Chapter 5
Long-Term Energy and Environmental Strategies

Yasumasa Fujii and Ryōichi Komiyama

Abstract This chapter investigates long-term energy and environmental strategies, employing a regionally disaggregated Dynamic New Earth 21 model (called DNE21) which allows us to derive a normative future image of energy systems through the comprehensive incorporation of forecasted future technologies. This integrated energy system model, explicitly considering the availability of advanced nuclear technologies such as nuclear fuel cycle and fast breeder reactors which can improve the usage efficiency of natural uranium resources, employs computational tools to evaluate the optimal global energy mix compatible with low atmospheric CO_2 concentrations. Simulation results in the model indicate that massive CO_2 mitigation targets can be achieved with the large-scale deployment of innovative technology, highlighting roles for nuclear, renewables, efficient use of fossil fuel, and carbon capture and storage (CCS). The results support the simultaneous pursuit of multiple technologies, rather than focusing merely on realistic technological options based on current perceptions. However, the validity about the expected role of nuclear energy for the future should be critically evaluated in the new technical and political contexts that exist after the Fukushima nuclear accident.

Keywords Energy model · Global energy mix · Nuclear fuel cycle

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5.1 Introduction

Innovative technologies are expected to play a key role in long-term transitions of the global energy system. This is particularly the case for the realization of climate change mitigation targets that stabilize atmospheric CO_2 concentrations at levels that avoid a greater than 2 °C increase in average global temperatures above pre-industrial levels. We have been investigating long-term energy and environmental strategies compatible with low atmospheric CO_2 concentrations, employing a regionally disaggregated Dynamic New Earth 21 model (called DNE21). The energy model used here employs computational tools to conduct quantitative analyses on future global energy systems, but the outputs of the energy models should not be like the illusions in a fortune-teller's mystical crystal ball. Its major concern is, therefore, not to forecast a likely future image of the global energy system by extending secular trends in the systems, but rather to derive a normative future image of the systems through the comprehensive incorporation of forecasted future parameters and scenarios published in related academic literature and governmental reports.

5.2 Regionally Disaggregated DNE21

DNE21 is an integrated assessment model that provides a framework for evaluating the optimal energy mix to stabilize low atmospheric CO_2 concentrations. The recent version of the DNE21 model [1] has featured a more detailed representation of regional treatments, including nuclear and renewable energy. The model seeks the optimal solution that minimizes the total system cost, in multiple time stages for the years from 2000 to 2100 at 10-year intervals in multiple regions, under various kinds of constraints, such as amount of resource, energy supply and demand balance, and CO_2 emissions. The model is formulated as a linear optimization model, in which the number of the variables is more than one million.

Figure 5.1 shows the division framework of world regions and assumed transportation routes. In the DNE21 model, the world is divided into 54 regions. In the model, large countries such as the United States, Russia, China, and India are further divided into several sub-regions. Furthermore, in order to reflect the geographical distribution of the site of regional energy demand and energy resource production, each region consists of "city nodes" shown as round markers in Fig. 5.1 and "production nodes" shown as square markers, the total number of which amounts to 82 points. The city node mainly shows representative points of intensive energy demand, and the production node exhibits additional representative points for fossil fuel production to consider the contribution of resource development in remote districts. The model takes detailed account of intra-regional and inter-regional transportation of fuel, electricity, and CO_2 between these points.

Fig. 5.1 Regional disaggregation by node and transportation routes

DNE21 involves various components that model energy production, conversion and transport, primary energy resources, secondary energy carriers, final energy demand sector, power generation technology, energy conversion process, and CO_2 capture (3 types) and storage. End-use electricity demand is assumed with a specific daily electricity load curve divided into six time intervals. Major modules considered in the model are as follows:

1. *Primary energy resources*: conventional fossil fuels (coal, oil, natural gas), unconventional fossil fuels (heavy crude oil and oil sand, oil shale, shale gas, other 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, integrated gasification combined cycle (IGCC) with CO_2 capture, nuclear, hydro, geothermal, solar, wind, biomass direct-fired, biomass integrated gasifier/gas turbine (BIG/GT), steam injected gas turbine (STIG), municipal waste-fired generation, hydrogen-fueled, 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, enhanced coal bed methane operation.

5.3 Nuclear and Photovoltaic (PV) Modeling

Additionally, the recent version of DNE21 incorporates a nuclear module, which describes in detail the nuclear fuel cycle and advanced nuclear technology. The new model takes account of the availability of advanced nuclear technologies, such as nuclear fuel cycle and fast breeder reactors, which can drastically improve the usage efficiency of natural uranium resources. Light-water reactors (LWR), light-water mixed oxide fuel reactors (LWR-MOX), and fast breeder reactors (FBR) are considered specific kinds of nuclear power generation technologies. This model considers four types of nuclear fuel and spent fuel (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 initial commitment, equilibrium charge, equilibrium discharge, and decommissioning discharge. Supply and demand balances of each type of fuel and SF during the term interval (10 years) were formulated to consider the effects of the time lags mentioned above. In the nuclear waste management process, SF, which is stored away from power plants, is reprocessed or disposed of directly. Uranium 235 and Plutonium (Pu) can be recovered through reprocessing of SF. Recovered Uranium 235 is recycled through a re-enrichment process. Some of the 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.

A new photovoltaic power (PV) module was incorporated in the most recent version of the model. The intermittent characteristics of PV power generation due to changes in weather conditions are taken into account by stochastic programming. 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. Each city node has its own occurrence probability of sunny days by season. When it is cloudy, the level of PV power generation output may drop substantially as compared to a sunny day. It is necessary to ready other types of power generation to compensate for the PV output drops. As a result, this model can calculate a more realistic power generation mix. It is assumed that the effective amounts of solar radiation for each node on sunny days and cloudy days are 80 and 30 % of the theoretical maximum value, respectively. The value of the occurrence probability of sunny days for each node and each season was estimated by comparing the theoretical maximum solar radiation with the actual measurement value.

5.4 Model Simulation

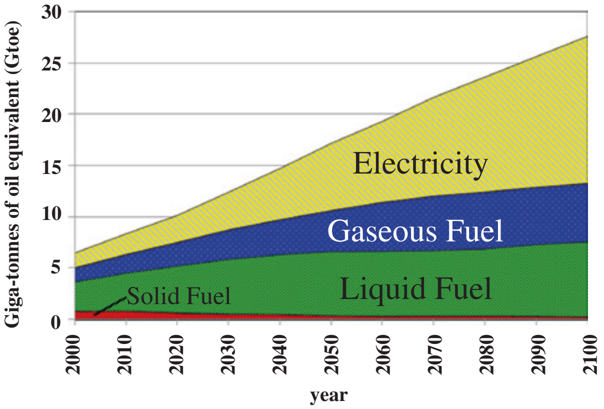
5.4.1 Simulation Assumptions and Settings

Table 5.1 shows data on nuclear fuel cycle [2] and photovoltaic costs. FBR is assumed to be available after the year 2030, and PV capital cost is reduced by 2 % per annum up to the year 2050 through technological progress. The maximum electricity supply by PV is limited to less than 15 % of the electric load for each time period when it is available, and that by wind power is less than 15 % of the electricity demand of all the periods. However, if water electrolysis or electricity storage is used, the upper limits on their supply share no longer apply. Natural uranium and depleted uranium contain 0.711 and 0.2 % U-235, respectively. In this simulation,

Table 5.1 Assumed cost data

	Unit	Cost
LWR capital cost	$/kW	2,000
FBR capital cost	$/kW	3,000
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	1,100
SF reprocessing	$/kg-HM	750
VHLW final disposal	$/kg-HM	90
SF storage	$/kg-HM/year	8
SF direct disposal	$/kg-HM	350
FBR cycle cost	$/MWh	10
Pu storage	$/kg-Pu/year	500
PV capital cost	$/kW	6,000
Discount rate	%	5
Life time of plant	year	30

Fig. 5.2 World energy demand scenario



the energy demand scenario is given exogenously with reference to SRES-B2 (Special Report on Emissions Scenarios-B2) by IPCC (Intergovernmental Panel on Climate Change) [3]. Figure 5.2 shows the world energy demand scenario.

Here we assume two cases for model simulation. One case is the no CO_2 regulation case (Base case) and the other is the CO_2 regulation case (REG case). The REG Case is the scenario to halve CO_2 emissions by the year 2050 for the world as a whole, and thereafter the emissions are regulated so that atmospheric CO_2 concentration is maintained at a level avoiding some 2 °C increase in the average global temperature from pre-industrial levels. Furthermore, in the REG case the developed countries (high-income OECD countries) are assumed to reduce CO_2 emissions by 80 % compared with 2,000 levels.

5.4.2 *Calculated Results*

Figure 5.3 shows electric power generation for the world and selected countries. In the Base case, a majority of the world's primary energy is almost exclusively derived from coal, gas, and oil until the middle of this century. In particular, coal, whose reserves and resources are abundant and economically affordable, shows remarkable growth in supply among fossil fuels. After the middle of this century, when the extraction of conventional sources peaks, unconventional oil and gas, which is more expensive than conventional oil and gas, will start to be produced. This decline in the economic efficiency of fossil fuel encourages in part the introduction of nuclear energy and, to a lesser extent, renewable energy such as solar, biomass, and wind power. This fossil fuel-intensive scenario leads to substantial CO_2 emissions, which in turn causes a rise in atmospheric concentrations.

By contrast, in the REG case, the imposition of a carbon regulation target encourages the large-scale adoption of carbon-free energy in addition to reduced demand from a combination of improvements in efficiency. On one hand, at the beginning of the century, coal, concentrated in thermal plants, becomes

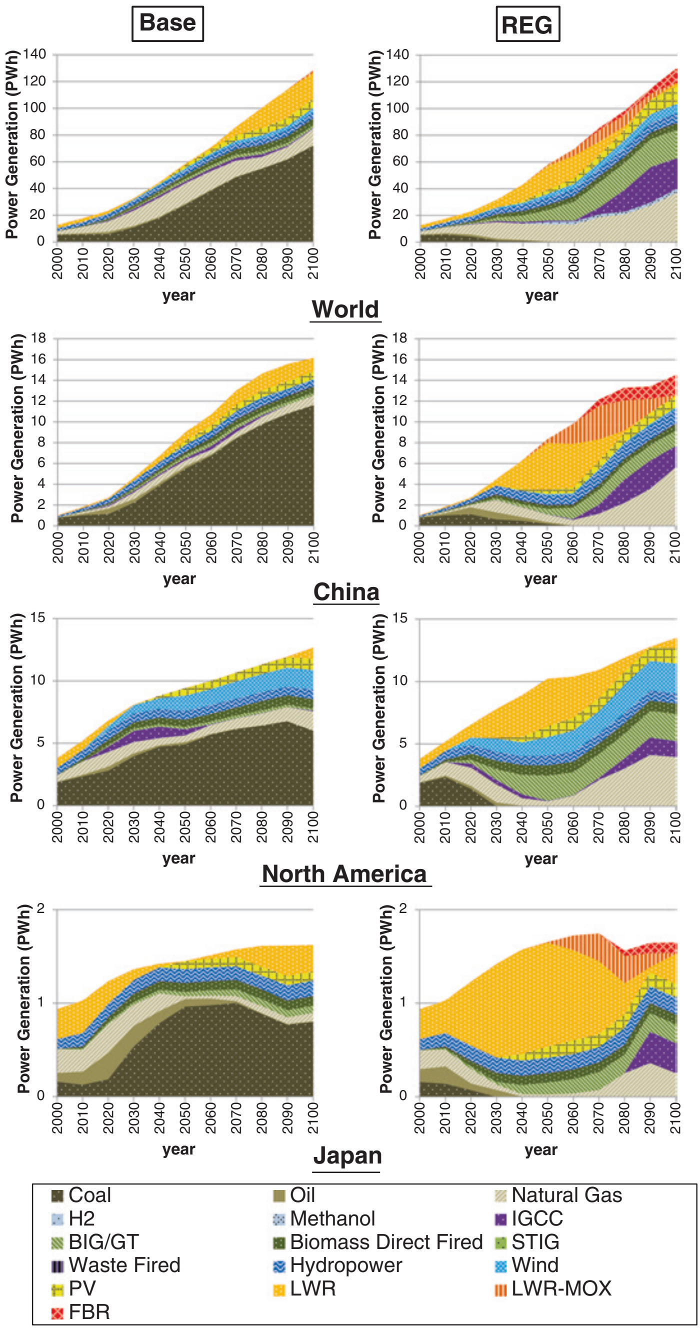


Fig. 5.3 Electric power generation (*Left* Base case/*Right* REG case)

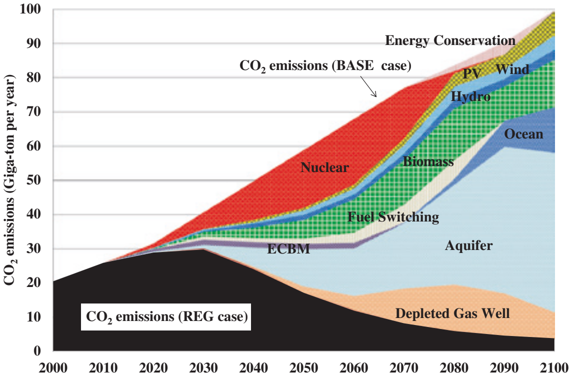
significantly less competitive due to the carbon penalty, although IGCC with carbon capture and storage (CCS) play an important role later in the century. On the other hand, natural gas, introduced early in the century based on its economic attractiveness, maintains this position later with the adoption of CCS, with gas-fired power plants supplying around a quarter of total electric power capacity in the second half of the century.

Concerning the perspective on nuclear energy, nuclear LWR is limited in the second half of the century by the exhaustion of uranium resources. Introduction of FBR reactors enables these technologies to supply power requirements well beyond 2050. In addition, achieving low stabilization does not appear to be possible without large-scale deployment of renewables over the long term. Later in the century, biomass, solar, and wind power are expected to play an essential role in decarbonizing the electric power supply. It is worth noting that renewable technologies are deemed essential for achieving low stabilization targets.

Concerning nuclear power generation, however, it is difficult to explicitly consider the impact of disruptive events such as the Fukushima nuclear disaster with the energy model developed here; the Fukushima accident has caused increased concerns about nuclear safety focusing on the resilience of nuclear facilities for a huge natural disaster and has amplified the uncertainty of nuclear energy in the global long-term energy mix due to the issue of public acceptance. In order to expect a certain role for nuclear energy in the long-term energy scenario as already described, it should be noted that an enormous technical and political effort will be necessary to resolve these concerns and recover public confidence in the safety of nuclear reactors.

Figure 5.4 represents CO_2 mitigation by technological measures by shifting from the Base case to the REG case to realize CO_2 emission levels. Toward the middle of the century, nuclear, biomass, and CCS in aquifers have considerable impact on reducing emissions. And thereafter to 2100, CCS in aquifers, depleted gas wells and oceans, combined with biomass, PV, and wind, greatly contribute to massive emissions abatement.

Fig. 5.4 CO_2 mitigation by technological measures in order to realize CO_2 emissions in REG case



5.5 Energy Modeling Challenge After Fukushima

Basically, the long-term energy model as explained in this chapter serves to yield a normative future scenario for the energy systems under specific given conditions, and it is currently difficult to develop a future scenario explicitly considering the unexpected impact of short-term disruptive events such as the Fukushima incident in a consistent way. The challenge in energy modeling is to consistently incorporate both long-term structural risks, such as climate change and energy resource depletion, and short-term contingent risks, such as disruptive shortages of energy supply as observed in Fukushima and fuel embargo, in order to allow us to effectively evaluate the concept of resilient energy systems. After Fukushima, resilience is regarded as an indispensable element in energy systems under various unanticipated risks for short-and long-term perspectives.

The Fukushima nuclear disaster triggered the shutdown of all of the country's nuclear power plants, which produced 30 % of the country's electricity supply at that time. Since the utilization of nuclear power generation significantly declined due to the accident and to political reasons, fossil fuel consumption for power generation shows the highest level in the last three decades. This meant Japan's fuel imports bill jumped immediately as power companies ramped up gas-fired (LNG-fired) and petroleum-fired power generators, as illustrated in Fig. 5.5. In particular, a radical shift to LNG occurred to compensate for the loss of nuclear energy, and its imports dramatically increased.

In addition, the nuclear suspension and the rise in Japan's LNG import added pressures to push up its already high prices even higher. Japan's LNG is traded at the highest price over the world at around \$15/MMBtu, while U.S. natural gas is priced at around \$5/MMBtu, as shown in Fig. 5.6. The total import costs of LNG for power generation increased by 64 % after Fukushima, causing the balance of payments to turn negative in fiscal year 2011 for the first time since 1980. Before

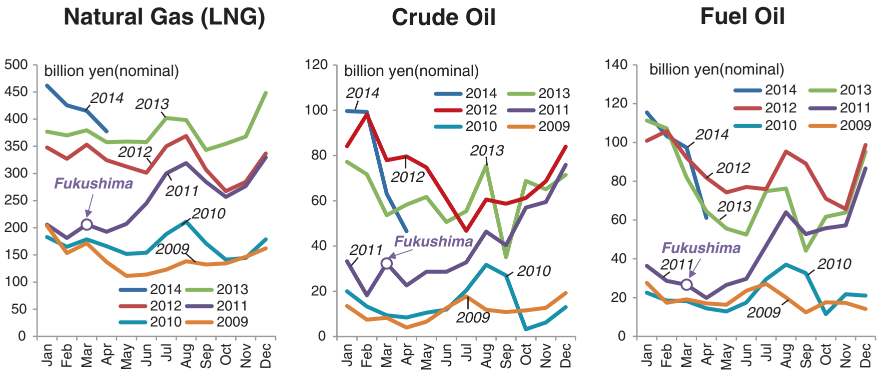


Fig. 5.5 Fuel import cost for power generation in Japan before and after the Fukushima nuclear plant accident [4–6]

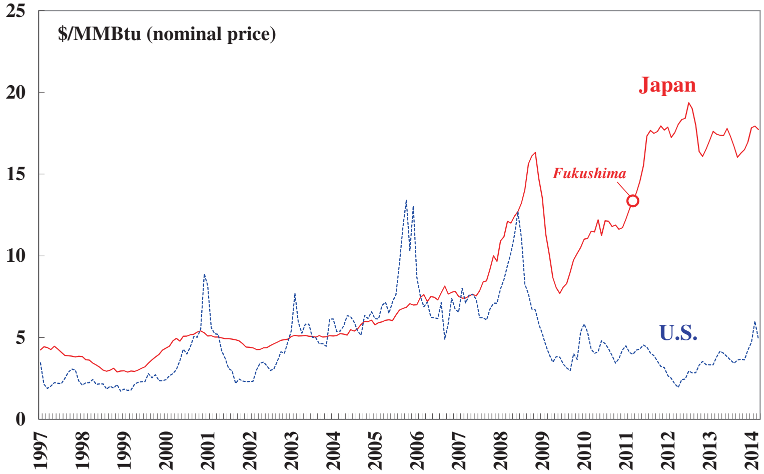


Fig. 5.6 Gas price movement between U.S. and Japan [5, 7]

the Fukushima disaster, nuclear power was considered to serve as a bargaining chip for Japan to purchase LNG at affordable prices.

Resilience is expected to play a role in building a robust energy system to contend with such aforementioned emergent events. The future energy model should enable us to evaluate the amount of adaptive capacity needed to withstand extreme shocks with minimal disruption, to facilitate a recovery from the shocks, and to provide favorable persistent features such as stability, sufficiency, affordability, and sustainability. This model also needs to serve as a platform for discussing appropriate wider responses to the growing risks faced by societies and economies and for suggesting the short- and long-term countermeasures to intensify diversification, redundancy, and emergency responsiveness of energy system.

5.6 Conclusion

The calculated result indicates that nuclear power plants with fuel recycling, renewable energies, and CCS technologies are estimated to play significant roles to reduce CO_2 emissions. Under a great deal of uncertainty it is difficult to draw firm conclusions as to which options have the greatest potential in achieving significant CO_2 reduction. However, the simulation results in the model indicate that massive CO_2 mitigation targets can be achieved with the large-scale deployment of innovative technology, highlighting roles for nuclear, renewables, efficient use of fossil fuel, and CCS. The results support the simultaneous pursuit of multiple technologies, rather than focusing merely on realistic technological options based on current perceptions.

Although we assumed the availability of fuel recycling of nuclear spent fuels and the upper limits of intermittent renewables in the total power generation capacity, the validity of those assumptions should be critically evaluated in the new technical and political contexts that exist after the Fukushima accident. The Fukushima nuclear disaster has caused increased concerns about nuclear safety and has heightened the uncertainty of nuclear energy in the long-term energy scenario, although considerable growth of nuclear energy utilization in emerging Asian countries is actually projected even after Fukushima. Consequently, in order to effectively position nuclear power in the long-term energy mix, nuclear policy needs to highlight nuclear safety even more by developing advanced nuclear technologies and by upgrading nuclear safety standards continuously after Fukushima.

The quantitative value of uranium as an underground natural resource is estimated to be equivalent to that of conventional oil if we consider light-water reactor use only, and it is far less than that of coal. If we abandon the technological option of nuclear fuel recycling, it is self-evident that we will deplete uranium resources within a few decades, rather than conserving it for future generations.

The extensive introduction of intermittent renewable power generation in power systems is definitely considered to have significant influences on power system operations and their optimal configurations. However, nobody knows the clear answer to the question of to what extent power systems should rely on intermittent renewables.

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