optimal energy system development path over the time horizon with the $CO_2$ emissions constraints. The obtained results indicate that the world electricity in 2050 is to be mainly provided by natural gas-fired power plants and LWR (light-water reactors), and that in 2100 is to be done by FBR (fast breeder reactors) and IGCC with CCS. The results also indicate that the relative importance of major technologies, such as FBR and CCS, may differ significantly due to the regional availabilities of energy resources and $CO_2$ storage capacities.

*Keywords*:energy model, global warming, linear optimization, nuclear fuel cycle ;

## 1. Introduction

There is growing attention to the regulation of greenhouse gas (GHG) emissions to mitigate the global warming, and the target of 50% reduction of GHG emissions by 2050 has been discussed in concrete as a long-term goal. Therefore, a method of a quantitative analysis for reducing $CO_2$ emissions is becoming increasingly important for future international discussions. Energy models are often used in such an analysis, and the authors' research group has been developing a regionally disaggregated world energy model [1], of which the geographical resolution is raised to describe in detail international energy and $CO_2$ transports to evaluate accurately $CO_2$ mitigation technologies such as $CO_2$ capture and storage technology (CCS). However, the present energy model is insufficient for the evaluation of nuclear related technologies which have attracted a great attention as an alternative source of primary energy and $CO_2$ reduction technology, and the model has not taken into account the uncertainty of photovoltaic power outputs due to fluctuation of weather conditions. The purpose of the study is to evaluate the long-term technological options to reduce $CO_2$ emissions substantially. This paper shows simulation results of

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system optimization calculation in the scenario to halve $CO_2$ emissions by the year 2050 with a newly revised world energy model from the aspect of nuclear and photovoltaic power generation technologies.

## 2. Regionally disaggregated world energy model

First, the structure of the energy model is briefly explained. In the model, the world is divided into 54 regions. The model can describe in detail international energy and $CO_2$ regional transports and energy flows of multiple time stages for the years from 2000 to 2100 at ten-year intervals and multiple regions, and the model seeks the solution that minimizes the total system cost under various kinds of constraints, such as amount of resource constraints, energy supply and demand balance constraints, and $CO_2$ emissions constraints. The model is formulated as a linear optimization model, of which the number of the variables is more than one million.

Figure 1 shows the division framework of world regions and assumed transportation routes. With respect to the division framework, some countries which resemble each other in terms of geographical and socioeconomic conditions are basically treated as one aggregated region. However, several large countries such as the United States, Russia, China and India are further divided into several sub-regions to reflect the variations in domestic energy systems and domestic energy transports. In Figure 1, round markers are called city nodes. They show representative points of the respective regions color-coded in the figure. The model takes account of transportation of fuel, electricity and $CO_2$ between these points. The square markers in the figure are called production nodes. They are additional representative points for fossil fuel production to consider the contributions of resource developments in remote districts.

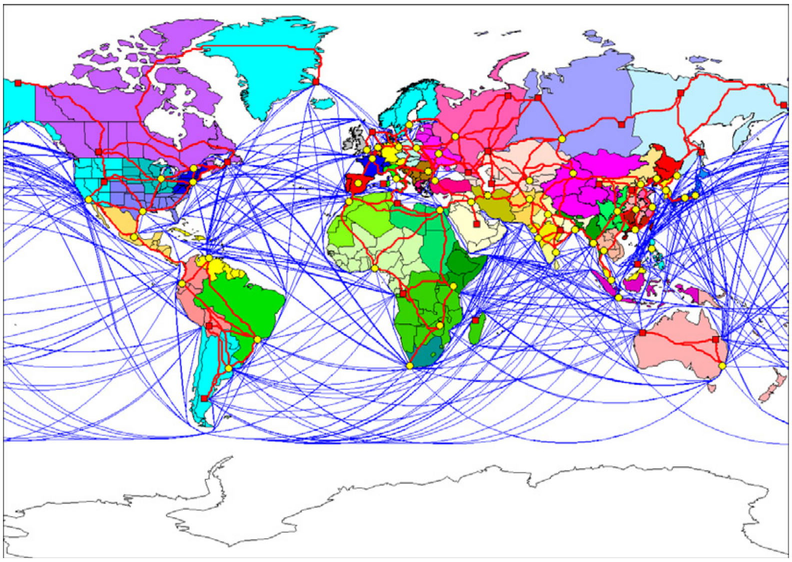

Figure 1 Division framework of world regions and transportation routes

The model involves various components to model the energy production, conversion and transport. The energy system components are as follows,

(1) Primary energy resources

conventional fossil fuels (coal, oil, natural gas) , unconventional fossil fuels (heavy crude oil & oil sand, oil shale, unconventional gas) , biomass (energy crops, forestry biomass, residue logs, black liquor, waste paper, sawmill residue, crop residue at harvest, sugar cane residue, bagasse, household waste, human feces, animal dung), nuclear power, hydro power, geothermal power, solar power, and wind power

(2) Secondary energy carriers

hydrogen, methane, methanol, dimethyl ether (DME), oil products, carbon monoxide, electricity

(3) Final energy demand sector

solid fuel demand, liquid fuel demand, gaseous fuel demand , electricity (daily load curves with seasonal variations) demand

(4) Power generation technology
coal-fired, oil-fired, natural gas (Methane)-fired, IGCC with $CO_2$ capture, nuclear, hydro, geothermal, solar, wind, biomass direct-fired, BIG/GT, STIG, municipal waste-fired generation, hydrogen-fueled and methanol-fired
(5) Energy conversion process
partial oxidation (coal, oil), natural gas reformation, biomass thermal liquefaction, biomass gasification, shift reaction, methanol synthesis, methane synthesis, dimethyl ether (DME) synthesis, diesel fuel synthesis, water electrolysis, biomass methane fermentation, biomass ethanol fermentation, hydrogen liquefaction, liquid hydrogen re-gasification, natural gas liquefaction, liquefied natural gas re-gasification, carbon dioxide liquefaction, liquefied carbon dioxide re-gasification
(6) $CO_2$ capture (3 types) and storage
chemical absorption, physical adsorption, membrane separation, enhanced oil recovery operation, depleted natural gas well injection, aquifer injection, ocean storage, and enhanced coal bed methane operation

## 3. Nuclear fuel cycle model

### 3.1 Nuclear cycle model configuration

First, we explain a new part to model nuclear related technologies. The new nuclear model was developed with reference to" Fuel cycle optimization model" [2]. The new model takes account of the availability of advanced nuclear technologies such as nuclear fuel cycle and fast breeder reactors, which can improve drastically the usage efficiency of natural uranium resource. Figure 2 shows the outlines of the nuclear fuel cycle model.

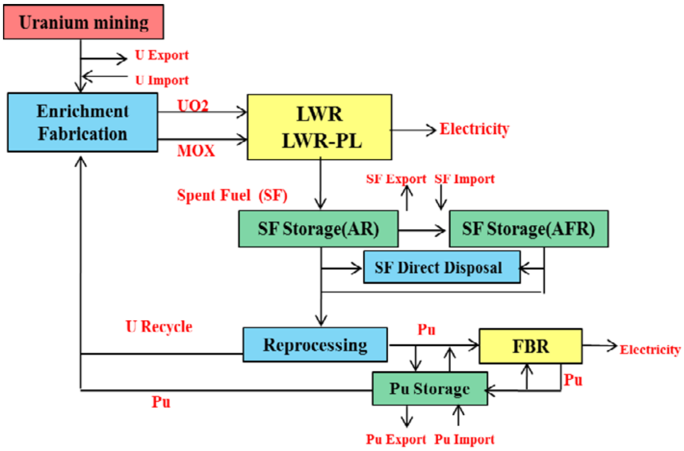

Figure 2 Outline of nuclear fuel cycle model

Light-water reactors (LWR), light-water MOX reactors (LWR-MOX), and fast breeder reactors (FBR) are considered as specific kinds of nuclear power generation technologies. Fuel flow is as follows: according to the capacity of new power plant construction, certain amounts of nuclear fuel are assumed to be loaded for initial commitment, and according to the amount of nuclear power generation, fuels for equilibrium charge are loaded. Spent fuel (SF) is assumed to be discharged periodically from the cores of reactors during operation. When power plants are decommissioned, SF is also discharged. All of SF is stored in power plants (SF storage AR) for a certain period (cooling time). Some of SF is stored away from power plants (SF storage AFR) if necessary. Then SF is reprocessed or disposed of directly. Uranium 235 and Plutonium (Pu) can be recovered through reprocessing of SF. Recovered Uranium 235 is recycled through re-enrichment process. Some of recovered Pu is stored if necessary and the remaining Pu is used as FBR fuel and LWR-MOX fuel. In this model, it is assumed that SF of FBR is also reprocessed after cooling to provide Pu. The storing period of SF and Pu is decided by the optimized algorithm.

### 3.2 Modeling of nuclear fuel charge and discharge

This model considers four types of nuclear fuel and SF: fuel for initial commitment, fuel for equilibrium charge, SF from equilibrium discharge, and SF from decommissioning discharge. Fuel for initial commitment is demanded when new nuclear power plants are constructed. Equilibrium charged fuel and equilibrium discharged SF are proportional to the amount of electricity generation. Decommissioning discharged SF is removed from the cores of decommissioned plants. This model also considers time lags of various processes in the system. For example, fuels for initial commitment and equilibrium charge must be prepared a few years before loaded. SF from equilibrium discharge and decommissioning discharge must be stored for a few years for cooling. Figure 3 shows relationships between power plant capacity and each fuel supply and demand with the time lags.

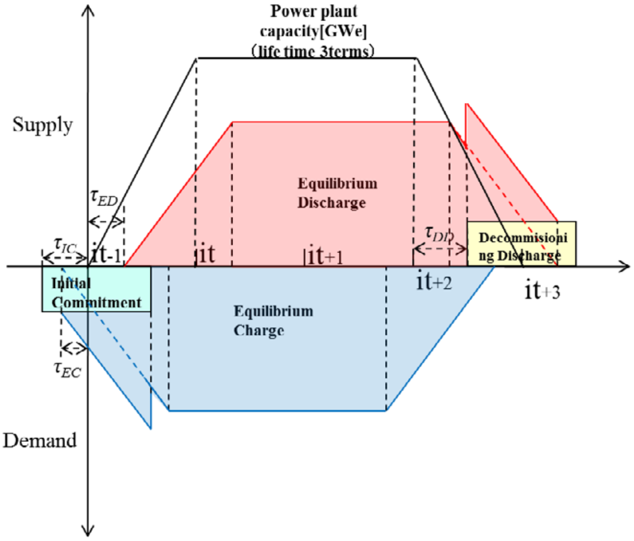

Figure 3 Relationships between power plant capacity and each fuel supply and demand with time lag (τ)

Therefore we formulated supply and demand balance of each type of fuel and SF during the interval of term (ten years) to consider the effects of the time lags mentioned above. For example, demand and supply balance constraint of fuel for initial commitment can be shown with Eq. (1)

$$Y\cdot\frac{LIC(it,r)+LIC(it-1,r)}{2}=\frac{(Y-\tau_{IC})\cdot GLW(it,r)+\tau_{IC}\cdot GLW(it+1,r)}{Y} \tag{1}$$

where $LIC(it,r)$: amount of fuel for Initial Commitment [tHM], $GLW(it,r)$: new LWR plant construction [GWe], $it$: term index, $r$: region index, $Y$: interval of term, $\tau_{IC}$: time lag of initial commitment.

## 4. Photovoltaic power model

We also developed a new photovoltaic power (PV) model which takes into account the intermittent characteristics of PV power generation due to changes in weather conditions in a way of stochastic programming. The outline of the model is described as follows. The model considers two states of weather conditions (sunny and cloudy) and the amounts of PV power generation are calculated by node, year, season, time, and weather. Every city node has its own occurrence probability of sunny day by season. The number of sunny days in each season depends on the probability. When it is cloudy, the level of PV power generation output may drop substantially as compared with sunny day. It is necessary to prepare other types of power generator to compensate the PV output drops. As a result, this model can calculate more realistic power generation mix. Each node's PV power and the probability of sunny day are calculated with reference to NEDO reports [3]

According to NEDO reports, every 10 minutes PV power output can be calculated from the data on latitude, longitude, altitude, sunshine duration and precipitation. The hypothetical amount of global solar radiation for the case where the sky is kept cloudless during a whole day is calculated by using this calculation method, which is the maximum value of the amount of global solar radiation. It is assumed that the effective amounts of global solar radiation on sunny day and cloudy day are 80% and 30% of that maximum value, respectively. We can estimate the value of the occurrence probability of sunny day for each node and each season, by comparing the hypothetical maximum global solar radiation with the actual measurement value from SeaWIFS Satellite Sunlight Data [4]. PV power constraint can be shown with Eq. (2),

$$PV(r,s,h,it,w) \leq \sum_{t2=0}^{t} Rem_{CPV}(it,it2) \times CPV(r,it2) \cdot PU_{PV}(r,s,h,w) \cdot Term(s) \cdot Term(h) \cdot Probability(r,w) \tag{2}$$

where *r*:region index, *s*:season index, *h*:hour index, *it*:term index, *w*:weather index, *PV*(*r,s,h,it,w*):PV power generation [TWh], *RemCPV*(*it*, *it2*): equipment remaining rate, *CPV*(*r*, *it2*): new PV plant construction[GWe], *PUPV*(*s,h,w*): capacity factor, *Term*(*s*): season length, *Term*(*h*): day length, *Probability*(*r,w*): occurrence probability of sunny day.

## 5. Simulation results

### 5.1 Setting data

Table 1 shows data on nuclear fuel cycle and photovoltaic costs. FBR is assumed to be available after the year of 2030, and PV capital cost is reduced by 2% per annum by the technological progress. Table 2 shows nuclear reactor characteristic data. Natural uranium and depleted uranium contain 0.711% and 0.2% U-235, respectively. In this simulation, energy demand scenario is given exogenously with reference to SRES-B2 by IPCC [5]. Figure 4 shows world energy demand scenario.

Table 1 Cost data [2]

| | unit | cost |
|---|---|---|
| LWR capital cost | \$/kW | 2000 |
| FBR capital cost | \$/kW | 3000 |
| LWR/FBR load factor | % | 80 |
| annual leveling factor | % | 19 |
| $^{235}$U enrichment | \$/kg-SWU | 110 |
| UO$_2$ fabrication | \$/kg-U | 275 |
| MOX fabrication | \$/kg-HM | 1100 |
| SF reprocessing | \$/kg-HM | 750 |
| VHLW final disposal | \$/kg-HM | 90 |
| SF storage | \$/kg-HM/yr | 8 |
| SF direct disposal | \$/kg-HM | 350 |
| FBR cycle cost | \$/MWh | 10 |
| Pu storage | \$/kg-Pu/yr | 500 |
| PV capital cost | \$/kW | 6000 |
| Discount rate | % | 5 |
| Life time of plant | yr | 30 |

Table 2 Nuclear fuel characteristics by reactor [2]

| | LWR | LWR(MOX) | FBR |
|---|---|---|---|
| Initial Commitment | | | |
| U (t/GWe) | 76.7 | 76.7 | 68.161 |
| $^{235}$U content (%) | 3.2 | 3.2 | 0.3 |
| Pu (t/GWe) | 0.0 | 0.0 | 4.286 |
| Heavy metal (t/GWe) | 76.7 | 76.7 | 75.502 |
| Equilibrium Charge | | | |
| U (t/GWe) | 18.5 | 17.61 | 10.692 |
| $^{235}$U content (%) | 4.6 | 0.711 | 0.3 |
| Pu (t/GWe) | 0.0 | 1.233 | 0.715 |
| Heavy metal (t/GWe) | 18.5 | 19.46 | 11.75 |
| Equilibrium Discharge | | | |
| U (t/GWe) | 17.4 | 17.04 | 9.476 |
| $^{235}$U content (%) | 1.07 | 0.44 | 0.129 |
| Pu (t/GWe) | 0.15 | 0.79 | 0.882 |
| Heavy metal (t/GWe) | 17.6 | 18.22 | 10.747 |
| Decommissioning Discharge | | | |
| U (t/GWe) | 73.3 | 68.01 | 63.09 |
| $^{235}$U content (%) | 1.79 | 0.53 | 0.183 |
| Pu (t/GWe) | 0.56 | 3.615 | 5.128 |
| Heavy metal (t/GWe) | 74.0 | 73.625 | 70.429 |

### 5.2 Simulation case

This paper shows simulation results in two cases. One case is no CO$_2$ regulation case (Base case) and the other is CO$_2$ regulation case (REG case). REG case is the scenario to halve CO$_2$ emissions by the year 2050 for the world as a whole. Moreover, in REG case the developed countries (high-income OECD countries) are assumed to reduce CO$_2$ emissions by 80% compared with 2000. Figure 5 shows the upper limit of global CO$_2$ emissions in REG case.

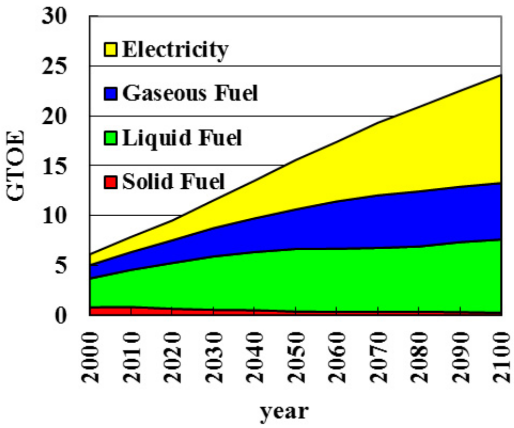

Figure 4 World energy demand scenario by IPCC

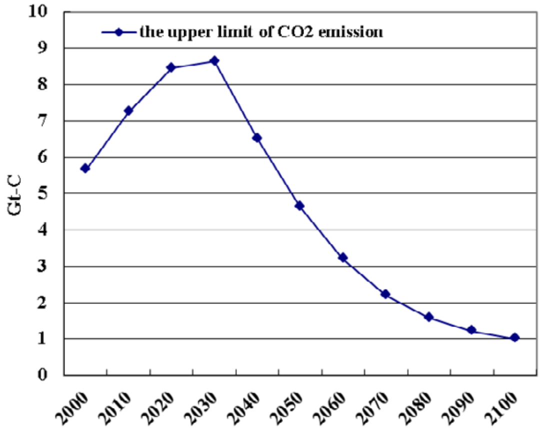

Figure 5 Upper limit of $CO_2$ emission in REG Case [6]

### 5.3 Major results

The calculation results are indicated in the following. Figure 6 shows world primary energy production and fig. 7 shows world electric power generation. Figure 8 shows $CO_2$ capture and storage balance and total amount of $CO_2$ storage in REG case. Figures 9-11 show electric power generation for Japan, China and USA, respectively.

The calculation results of our new energy model can be summarized in the following. First, in Base case, around 50% of the world's primary energy is provided by coal which is abundant and inexpensive. In power generation, after the year 2060, LWR generation increases. SF reprocessing is not conducted due to high cost. However, in REG case, biomass, solar, hydro, and nuclear energy which emit no $CO_2$ increase their shares in primary energy portfolio. LWR increases until the year 2050 and LWR (MOX) and FBR begin to be introduced after the year 2050. In 2100, all nuclear plants are to be replaced with FBR and about 30% of the world's power generation is provided by FBR. After the year 2060, the world's energy demand outpaces the supply potentials of those no fossil energy resources, and coal production is expected to increases again. In power generation, all coal-fired plants are to be replaced by IGCC with $CO_2$ capture facility, and all of $CO_2$ emitted from the power generation sector is to be captured and sequestrated in storage sites to reduce $CO_2$ emissions into the atmosphere. The results also indicate that the relative importance of major technologies, such as FBR and CCS, may differ significantly due to the regional availabilities of energy resources and CO2 storage capacities.

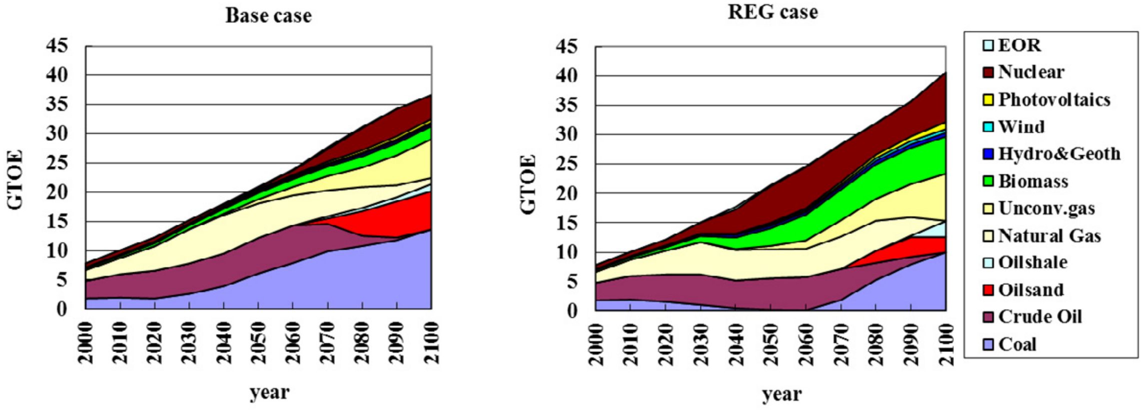

Figure 6 World Primary Energy Production

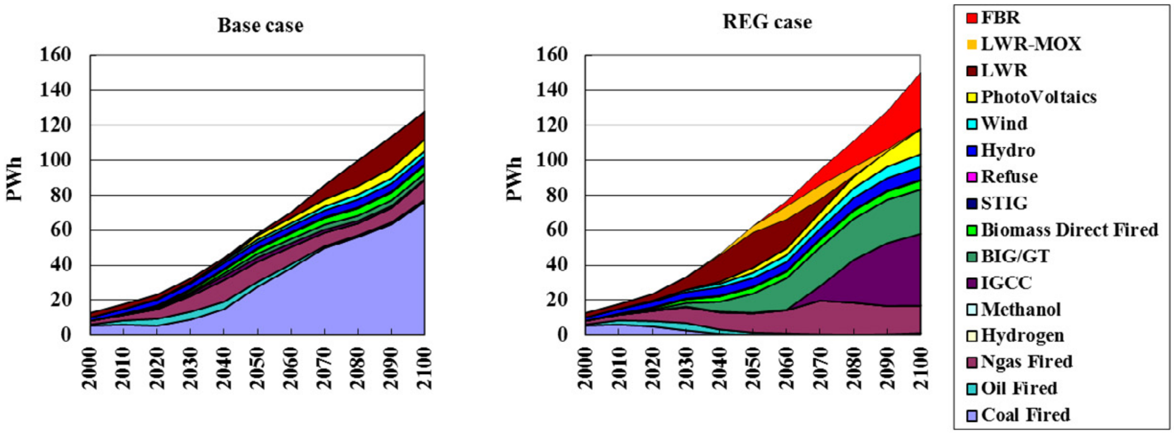

Figure 7 World Electric Power Generation

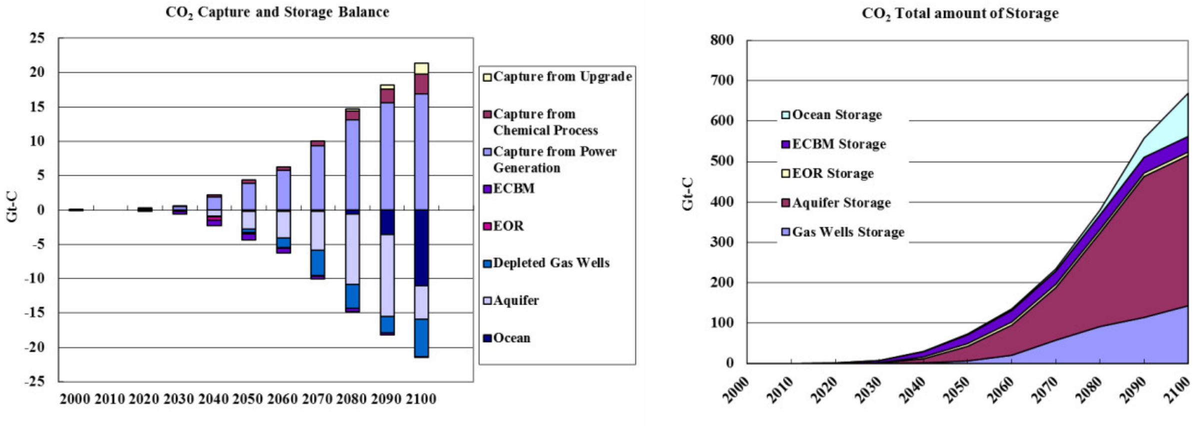

Figure 8 World CO$_2$ Capture and Storage Balance and Total amount of Storage (REG case)

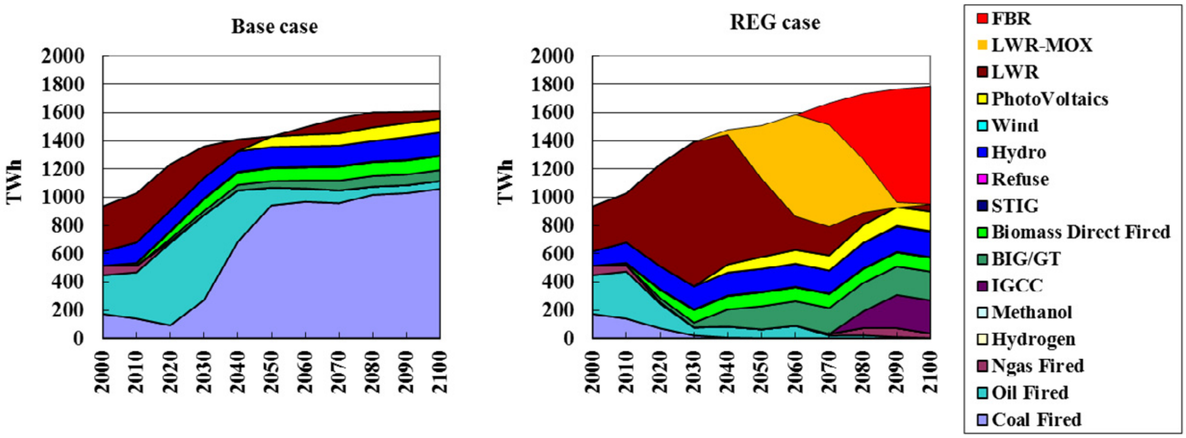

Figure 9 Electric Power Generation in Japan

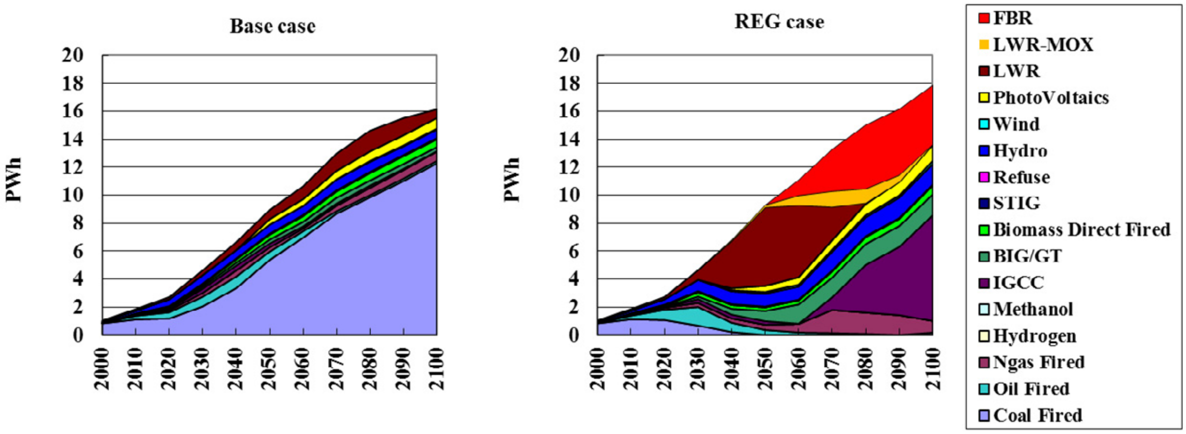

Figure 10 Electric Power Generation in China

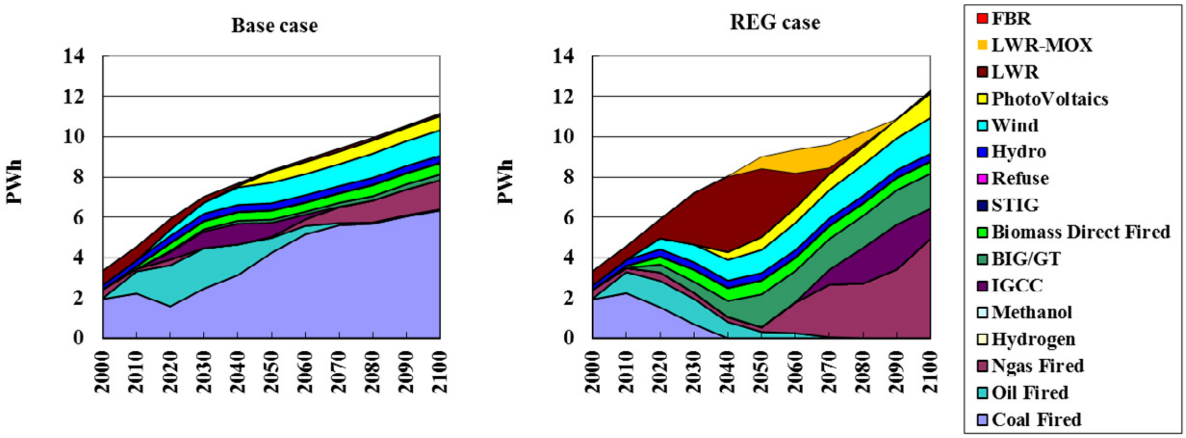

Figure 11 Electric Power Generation in USA

## 6. Conclusion and future work

This paper shows simulation results of system optimization calculation in the scenario to halve $CO_2$ emissions by the year 2050 with the newly revised world energy model from the aspect of nuclear and photovoltaic power generation technologies. The result indicates that nuclear power plants with fuel recycling and CCS technologies are estimated to play significant roles to reduce $CO_2$ emissions. In the future, the authors will develop the more detailed nuclear fuel cycle model and calculate various prerequisites, for example, commercially deployable year of FBR.

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