TECHNOLOGY ASSESSMENT: DYNAMIC NEW EARTH 21 MODEL

Kenji Yamaji
School of Engineering, University of Tokyo, Japan

Keywords: Global energy system, energy model, CO_2 problem, technology assessment, inter-temporal optimization

Contents

Summary

Dynamic New Earth 21 was developed to make a comprehensive assessment of the technological measures for mitigating global warming and to sketch concrete scenarios for the desirable future development of the global energy system over the twenty-first century. *Dynamic New Earth 21* was formulated on the basis of the *New Earth 21* model. The *Dynamic New Earth 21* model was built to cope with newly emerging research topics such as integrated assessment of climate change. This paper presents the latest numerical results of this model and its outlined descriptions.

In the framework of the energy model built here, the whole world is divided into ten regions so that it can explicitly evaluate the differences in regional economic and geographical conditions. The model can assess the various technological options up to the year 2100, optimizing inter-temporally the sum of the discounted total energy system costs. With specific technological options, the model takes account of the following categories of technologies: energy savings in end-use sectors, efficiency improvement in energy conversion sectors, utilization of various less carbon-intensive energy resources, disposal and recycling of CO_2 recovered in the energy systems, and

innovative system technologies especially with respect to hydrogen use.

The results of the study suggest that the CO_2 problem cannot be easily settled by any single technological option. However, they also suggest that if those options are reasonably combined with one another, there exists great technological potential for CO_2 emission reduction. For limiting atmospheric CO_2 concentrations below 550 ppm over the twenty-first century, the computed optimal CO_2 emission trajectory indicates that relatively modest abatement actions are expected in the near future, implying that immediate CO_2 emissions reduction or stabilization strategies will not necessarily lead to economically efficient outcomes.

1. Introduction

The global warming problem associated with anthropogenic emissions of greenhouse gases (GHGs) is one of the most crucial environmental issues in the world. We expect that these GHGs will increase the global mean temperature by around 2 K by the end of the next century. This global warming is thought to cause serious climate changes, which will have great impacts on humanity.

Some of these GHGs have potentially greater effects on global warming than others. Many researchers have studied the relative contributions of these gases. Although CO_2 causes the least effects on a per mole basis, recent studies show that CO_2 has been responsible for more than half the total additional radiative forcing, because of its large absolute increase in atmospheric concentration.

This CO_2 related problem has attracted considerable attention all over the world, and has developed from a merely scientific subject into an international political issue. Many efforts toward a settlement of this problem have already been made through internationally organized meetings, such as the Intergovernmental Panel on Climate Change (IPCC). It is likely that certain targets will be set for reductions in the CO_2 emissions of individual countries to realize the ultimate objectives.

In such a context, it is important to make a comprehensive assessment of the technological measures for limiting the atmospheric CO_2 concentration at a level that would prevent dangerous anthropogenic interference with the climate system, and then to sketch concrete scenarios for the desirable future technological development of the global energy system.

To conduct the assessment, a new global energy system model, *Dynamic New Earth 21*, was developed on the basis of the *New Earth 21* model. Our major concern is not to predict either the volume of future energy demand or the growth rates of world economy, but rather to develop future scenarios of the CO_2 abatement technologies.

The model attempts to draw pictures of desirable development for future energy systems under a given reference final energy demand scenario. The outline and the numerical results of *Dynamic New Earth 21* model are presented with full reference to the detailed description of the model.

2. Outline of the *Dynamic New Earth 21* Model

2.1. Basic Framework

There have already been a number of attempts to develop energy models appropriate for envisaging future energy and environmental scenarios. A typical example is the Edmonds and Reilly model used by US Environmental Protection Agency to make a one hundred-year scenario for greenhouse gas emissions in the world. The model is a network of regional energy models interconnected by the linkage of international energy trade. The Edmonds and Reilly model, however, does not sufficiently deal with the technological details of energy system structures, so it is limited in its ability to investigate details of future energy supply-demand structures, such as the combined use of different energy resources in energy conversion processes.

The MARKAL model developed by International Energy Agency (IEA) is a well-known engineering process model with linear programming technique for investigating the details of energy supply systems. The MARKAL model can be used to evaluate energy technologies given the criterion to be optimized. The various versions of the MARKAL models are widely used in the world as nationwide energy models and modeling activities have been coordinated by IEA. The MARKAL model is too complicated, however, to be used as a global model by networking a number of their regional versions. The MARKAL models have so far been used only as national models mainly for developed countries.

Taking into consideration that the climate change issue is of genuine global character, we need another technologically detailed energy model, which covers all world regions on the globe. In response to this specific need, on the basis of *New Earth 21* model, *Dynamic New Earth 21* model has been developed with the basic framework described in the following sections.

Geographical coverage: The technological potentials are often constrained by regional factors, such as the sectoral structure of energy consumption and the availability of natural resources. For a logical and consistent technology assessment, it is necessary to identify energy systems of different world regions. *Dynamic New Earth 21* was formulated as a multiregion model, and the whole world is geopolitically divided into 10 regions as shown in Figure 1.

1. North America
2. Western Europe
3. Japan
4. Oceania
5. Centrally Planned Economy Asia
6. South and East Asia
7. Middle East and Northern Africa
8. Subsaharan and Southern Africa
9. Latin America
10. Former USSR and Eastern Europe

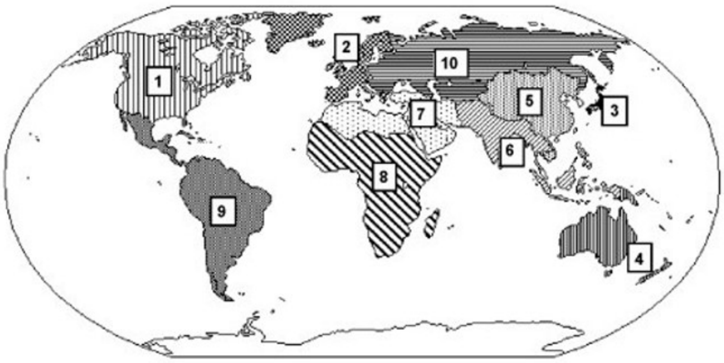

Figure 1. Divisions of the world's countries

Time framework: The CO_2 problem requires quite a long-term analysis of future energy systems. The published literature on the CO_2 problem indicates that it is unlikely that we can settle the problem early in the twentieth century, and an emerging research topic of integrated assessment of climate change suggests that the time horizon of this kind of analysis should be as far as the end of this century. However, a longer time horizon does not necessarily yield more meaningful results of the analysis. The time horizon is inevitably restricted by one fundamental factor, that is uncertainty in the long-term projections on future energy demand and technological innovation. Therefore we decided that the moderate terminal year of *Dynamic New Earth 21* model should be the year of 2100. Under exogenously projected scenarios of reference energy demand, the *Dynamic New Earth 21* model seeks the optimal development path for the future world energy system at intervals of ten years up to the year 2050 and at longer intervals of twenty five years thereafter.

Methodology: The *Dynamic New Earth 21* model is mathematically formulated as a multiperiod inter-temporal nonlinear optimization problem with inequality and equality linear constraints. The constraints represent supply-demand balances, energy, and CO_2 balances in the various types of energy processing plants of each period, and several inter-temporal dynamics such as depletion of fossil fuel resources, buildup of the atmospheric CO_2 concentrations, and limitations on the maximum growth rates of annual fuel production. The objective function of the problem is defined as the sum of the discounted total energy system costs distributed over the time, which include energy saving costs, fuel costs, levelized plant fixed costs comprising capital and maintenance costs, inter-regional energy transportation costs, CO_2 recovery and disposal costs, and so forth. The cost functions of renewable energy supply and energy saving in final consumption sectors are assumed to have nonlinear characteristics, while the supply cost curves of fossil fuels are expressed in step-wise linear function with respect to their amounts of cumulative production. Our model can therefore take account of the dynamics of the energy systems, and can sketch out fully consistent scenarios of their normative future evolution.

2.7. Energy Demand and Saving in Final Consumption Sectors

Energy demand: The final consumption sector of the model is disaggregated into the following four types of secondary energy carriers: 1) gaseous fuel, 2) liquid fuel, 3) solid fuel, and 4) electricity. The liquid fuel demand is again decomposed into three types of oil products or their equivalents: 1) gasoline, 2) light fuel oil, and 3) heavy fuel oil. In the case of electricity demand, we explicitly take into account daily load duration curves expressed simply with three time periods: peak period, intermediate period, and off-peak period. The potentials of future energy demands are exogenously given as reference scenarios by type, region, and year. The reference scenario of energy demand in this study was derived from the well-known IPCC emission scenario of IS92a which have been often referred to as a business-as-usual scenario in many studies. It is to be noted that we made some modifications in the original IPCC scenario so as to make it consistent with the disaggregation framework of our model. Figure 2 shows the assumed reference energy demand scenarios.

Energy saving: There are two different approaches to compose the cost curves associated with energy saving. One is a bottom-up approach by accumulating costs of individual technologies, and the other is a top-down approach by adopting the macroeconomic concept of price elasticity of energy demand. Because of the difficulty in arranging detailed and comprehensive data sets for the bottom-up approach, we adopted a top-down approach in which the saving cost is calculated from a cost curve represented with only a couple of parameters, i.e. a price elasticity and a reference energy price. Outputs of the model therefore indicate only aggregated behaviors of energy saving, and cannot highlight explicitly any particular kinds of energy-saving technologies as computational results.

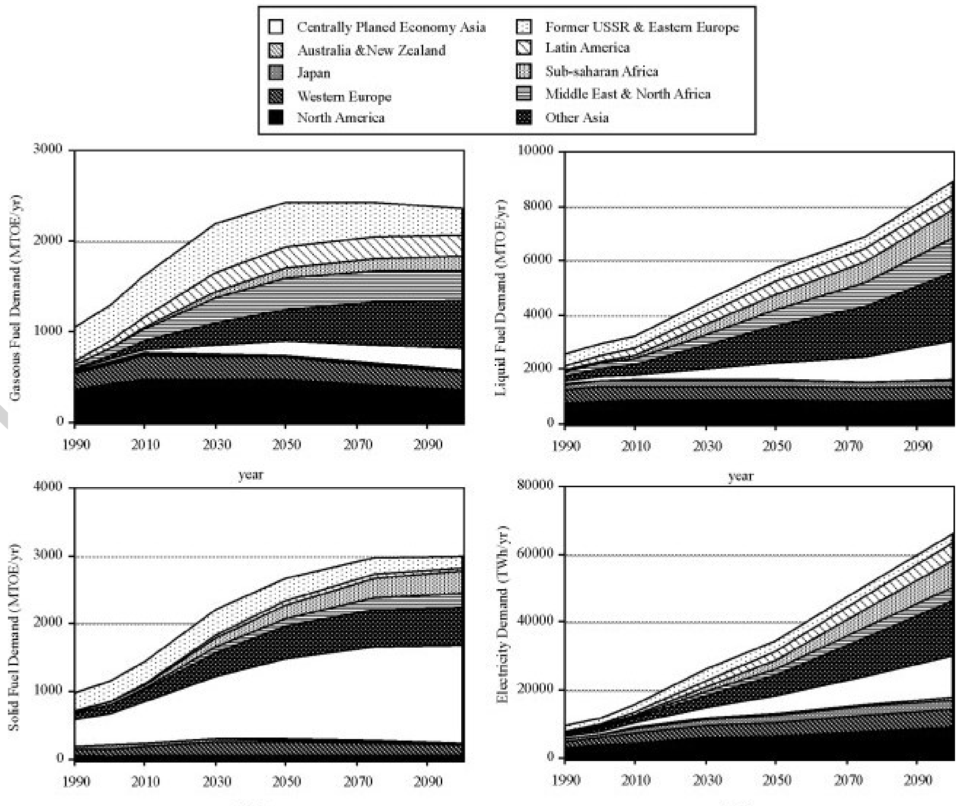

Figure 2. Reference energy demand scenario for the world

It is to be noted here that there are two different factors underlying energy saving behaviors, i.e. autonomous energy efficiency improvements (AEEI), and energy saving induced by price increases. In this study, the effect of AEEI is assumed to have been already incorporated in the process of building the above reference energy demand scenarios by IPCC.

Costs for price-induced energy saving are counted by integrating inverse demand functions in this study. The cost thus measured is interpreted as the loss of consumers' utility in welfare economics. The derivation of the utility loss is formulated as follows. First let us introduce a demand function $D(P)$ of Eq. (1) which is simply characterized by long-term price elasticity α, reference retail energy price P_0 and reference energy demand D_0. (Here we omit the subscripts for region, sector, and year.) In the *Dynamic New Earth 21* model, a set of reference energy demands and price elasticities are given as exogenous inputs for each final demand sector. Regarding reference retail energy prices in the future, they are to be calibrated as mentioned later in this section.

$$D(P) = D_0 \left(\frac{P}{P_0} \right)^{-\alpha} \quad (\alpha > 0) \tag{1}$$

Then we can derive the inverse-demand function *P(D)* from the above equation. Introducing the amount of saved energy S, and replacing D with $D_0 - S$, the following cost function of Eq. (2) can be obtained.

$$P(S) = P_0 \left(\frac{D}{D_0} \right)^{-1/\alpha} = P_0 \left(\frac{D_0 - S}{D_0} \right)^{-1/\alpha} \tag{2}$$

According to welfare economics, the utility loss $C(S)$ associated with energy saving S is defined to be an integral of the inverse-demand function as follows. The integral of Eq. (3) corresponds to the hatched area illustrated in Figure 3.

$$C(S) = \int_0^S P(s)ds = \frac{\alpha}{1-\alpha} D_0 P_0 \left\{ \left(1 - \frac{S}{D_0} \right)^{\frac{\alpha-1}{\alpha}} - 1 \right\} \quad (\alpha \neq 1) \tag{3}$$

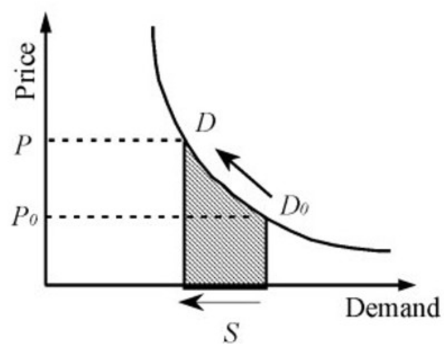

Figure 3. Energy saving costs measured as a loss of consumers' utility (hatched area)

The value of the reference demand D_0 is described in Figure 2, and that of α is found in Table 1.

An additional process is necessary to determine the specific value of P_0, if we assume no price-induced energy saving behaviors in a BAU (business-as-usual) case. This assumption requests us to set P_0 exactly equal to *SPBAU*, that is the shadow price of secondary energy in a BAU case. *SPBAU*, therefore, must be calculated in advance, by solving the optimization problem in which energy demands are fixed to the reference ones with no abatement policies for CO_2 emissions reduction.

However, *SPBAU* thus calculated does not necessarily represent a corresponding real retail energy price listed in Table 1. This is because the model cannot take account of all the costs associated with energy use and distribution. To make P_0 more consistent with the real price, we additionally introduced *DP* defined in Eq. (4), and set the reference energy price of P_{0t} using both *DP* and $SPBAU_t$ by region, sector, and year as shown in Eq. (5). (We omit the subscripts for region and sector.)

Secondary Energy	North America	Western Europe	Japan	Oceania	The Rest of the World	Long-term Price Elasticity
Gaseous Fuel	200	285	920	170	170	- 0.4
Liquid Fuel	340	710	590	500	280	- 0.4
Solid Fuel	60	160	120	50	50	- 0.4
Electricity	70	110	160	70	50	- 0.4

Table 1. Retail energy prices and long-term price elasticities
(unit: $/TOE for fuel, $/MWh for electricity)

$$DP = P_{1990} - SPBAU_{2000} \qquad (4)$$

$$P_0 t = SPBAU_t + DP \qquad (5)$$

Where

P_{1990}: real retail energy price in the year 1990
$SPBAU_{2000}$: computed shadow price for the year 2000
P_{0t}: reference retail energy price for the year *t*
SPBAUt: computed shadow price for the year *t*

*DP*s are different by region and sector, and are interpreted as aggregated costs, which involve various distribution costs; subsidies and/or conventional indirect taxes levied on energy use.

Because there is no information about time profiles of *DP*s in the future, we therefore simply assumed constant *DP*s throughout the time horizon.

-
-
-

Bibliography

Dessus B. (1992). World Potential of Renewable Energies. *Extraits de la Houille Blanche* **No. 1**, 1992. Paris.

Edmonds J. and Reilly J. (1983). A Long-Term Global Energy-Economics Model of Carbon Dioxide Release from Fossil Fuel Use. *Energy Economics* **5**(2), 74–88.

Edmonds J. et al. (1985). *Global Energy, Assessing the Future*. Oxford University Press.

Endo E. and Koyama S. (1986). *Studies on Computerization and Application of Energy System Model "MARKAL,"* Research Report 869, July 1986. Tokyo: MITI Electro-technical Lab. [In Japanese.]

Energy Modeling Forum (1995). *Second Round Study Design for EMF 14: Integrated Assessment of Climate Change*. Stanford, CA, US: Stanford University Terman Engineering Center.

Fujii Y. and Kaya Y. (1993). Assessment of Technological Options for Reducing CO_2 Emissions from Man's Global Energy System. *Trans. Institute of Electrical Engineers of Japan*, **Vol. 113–B**, No. 11, pp. 1213–1222. [In Japanese.]

Fujii Y. and Kaya Y. (1993). *Assessment of the Roles of New Energy Technologies for the Abatement of CO_2 Emissions* (Proceedings of the First International Conference New Energy Systems and Conversions, Yokohama, Japan, June 27–30, 1993), pp. 793–804. Yokohama, Japan.

Fujii Y. and Yamaji K. (1998). Assessment of Technological Options in the Global Energy System for Limiting the Atmospheric CO_2 Concentration. *Enviromental Economics and Policy Studies*, **Vol. 1**, No. 2.

Häfele W. et al. (1987). The Concept of a Novel Horizontally Integrated Energy System. Proceedings of 10th IFAC World Congress, **Vol. 5**, pp. 155–161. International Federation of Automatic Control.

IPCC (1996). *Climate Change 1995—The Science of Climate Change* Cambridge University Press.

Ishitani H., Matsuhashi R., Oomura S., Shimada S. and Suyari T. (1991). Feasibility Study on CO_2 Disposal in the Ocean, *ENERGY AND RESOURCES*, **Vol. 12**, No. 3. Japan: Japan Society of Energy and Resources. [In Japanese.]

Ishitani H., Matsuhashi R., Oomura S. and Takeda I. (1993). Economic Evaluation of Systems for the Recovery and Disposal of CO_2 in the Ocean. *Energy and Resources* **Vol. 14**, No. 1, Japan: Japan Society of Energy and Resources. [In Japanese.]

Japan Petroleum Development Association (1986). *Studies on Resources of Oil and Natural Gas*, Tokyo: JPDA Working Group for Resource Assessment. [In Japanese.]

Japan Petroleum Development Association (1991). *Studies on Resources of Oil and Natural Gas*, Tokyo: JPDA Working Group for Resource Assessment. [In Japanese.]

Koide H. et al. (1992). Subterranean Containment and Long Term Storage of Carbon Dioxide in

Unused Aquifers and in Depleted Natural Gas Resources. *Energy Convers. Mgmt.* **Vol. 33**, p. 619.

Mailer-Reimer E. and Hasselmann K. (1987). Transport and Storage of CO_2 in the Ocean—An Inorganic Ocean-Circulation Carbon Cycle Model. *Climate Dynamics* **No. 2**, 63–90.

Masters Charles D. et al. (1994). World Petroleum Assessment and Analysis. Proceedings of the 14th World Petroleum Congress. Stavanger, Norway: John Wiley and Sons, Ltd.

Nakicenovic N. (1993). *Long-Term Strategies for Mitigating Global Warming*. *Energy* **Vol. 18**, No. 5, pp. 448–449.

OECD (1991). *Energy Prices and Taxes.* Paris.

Pak P.S., Nakamura K., Suzuki Y. (1990). Coal-Gas-Burned High Efficiency Power which Recovers Carbon Dioxide Generated. *Trans. Institute of Electrical Engineers of Japan* **110–B**, 155. [In Japanese.]

Pepper W. et al. (1992). *Emission Scenarios for the IPCC an Upgrade, Assumptions, Methodology, and Results.* IPCC Working Group 1.

Steinberg M. et al. (1984). A Systems Study for the Removal, Recovery and Disposal of Carbon Dioxide from Fossil Fuel Power Plants in the US. *Brookhaven National Laboratory-35666*. Brookhaven, NY: US Atomic Energy Commission.

Solar Energy Research Institute (1990). *The Potential of Renewable Energy—An Interlaboratory White Paper*, SERI/TP-260-3674, DE90000322. US: Solar Energy Research Institute.

World Energy Council (1989). *Survey of Energy Resources.* London: World Energy Council.

Wigley T.M.L. (1993). Balancing the Carbon Budget. Implications for Projections of Future Carbon Dioxide Concentration Change. *Tellus* **Vol. 45B**, 409–425.

Yamaji K. (1999). Long-range Strategy for the New Earth 21 Plan. *Japan Review of International Affairs* **Vol. 12**, No. 4 Winter 1999.

Biographical Sketch

Dr. Kenji Yamaji is Professor of Engineering at the University of Tokyo, Japan. He was on the staff of the Central Research Institute of Electric Power Industry (CRIEPI) in Tokyo for some 17 years until his appointment to his current position in August, 1994. He has led many CRIEPI research projects on nuclear fuel cycle analysis, energy modeling, load management, and CO_2 control strategies. He was a visiting researcher at the Electric Power Research Institute in Palo Alto, CA, US, from 1981 to 1982, and Associate Professor of the Global Environmental Engineering Laboratory, the University of Tokyo from 1991 to 1993.

Dr. Kenji Yamaji graduated in nuclear engineering from the University of Tokyo in 1972 and received M.E. and Dr. Eng. degrees from the same university in 1974 and 1977, respectively. He has so far published more than one hundred papers, articles, and books on energy and environmental issues.