Outline of the Integrated Assessment of Global Warmingand its Mitigation Technologies in the Changing World Economy and Industry Project and some extensions of MARIA

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1. Introduction

The global warming issues are today regarded as a visible barrier against the sustainable development of human beings. Since the Kyoto-meeting in 1997, both developed and developing countries have proposed some kind of global warming mitigation programs apart from the approval of Kyoto Protocol. The global warming issues have thus moved from the scientific investigation stage to the planning and action one.

While the global warming is caused by the anthropogenic emissions of greenhouse gases, their mechanism is based on the geo-science which deals with the long range and large spatial views. The phenomenon of global warming is agreed by the natural scientists but there remain so many uncertainties and unknown facts especially in the effects of global warming on the economy, society and human settlements. However, as long as the irreversible and large disasters are foreseen, global warming mitigation strategies should be established based on the global and long term views.
Intergovernmental Panel on Climate Change (IPCC) established in 1988 has published assessment reports in 1990, 1995 and 2001 summarizing the scientific findings on climate science, effects and adaptation options. These reports demonstrate the progress of research activities suggesting, however, the limits of current researches and the needs for the future studies.

This project is developed by the RITE, Research Institute of Innovative Technology for the Earth, supported by the Ministry of Economy, Trade and Industry as a part of an “International Research Promotion Funds for the Global Environment” started in 2002 to assess and provide the global warming policies based on the scientific knowledge since IPCC Third Assessment Report (IPCC-TAR) with the partnership with International Institute for the Applied Systems Analysis in Austria.

2. Climate Change and Models as Policy Tools

2.1 Climate change policy and decision making

IPCC-has summarized the scientific findings on climate change, its impacts and control and adaptation opportunities since the first report in 1990. IPCC pointed out that the global warming will gradually appear and that its impact will be apparent in the end of this century in spite of so many uncertainties. It might sound that the climate control policy is not an urgent issue. IPCC Special report on Emission Scenarios (IPCC-SRES, 2000) and IPCC-Third Assessment Report (IPCC-TAR, 2001) gathered and summarized the model simulation results on the given six scenario families with and without climate control policies. Figure 1 summarizes the emission ranges (IPCC-TAR-WG3, Chap.2).

These figures tell us that (1) the uncertainty mainly comes from the variety of the future society and (2) the bifurcation of with and without control policies appears before 2040. Since the life cycle time of fixed capital stock often exceeds twenty years, the decision making to invest under climate control policy or not is not the long future story. For instance, assuming the life time of automobiles ten years, the owner will have four chances to purchase a new car until 2040. If all the automobiles in the world should be replaced by "controlled type" by 2040, all automobiles in the market should be replaced by 2030 suggesting that all automobile factories have invested the new technologies by that.

Figure 2(a) and Figure 2(b) are the profiles of transportation fuels generated by the MARIA model (Mori, 2000). Supply of oil saturates after 2050 while total transportation energy demands continue to increase in both world total and non-Annex I region. The conventional fossil fuel resources are replaced by the unconventional ones. The above observation suggests the importance of the "middle-term" assessments as the transient between "existing" technologies and "future" ones.

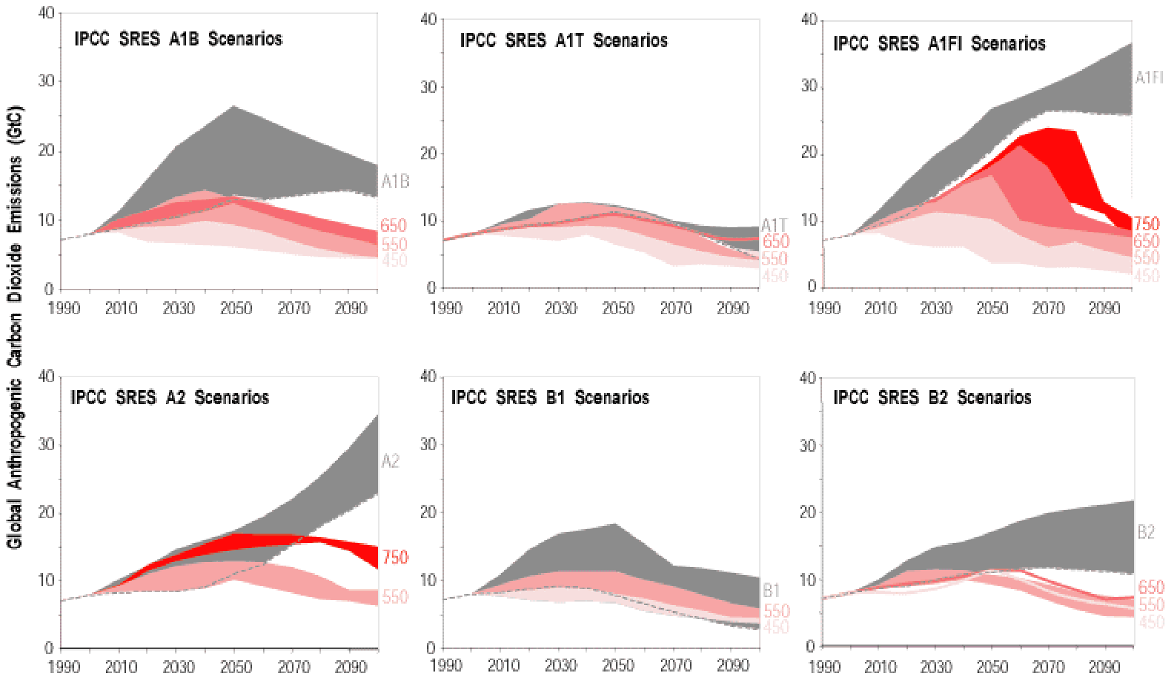
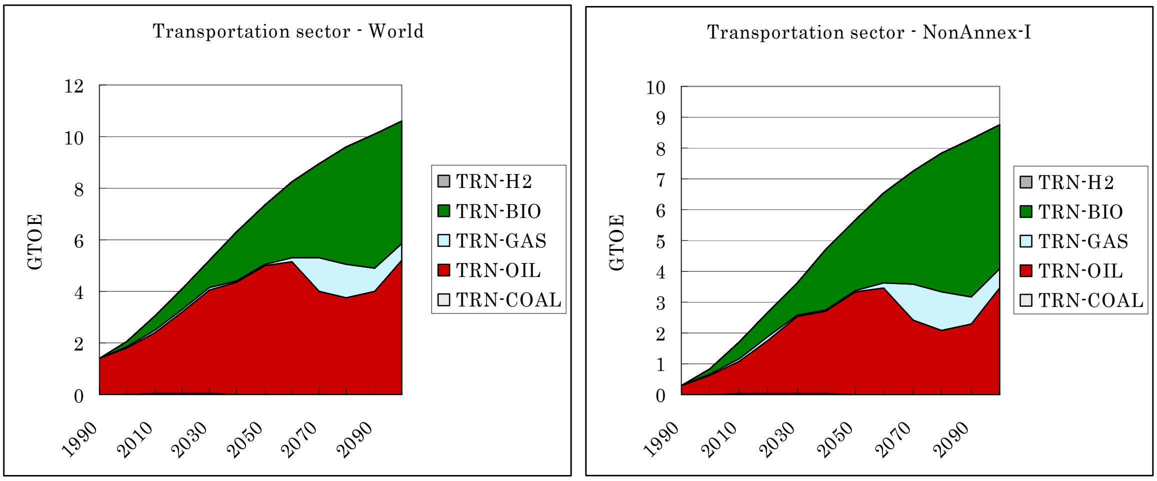


Figure 1 Carbon emission trajectories with and without control policies in SRES six scenario families (IPCC-TAR, 2001)



(a) World (b) Non-Annex I region

H2:hydrogen BIO:biofuels GAS:natural gas OIL:petroleum COAL: liquid coal

Figure 2 Simulation results on the transportation fuel supply profiles by the MARIA model on SRES-B2 scenario family

2.2 Importance of "qualitative" factors and uncertainties

Needless to say, both energy demands and supplies are driven by so many non-economic factors. Technological developments have been the major role in the stories of social changes. However, the inventions and innovations are not always the monotonous function of the R&D investments in the history. Furthermore, the development of technologies has often appeared as discontinuous phenomena as talked in many literature although there can be observed the ex-post historical substitution trends. (Gruebler, 1998)

Besides the technologies, there are so many non- or less-quantitative factors which may change the social and economic structures. For instance, political events or unexpected accidents such as TMI and Chernobyl Nuclear Power Station have strongly affected the nuclear power policy. The first and the second oil crisis are also the cases. Other than the above stochastic events, there are also unclear relationships which will be the key driver of societal changes. The relationships between the penetration of IT equipments and environmental impacts are not well defined. Civilization policies and the results of aging society will be discussed in this context.

The importance of the above qualitative factors is stressed in the IPCC-SRES study and many pages in SRES discussed the narrative analysis to develop the storylines. However, when we analyze the complicated relationships among technologies, warming impacts, policy options and other events, we can apply more sophisticated methods to keep the consistency of the context. During 1965-1975, so many technological forecasting methods were developed to extract the compatible scenarios based on the experts' subjective judgments, e.g. Delphi, scenario writing, PATTERN, Cross Impact (X-I) method, etc. Although most of them are not so much used in the global warming debate, I would reconsider the application of the methods to deal with the above factors to analyze the interrelationships and to construct the consistent scenarios.

2.3 Role and practical issues of model development

The existing studies including IPCC reports mention so many control options classified into three major categories: regulations, economic instruments and technological solutions. What is important is, however, these options often offset the outcome of others and provide ancillary benefits. For instance, in case of the mitigation of the environmental impacts of transportation sector, the policy maker will have to assess the synergy and also the rebound effects among users' behavior, technological progress, social structural changes, rebound effects, free riders, etc. The quantitative model will contribute to analyzing the interactions. As the side but important effect, the model development procedure often provide the common understandings through the communications among the experts of from various fields as well as stake holders. Thus, the model development will contribute to the followings:

(+) Mathematical models can be the basis of compatible understanding among various participants based on the logical context.
(+) Computable models can provide quantitative assessment information integrating benefits and damages.

while

(-) Mathematical models often include only "operational" and "well known" relationships.
(-) Computable models often neglect the "qualitative" factors.

Once the model is developed, it must be utilized by the policy maker and stakeholders to assess the options rather than the researchers. However, there are some practical issues. Models are usually developed by the researchers as a part of academic interest, but they should be maintained and tuned further to give the useful information.

(+) Model development is a good opportunity for the training and communication among the participants. (case of AIM, LINK, GTAP, etc.)
(+) Needs for the data, theory, tools (hardware and software), etc. are widely understood.

(-) All knowledge (data, model structure, algorithm, know-how, etc.) tends to concentrate to the model developer and is often hard to transfer to other users.

(-) “Model” tends to become larger and often goes beyond the understandable area. Very few participants can see the whole behavior of the model and hard to revise the part for other participants.

The model approach is still an only way to evaluate the option basket based on the common knowledge and language. Since the global warming issues need the comprehensive and consistent assessment involving current and future generations, optimality and equity among regions under the various uncertainties, the modelers should think about how the models can be applied to the policy decision making beyond the academic interest.

3. Targets of the Project PHOENIX

The decision making on the global warming mitigation should be based on the integrated views including short and long, global and local and public and private issues. Integrated assessment models (IAMs) have been developed since 1990s as a powerful tool for this subject. IPCC-TAR touched upon this method providing future scenarios on energy, economy and environmental paths. At the same moment, the following issues have been pointed out as the limits of current studies:

(1) Economic developments and technologies are well discussed in the IPCC reports no further than 2020 while IAMs mainly discussed the mitigation options in the second half of this century. The figures around the mid of 21-st century are, however, not discussed well although around the 2050 is regards as the bifurcation turning point in the context of energy resource and technology policies.
(2) Regional factors are important to assess the biomass energy utilization, distributed energy systems and recycling as well as the global warming effects while the current model studies have dealt with no more than ten world regions.
(3) Ssuch factors as civilization, technology transfer, international industry allocation and progress of IT, which will cause the social structure changes, are not explicitly discussed.

It should be pointed out that the energy demand forecasting are not well studied yet comparing with the supply technologies, e.g. power generation technologies and energy conservation possibilities. Food and water demands are also the case.

Let me start the importance of industry structure changes. Table 1 shows the growth rates of international trades. The rapid growth of trades will change the domestic industry structure affecting on the energy consumption and the social structure. Figure 3 exhibits the profiles of industry structure changes for 1980-1999. For instance, in China the service industry has grown up from 21% in 1980 to 33% in 1999. The industrial structural changes are apparent and they determine the future societal context and energy demand patterns. However, the existing Input-Output studies have not well provided the ways to forecast such structural changes especially in the middle- to long-term views except for some Leontief's experiments (Leontief, 1983). Needless to say, such industry structure changes did not occur only by the economic reasons. The policy decision to promote the domestic industry or to open the market by the expansion of foreign direct investments (FDI) is an outcome of internal societal context and external conditions (technology development, etc.) which will not be the simple function of economic activities.

On the other hand, if we can observe some fundamental historical trends across the countries, they will be used to set the starting points of the future scenario construction.

Figure 4 shows the relationship between the electric power demand in public and household sector per capita and the per capita income, where Figure 4(a) employs the GDP market exchange rate (GDP-mex) in 1995 price and Figure 4(b) does the GDP-purchasing power parity (GDP-PPP),

Table 1 The annual grow rates of internation trades

	1990～1993	1994～1995
World	4.4	9.2
OECD intra-regional trade	2.2	7.8
OECD-Non OECD trade	7.5	10.7
NonOECD intra-regional trade	8.8	15.2

Source: OECD, "World Economy in 2020", 1999

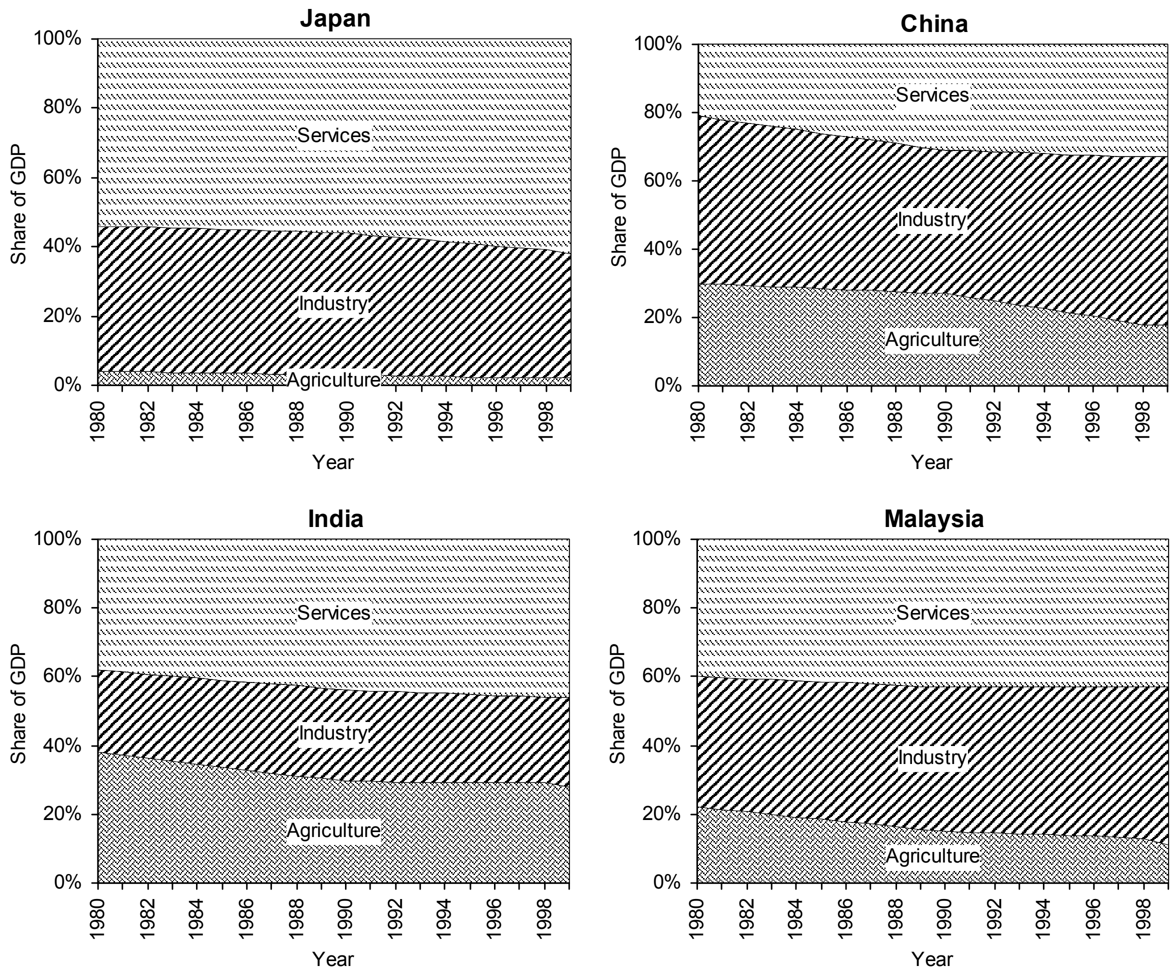
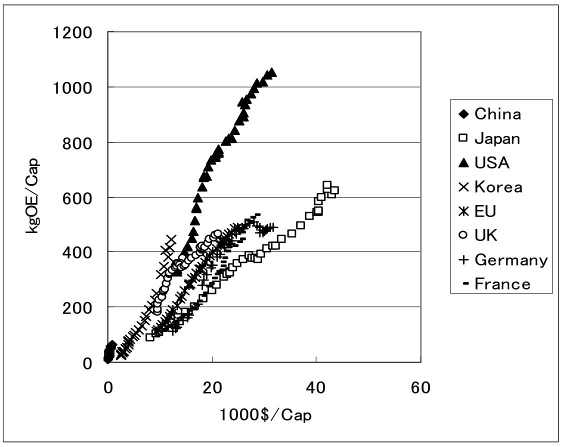


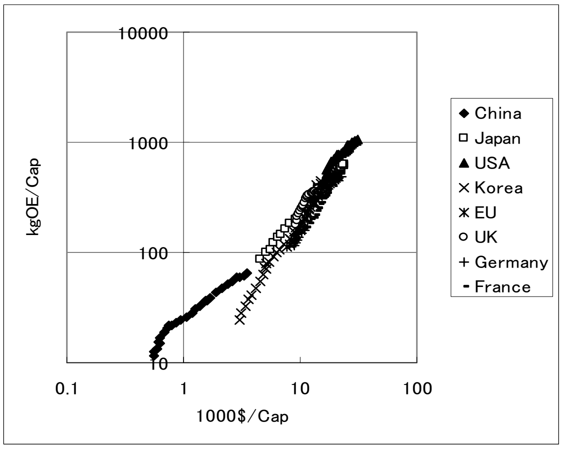
Figure 3 Industry structure change profiles for 1980-1999
Source：World Bank, World Development Indicators 2000; 2001）

Figure 4 tells that the Figure 4(a) using GDP-mex suggests that each region has its own electric demand growth pattern while Figure 4(b) suggest the regions follow the common growth path. If we can find the patterns similar to the Figure 4(b) for other demands, they will be applicable to assess the reference future demands. This observation is applicable to the detailed regions shown in Figure 5(a). One can observe that the per capita electric power consumption converges into a certain trend involving Japan, EU, USA, developing countries except for Africa.

Figure 5(b) shows the case of the demands of transportation oil products. We can observe that the regions can be classified into some categories.

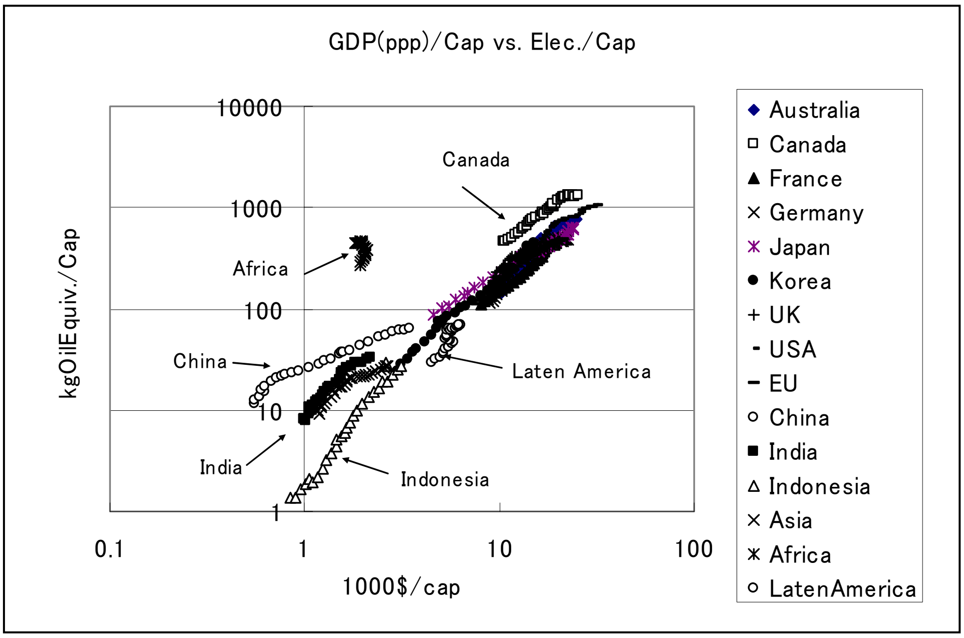
I do not say that the GDP-ppp is a better index than GDP-mex since the manufacturing products such as machinery and information technology equipments are not the case, but that the historical stable trends are the good starting point to construct the future scenarios.



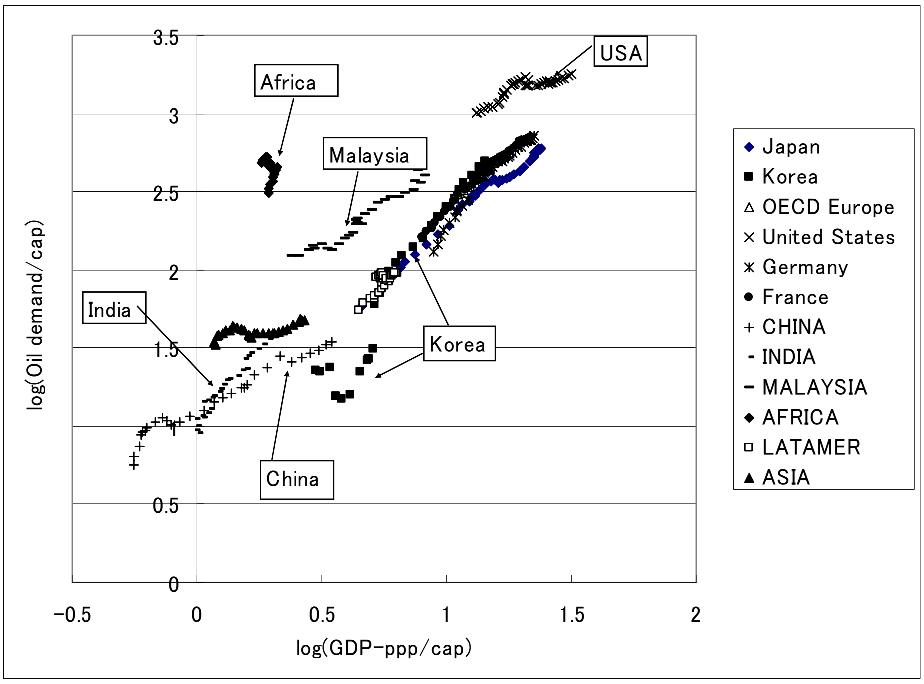


(a) GDP-mex in 1995 prices (b) GDP-PPP in 1995prices

Figure 4 The relationship between the electric power demand in public and household sector per capita and the per capita income



(a) Per capita electric power consumption vs. per capita GDP-PPP



(b) Per capita transportation demands and Per capita GDP-PPP
Figure 5 The relationships between energy consumption per capita and income per capita

As a whole, we set the following activity targets:

(1) 2002-2004 (The first stage)

Such global warming factors as population, economic growth, energy consumption, technology progress, deforestation, land use change, etc. are surveyed and summarized to find the trends. International industry allocation and others will be discussed on both quantitative and narrative factors. These information is used to construct a new model dealing with the environment, economy and industry structure changes applying X-I method (Cross Impact method) and its extensions (See APPENDIX-1). The model will generate the assessments of global warming mitigation options especially focusing on 2030-2050 transient middle term periods including 15-20 regions and 20-30 industry sectors. The affects of global warming will be studied gathering the available data sets and information.

(2) 2004-2006 (The second stage)

The energy, resource, economic growth, industry structure and social changes will be integrated with the global warming effects. Based on that, the model will be extended to provide the most rational strategy for the global warming mitigation.

For the above activities, the cooperation with the foreign researchers and the institutes is indispensable. In this project, we work with the International Institute for the Applied Systems Analysis (IIASA) in Austria which is known as one of the top world research centers exchanging data, information and research outcomes.

4. Research Procedure

RITE has already achieved extensive academic results in this field. For instance, global energy technology mode; DNE-21 and LDNE-21 have contributed to assess the new energy technologies as well as the carbon sequestration and other global warming mitigation options such as carbon tax. Simplified carbon circulation model MAGICC and large global carbon circulation model outputs have been integrated to generate the regional climate changes. In this project, these outcomes are allocated in the research frame.

We introduced three working groups: the model development WG, the global warming factor research WG and the global warming impacts WG. The model development WG plans to use GTAP model to assess the international trade and sectoral activities. Energy flow model block of DNE-21 and LDNE-21 will be integrated in the economic model. Other two working groups gather and integrate the scientific information and the statistics since the global warming issues involve so many fields. To reflect the importance of "qualitative" or "narrative" factors, technological forecasting methods will be employed to generate the background contexts for the quantitative projection.

The concrete research activity frame is shown in Figure 7. The groups will work according to the framework.

A:Model development WG aims at the development of the basic assessment tools.
(1) integration of static GTAP model and energy technology models (DNE-21, LDNE-21)
(2) dynamic extension of the model
(3) assessments of structural changes in the model
(4) expansion of regions and sectors

B: Global warming factors WG aims at the development of scenarios in terms of the global warming factors.
(1) collecting and summarizing the statistics and information
(2) extracting the key trends in the statistics
(3) providing the energy, food and other demand scenarios
(4) assessing the structural changes based on the narrative and qualitative events applying technological forecasting methods
(5) assessing the regional development scenarios toward the assessments of CGS and other regional options. (2nd stage)

C: Global warming impacts WG aims at the development of the scenarios on the warming impacts and mitigation options.
(1) collecting and summarizing the statistics and information
(2) extracting the key trends in the statistics using GIS
(3) assessing the relationships between climate change and the impacts focusing on the water resources, food production, vegetation, land use changes, health effects etc.
(4) assessments on ex-ante investments and ex-post expenditure toward the integrated assessments (2nd stage)

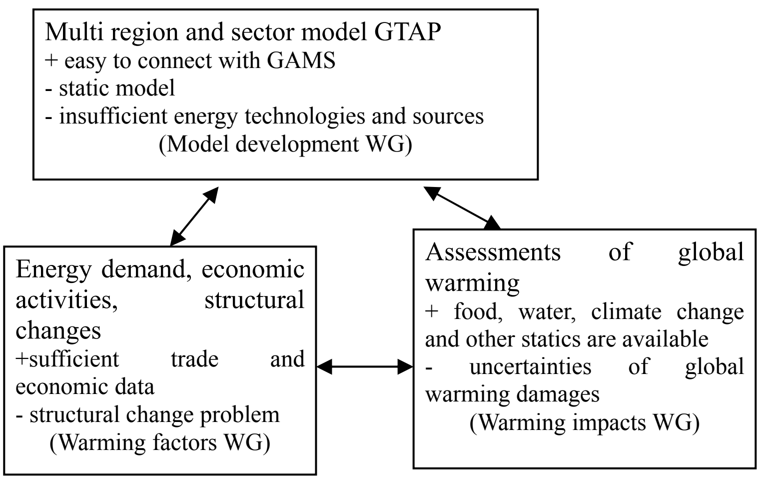


Figure 6 Three working groups in the project

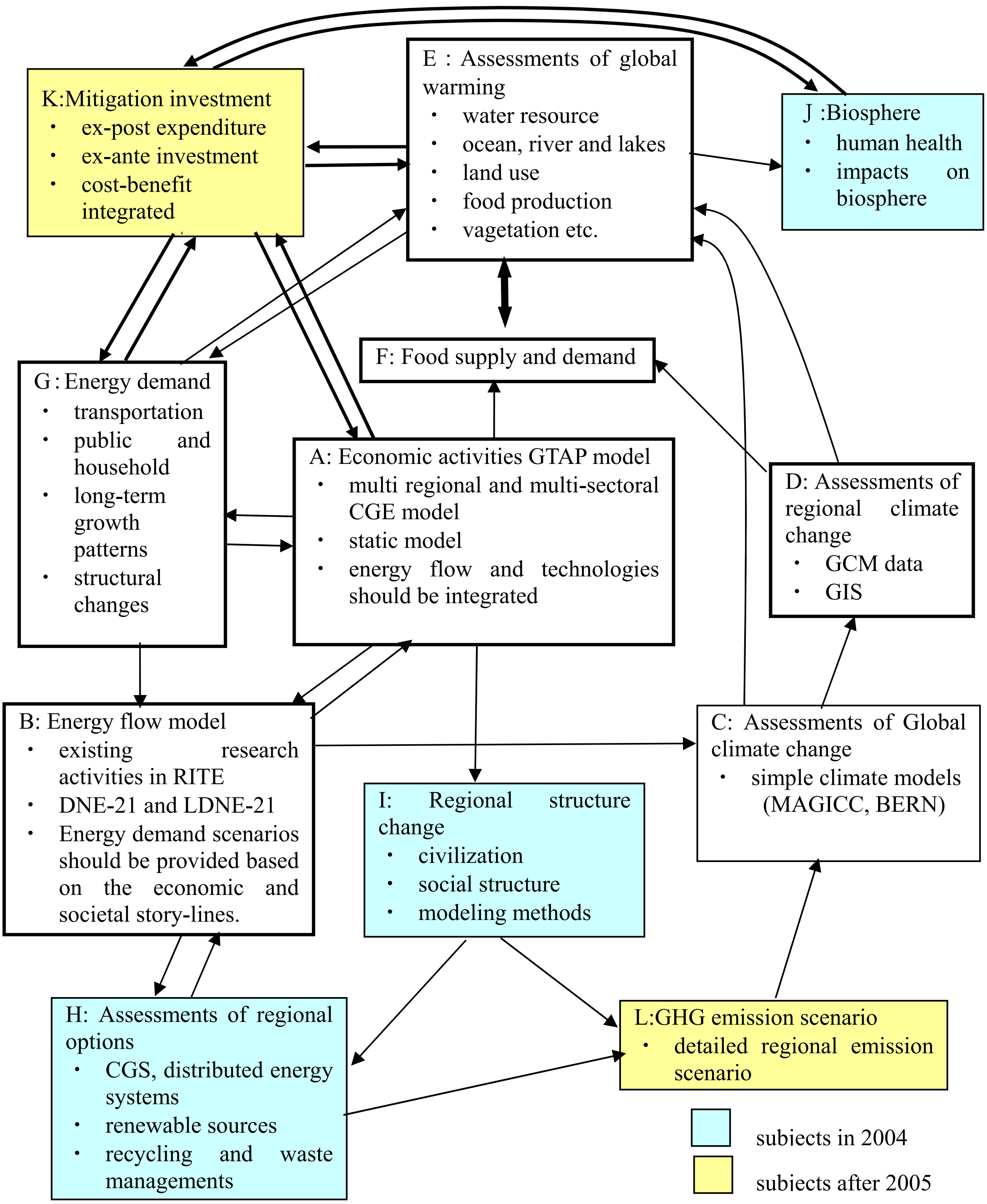


Figure 7 Phoenix project research activity flow map

In the above procedure, the structure analysis of the relationships among quantitative and qualitative factors is essential. For instance, IPCC-WG2 summarized the possible impacts of global warming on biosphere, human settlements, etc. as well as the adaptation options. However, since the impacts and the adaptation options are not mutually independent, the adoption of the certain adaptive options - such as the improvement of drainage system or the reinforcement of embankments against the floods - will derive ancillary benefits and strengthen the adaptive capability. On the other hand, penetration of air-conditioning systems will mitigate the heat stress but increase the energy consumption quickening the global warming. Energy technology developments will be also influenced by the social context as is already pointed out in

IPCC-SRES. In the A2 world, coal is mainly used since the technological transfer is limited while the B1 world depends on biomass and other renewables in the environmental-oriented context. In these two different society, the industry structure, the adopted options and other social decisions should be completely different and thus the impacts and vulnerability of global warming will be different. Industry structure changes are also driven by such social conditions as well as the technological development. Land use changes strongly relate to them. Then the costs and benefits of global warming mitigation options vary depending on the social context. Thus, for the integrated assessments, the scenario development is substantial step. In other words, our project starts from the IPCC-SRES narrative scenarios and aims at constructing more detailed stories. Cross-Impact method will be employed in the first step. (Kaya, 1979, See Appendix-1)

The scenarios generated by the above procedure will be linked to the quantitative assessment models.The procedure is exhibited in Figure 8.

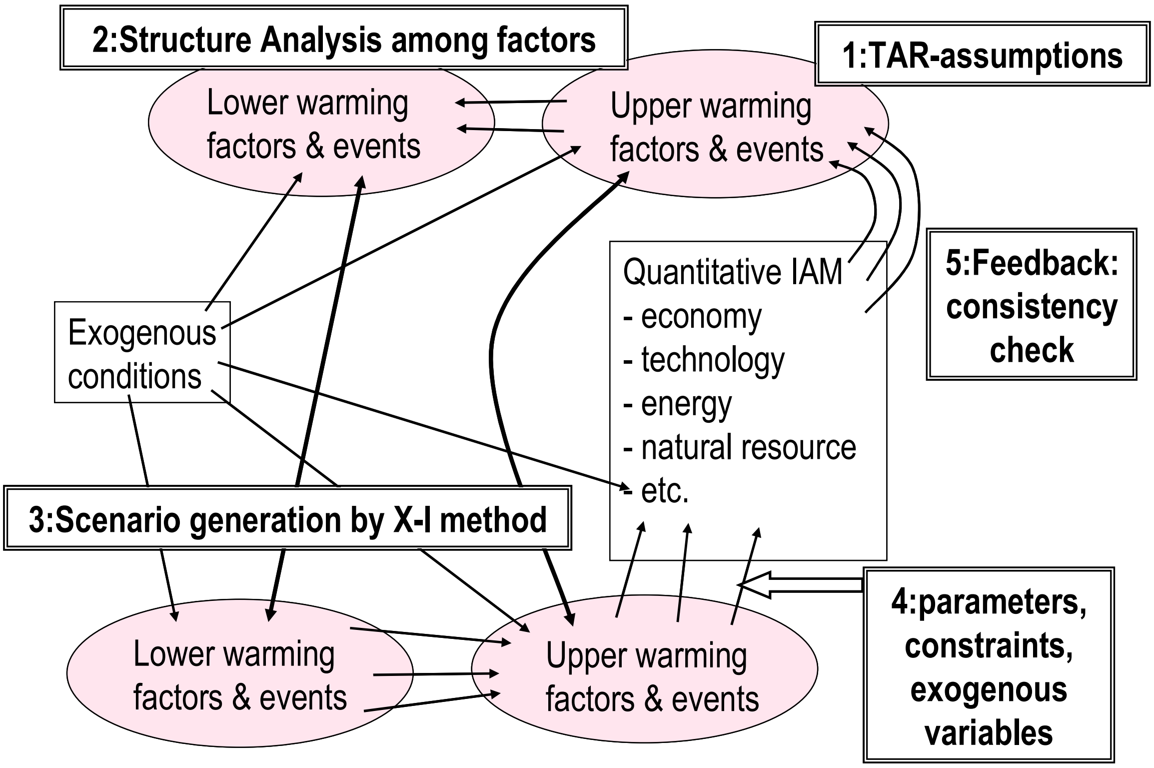


Figure 8 Procedure of integrated assessment including interactions among qualitative and uncertain events

(1) Global warming impacts are initially assumed following to the IPCC-TAR-WG2 findings.
(2) Based on the questionnaire as shown in Table 2, factors which will be impacted by the global warming are gathered as well as the factors which may be influenced by that, those which will accelerate that, and also the options and factors which will mitigate the undesirable impacts.
(3) Factors collected in the above are redefined and aggregated to clarify the interrelations.
(4) The causality and impact structure of the above is analyzed and the factors can be classified into the upper set which determines the model parameters and constraints directly, the exogenous factors which provide the conditions but are not affected by others, and others (lower set).
(5) The factors correlated to others strongly with uncertainty are analyzed by X-I method to extract the "most likely" scenario and alternatives.
(6) Impose the parameter settings, constraints and other possible conditions to the IAM according to the scenario.
(7) Check whether the outputs of IAM, e.g. global warming temperature, economic activities, land use, etc, are consistent with the initial assumptions.

Table 2 Questionnaire to extract the experts' judgments on the interactions among global warming impacts and factors

A:Global warming impact issues	B:Level of uncertainty	C: major regions	Major factors which will be affected by the issue	Factors which will accelerate the impact	Options and factors which will mitigate the undesirable impact
(ex.) shortage of urban water supply	High	China Africa	-Sanitation (H) -Health(M) -Maintenance of park (M)	-Rapid civilization (H) -Concentration of population (H) -Deterioration of water resources(H)	-usage of rainwater (M) -Advanced water recycle system (M)

(*) The reference climate change and impacts follow the IPCC-TAR-WG2.

The development of IAM is still the center of our work. since the quantitative assessments of options are needed by the policy makers. As mentioned in the previous section, based on the existing studies, we will focus on the middle-term policies considering regional conditions as possible. When we discuss the technology development policies concretely, the contribution of R&D investment and the accumulation of knowledge are indispensable. Although these issues require the non-convex optimization or the mixed integer optimization problem, thanks to the progress of the algorithm, software and computation abilities, many models incorporating such learning effects are developed in IIASA, RIVM, PNL, EPRI etc., recently. We have also proposed a model to assess the relationship between R&D strategies and the development in power generation technologies. (Akimoto, 2003) In the Appendix-2, a preliminary expansion of MARIA incorporating the learning effects and procedure are reported where a consideration on the "learning effect" and the "scale of economy" is touched upon.

5. Tentative conclusion - expected outcomes of PHOENIX project

The Phoenix project will provide the following information to the policy makers:

(1) The changes of the energy supply-demand systems as well as the industry structure changes and the international industry allocation scenarios will provide the basic information to assess the policy measures.

(2) Since Japan has less energy resources, the developments of energy strategies are important. The outcome of the project will give the helpful information.

(3) In the short- to middle- term, the most preferable burden sharing scenario on the carbon emission reduction can be generated,

(4) Industry policies on the R&D on the energy and environmental technologies, technology transfer, and other industry strategies can be assessed under the global warming mitigation policies.

As is well known, the global environmental issue is a huge decision making process incorporating efficient allocation of resources, equity, cross-generation issues etc. under various uncertainties such as lack of scientific knowledge, multiple criteria and multiple decision makers and conflicts among them.

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APPENDIX-I Outline of X-I method

1. History of Cross-Impact method

Cross Impact method (or X-I method) is originally developed by Gordon and Hayward in 1965 (Gordon, 1968). In 1960s, various technological forecasting method have been developed to see the future main stream of technologies. Cross-Impact method was originally developed to see the interrelationships among technologies with promoting or substituting each other. Gordon (1968) proposed a method to take into the impacts among future technologies (1) estimating the probability of occurrence of each technology (called event), (2) evaluate the degrees of impact among events, and then (3) revising occurrence probabilities using Monte Carlo simulation. In this procedure, the interactions among events are explicitly assessed. However, this procedure was criticized by Dalky (Dalky, 1972). He pointed out that the procedure lacked the mathematical (probability theoretic) basis and that the "revised" probabilities have no reason to be "more accurate" than the original ones. Duperrin and Godet (Duperrin, 1975) proposed a new method to provide the mathematical consistency using conditional probabilities and the revision procedure of two-dimensional probabilities to guarantee the existence of the consistent high-dimensional state probabilities. However, their method did not give the unique ranking. The difficulty of estimating "subjective" conditional probabilities is also pointed out.

Kaya et. al. (Kaya, 1979) expanded their method in two points: firstly, they proposed a causality probability instead of conditional probability based on the Markovian probability model to keep the dynamic mathematical consistency. Second, sequential linear programming method was employed to assess the range of high dimensional state probabilities.

After that, X-I model with Markovian model was expanded further to generate the dynamic scenario sequence (Mori, 1984) and incorporate continuous variable. However, these technological forecasting methods tended to phase out and became unfamiliar in 1980s as the main stream of technologies appeared gradually and clearly in many fields.

2. Procedure of X-I method

The procedure of X-I method by Kaya et. al. is as follows:

(1) Determine the set of events to be considered during the forecasting period. Each event should be defined as clearly as possible to assure the consensus among participants in the forecasting.
(2) Define the exogenous conditions affecting the event occurrences one-sidedly.
(3) Estimate the occurrence probability of event i (i=1,2…n) at the end of the forecasting period P(i).
(4) Estimate the “impact probability” $P(i \to j)$: the occurrence probability of event j at the end of the forecasting period given the condition that the event i occurs solely as fast as it can during the forecasting period.
(5) Calculate the two-dimensional probability $\{P(i,j)\}$ based on $\{P(i),\ P(i \to j)\}$ data. Markovian transition model is used in this procedure (Kaya (1978)). Conventional conditional probability $P(j \mid i)$ can be also used instead of $P(i \to j)$ according to the convenience of the participants.
(6) Construct the mathematically consistent probabilities $\{P^*(i),\ P^*(i,j)\}$ modifying estimated two dimensional probability data set $\{P(i),\ P(i,j)\}$ using the following criterion:

$$J = \sum_i w_i \{P(i) - P^*(i)\}^2 + \sum_{j \neq i} w_{ij} \{P(i,j) - P^*(i,j)\}^2 . \quad \text{(A.1)},$$

where wi and wij represent the optimization weights (usually unity is assumed.). The mathematically consistent probabilities $\{P^*(i),\ P^*(i,j)\}$ are represented by the linear combination of n-dimensional state probabilities. n-dimensional state is represented by the combination of the occurrence (1) or non-occurrence (0) of each event. Thus, the state can be represented by the n-bit series from $(0,0,\cdots 0)$ to $(1,1,\cdots 1)$. Then we can define the probability of the state k:

$\pi_k : n-\dim ensional\ occurrence\ state\ probability\ P\left(d_1^k, d_2^k, \cdots d_n^k\right)\left(k=1,2,\cdots 2^n\right)$. d_i^k =1 if even i occurs in the state k else d_i^k =0. Then the followings hold.

$$P^*(i)=\sum_k d_i^k \pi_k\ ,\quad P^*(i,j)=\sum_k d_i^k d_j^k \pi_k\ ,\quad \sum_k \pi_k=1\ ,\quad \pi_k \geq 0 \quad \text{(A.2)}$$

Minimizing J in (A.1) under the conditions of (A.2), one can calculate the unique consistent probability $\left\{P^*(i),\ P^*(i,j)\right\}$.

(7) Calculate the ranges of $\{\pi_k\}$ using linear programming. Namely,

$$\begin{matrix}\min.\\ \max.\end{matrix}\ \pi_k \quad \text{subject to}\quad P^*(i)=\sum_k d_i^k \pi_k\ ,\ P^*(i,j)=\sum_k d_i^k d_j^k \pi_k\ ,\ \sum_k \pi_k=1\ ,\ \pi_k \geq 0 \quad \text{(A.3)}$$

The above procedure has been expanded to generate the dynamic scenario set (Mori and Kaya (1984)). In this study, seven events on nuclear power technologies are picked up, (1)FBR: some FBR(Fast Breeding Reactor)s are already developed, (2)ATR: some ATR(Advanced Thermal Reactor)s are already developed, (3)CAND: some CANDU-PHW reactors are developed, (4)LWR-Pu: share of Plutonium recycling comes to one-third of total LWR fuel, (5) Repro: some reprocessing systems for LWR-Pu or ATR are operating, (6) Cent: some centrifugal separation plants are developed, and (7) Coal: the share of coal fired power generation comes to more than 20% of world electric power supply. Figure A.1 shows the generated dynamic scenario pathways, where two alternatives are extracted.

Unfortunately, due to the nuclear power technologies are not well implemented due to the accidents and other political reasons after that. However, the property of this method can be a useful tool to construct the future scenarios including uncertain and qualitative events in the global warming studies.

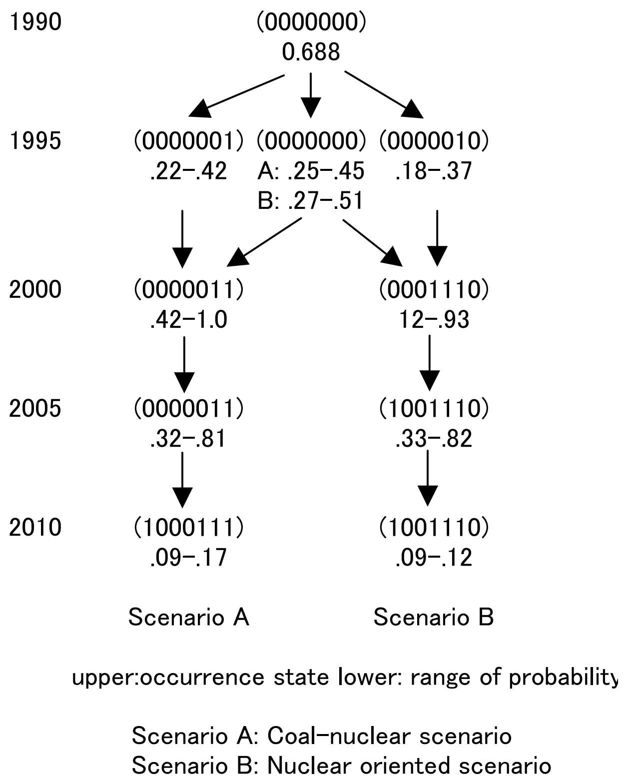

Figure A.1 Dynamic scenario sequences from 1990-2010

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Appendix-2 Preliminary results of MARIA with Learning Effects

Although the phenomenon of "learning effect" and "scale economy" where the marginal production cost decreases as supply increases are widely understood, they have not been employed in the optimization energy-economy models until recently due to the need for the solver of non-convex problem and the lack of statistics. It is well known that such "decreasing cost" or "increasing return" optimization problem can be solved by the mixed integer programming. Thanks to the progress of optimization algorithms and computation capability, integrated assessment models with endogenous decreasing cost functions can be solved practically in these years. The pioneering work of Messner (1995) introduced the learning curve in the MESSAGE model. In 2001, Kram (2001) and Miketa (2001) proposed two-factor learning curve model where cumulative production and R&D investments were the sources of decreasing costs. Barreto (2002) developed an energy system model with endogenous R&D activities using 2 factor learning model. Manne (2002), Klaasen (2002), Gerlagha(2002) and many researches were also presented at the IEW/EMF-19 2002. A new algorithm named BARON is also proposed by Manne(2002b). Lack of historical data on the learning process has been a barrier against the empirical analysis. IIASA eagerly gathered the data base and summarized the learning rates. (McDonald (2001))

Doubtlessly, this new computation tool develops new frontier of integrate assessment models especially in the technology policy assessment area.

In the Phoenix project, the assessment of energy technology options is one of the major subjects. The diffusion process or potential market of the certain technology provides key information on the policy direction as well as the relationship between R&D and the marketability. A method to analyze the relationship between R&D investment and the R&D duration is proposed by Akimoto (2002) and Akimoto (2003). In this Appendix, some preliminarily findings on MARIA with learning effects are presented.

The MARIA (Multiregional Approach for Resource and Industry Allocation) (Mori (2000)) is developed as an integrated assessment model incorporating energy resource and technologies, economic activities and global warming impacts dividing the world into eight regions. MARIA includes carbon sequestration technologies as well as nuclear power technologies with fuel recycling. The land use subsystems and food demand-supply equations are also imposed to evaluate biomass energy resources under food supply constraints. MARIA is formulated as an intertemporal non-linear optimization model including around 18,000 variables and 15,000 constraints. In this paper, however, nuclear fuel recycling and land use change as well as the food demand and supply blocks are removed to reduce the model size. Instead, learning by doing (LBD) formulations are imposed to see the penetration process of two renewables, i.e., PV and windpower, and three advanced fossil fuel based technologies: coal based integrated gas combined cycle (IGCC), solid oxide fuel cells (SOFC) and gas based combined cycle plant (GCC). In this paper, I focus on the three subjects on this preliminarily study.

A-1 Computation Procedure

The formulation of the decreasing cost curve is well known form. Figure A-1 illustrates the marginal production cost decreases as the cumulative production increases applying piecewise linear functions.

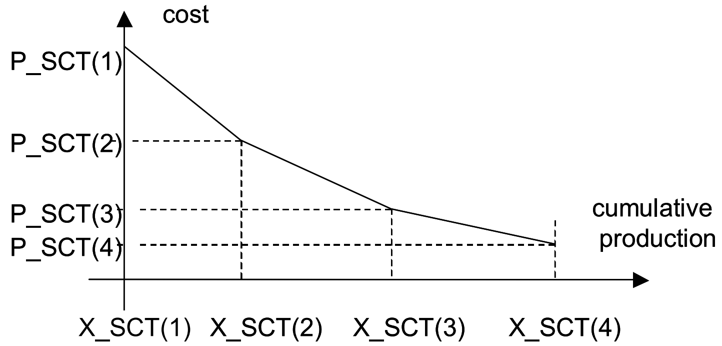


Figure A-1 Decreasing cost pattern

The above cost curve can be formulated by using binary variables $\{\delta_m\}(m=1..4)$ and positive variables $\{\lambda_m\}(m=1..4)$

$$X=\lambda_1 X\_SCT(1)+\lambda_2 X\_SCT(2)+\lambda_3 X\_SCT(3)+\lambda_4 X\_SCT(4) \quad (A.1)$$

$$P=\lambda_1 P\_SCT(1)+\lambda_2 P\_SCT(2)+\lambda_3 P\_SCT(3)+\lambda_4 P\_SCT(4) \quad (A.2)$$

$$\lambda_1 \quad -\delta_1 \quad \le 0 \quad (A.3)$$

$$\lambda_2 \quad -\delta_1-\delta_2 \quad \le 0 \quad (A.4)$$

$$\lambda_3 \quad -\delta_2-\delta_3 \quad \le 0 \quad (A.5)$$

$$\lambda_4 \quad -\delta_3-\delta_4 \quad \le 0 \quad (A.6)$$

$$\sum_k \delta_k = 1 \quad (A.7)$$

$$\sum_k \lambda_k = 1 \quad (A.8)$$

where X and P denote cumulative production and marginal production cost, respectively. However, GAMS 2.50 MINLP solver CONOPT2 + SBB often generates unstable local optimum solutions which are sensitive to the initial values. Currently, I employ the following three stage procedure:

Stage 1: Solve the model-1 without the above endogenous cost functions using NLP fixing the costs P_0 to be the certain initial values. This stage provides initial values other than the above endogenous cost function.
Stage 2: Add the constraints (A.1), (A.2) and (A.8) removing the constant conditions on the costs P. Solve this model (model-2) using NLP. The model can be solved easily but the relationship in Figure A-1 does not hold. When P differs from P_0 so much, fix P_0=P and go to Stage 1 again.
Stage-3: Find the section k where $X\_SCT(k) \le X < X\_SCT(k+1)$. New initial value of λ' and δ are calculated according to the solution of cumulative production X in Stage-2 and {X_SCT(m)} such that X is represented by $X=\lambda' X\_SCT(k)+(1-\lambda')X\_SCT(k+1)$. Modified P' is also calculated using λ' and {P_SCT(m)}. Adding the equations (A.3)-(A.7), solve the full model-3 using MINLP.

If the solution of P in Stage-2 is too far from the recalculated value P' in Stage-3, fix some λ_j to be zero and go to Stage-2. j can be chosen as the farthest section from k. The above procedure is an intuitive relaxation procedure to find the solution of the LBD model and does not guarantee the global optimum solution. In this sense, when more sophisticated solver is available, the above procedure will be useless. (At the moment, we have tested the new GAMS solver BARON.) However, currently, the above procedure provides MARIA with LBD stable solution not affected by the initial values. The GAMS source of Stage-3 is exhibited in the Appendix-3.

A-2 Learning process and Scale of economy

As is often pointed out, the decreasing cost phenomenon also appears in the existence of "scale of economy" other than the learning procedure. The distinction of these two effects is not easy based on the historical cost data. From the view of dynamic model formulation, these two may derive two expenditure types. Figure A-2 shows the historical observation of decreasing cost and cumulative production. When the cost curve represent "full" learning curve, the firm has to experience almost all the points along the line EC. Then the total expenditure between t and t+1 will be the area ABCE. However, if one period is short enough, the cost reduction will be the outcome of scale of economy. If the firm has an information of cost curve EC at the period t, or he knows the relationship among market demand, production volume and the average cost, he can produce the volume AB at period t without the experience of production between EC. In this case, the total expenditure is represented by ABCD. It should be noted that the area ABCD is not always a monotonous function of X so long as assuming the decreasing linear cost function while ABCE is always an increasing function of X. In the former case, the total expenditure can have multiple local optimum solutions. In this case, even if the cost curve is represented by a single line and there is only one cost curve section, the model can't be solved by the conventional NLP due to the lack of convexity. GA with continuous variables will be required.

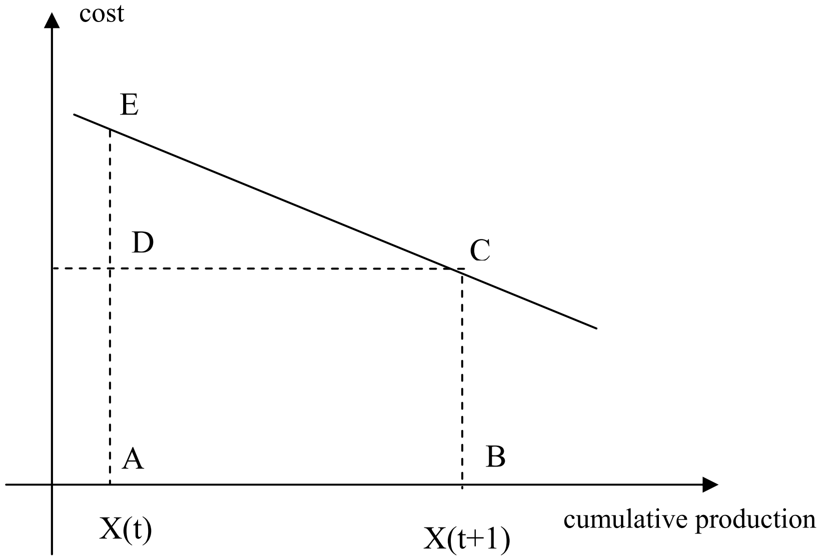


Figure A-2 Decreasing cost curve and expenditure

In the integrated assessment models, one decade is often adopted as one period to see the long term assessment. It seems to be appropriate that there are both short term "scale of economy" and middle term "learning effect" cost reduction. For instance, assuming that the process innovation occurs three times in one decade, the observed cost function and the expenditure represents the hatched area of Figure A-3.

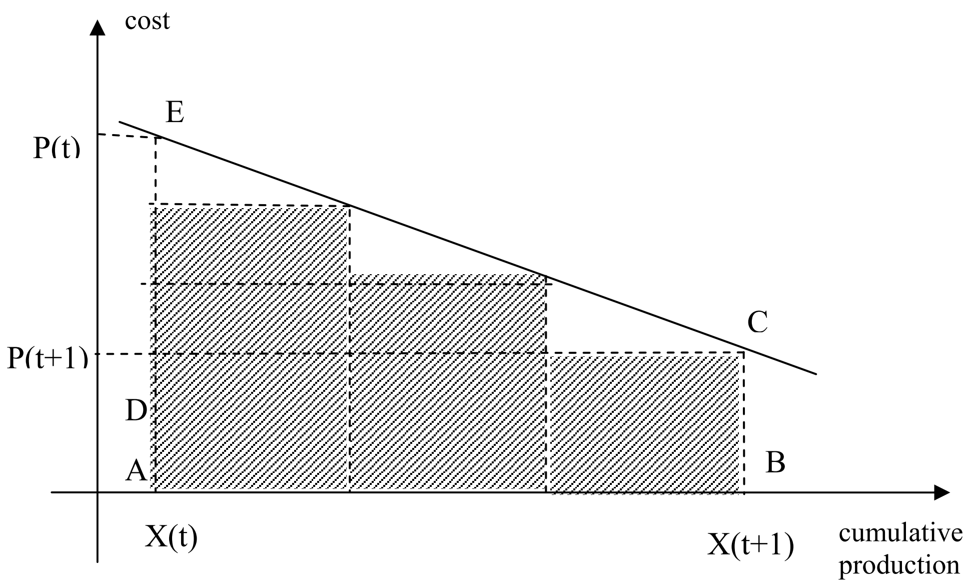


Figure A-3 Scale of economy and LBD cost reduction

Generally, we can easily see that the hatched area is represented by

$$\frac{X(t+1)-X(t)}{2}\left\{P(t+1)+\left(1-\frac{1}{n}\right)P(t)\right\} \qquad (A.9)$$

where n represents the innovations occurring in one period. Practically, it will not be easy to distinguish the above two effects in the historical data and currently the above is no more than simulation assumptions. However, in some cases, such as memory chips and logic LSI, we will be able to trace the innovations like process rules and price changes.

A-3 Preliminarily results of MARIA with LBD

Here some simulation results are shown as preliminarily experiments. As is already mentioned, MARIA with LBD incorporates two renewable sources and three fossil based technologies, say PV, windpower, IGC, SOFC and GCC. Parameter n in equation (A.9) is assumed 4. Figure A-4 and Figure A-5 show the primary energy supply profiles in BAU and carbon concentration control case at 550 ppmv. The key drivers are set according to the SRES-B2.

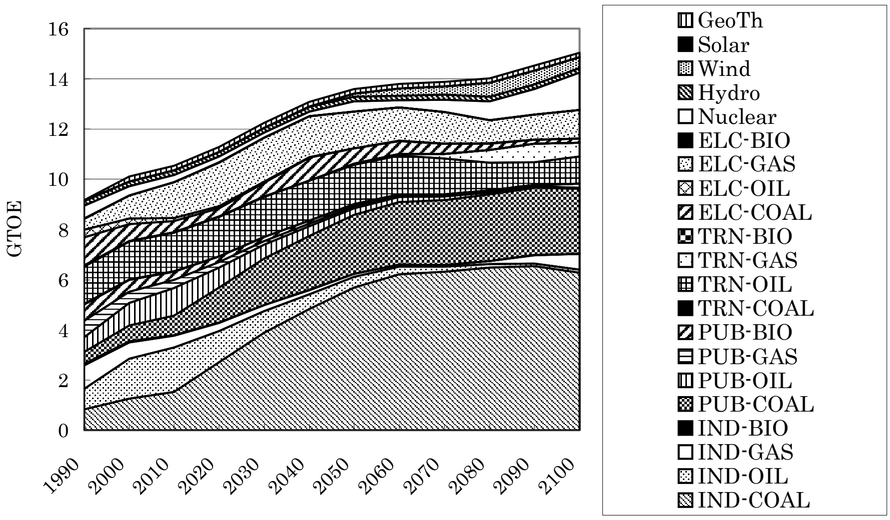


Figure A-4 Primary energy supply profile of MARIA-LBD in BAU

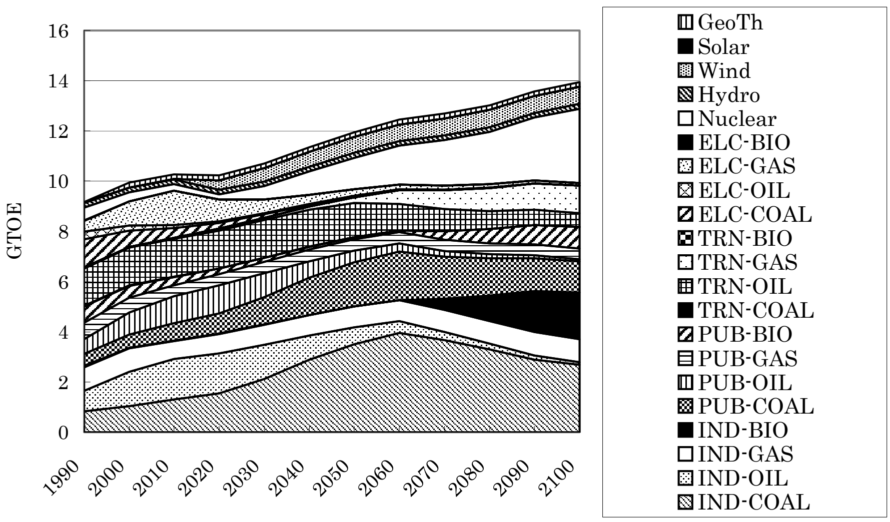
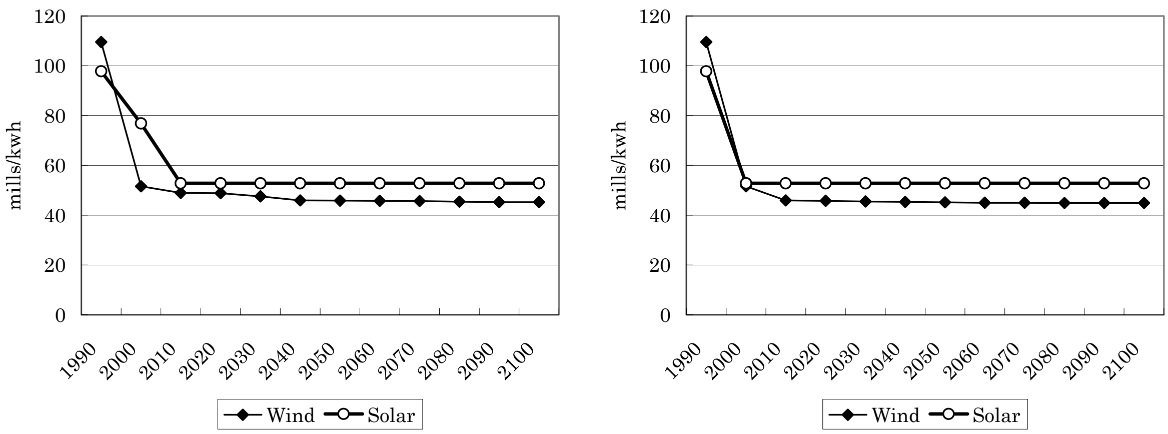


Figure A-4 Primary energy supply profile of MARIA-LBD in carbon control at 550ppmv case

We can see that the windpower increases significantly in carbon control case. But major increased energy sources are nuclear power and biomass substituting coal. Figure A-5(a) and (b) exhibit the trends of power generation costs of windpower and solar power.

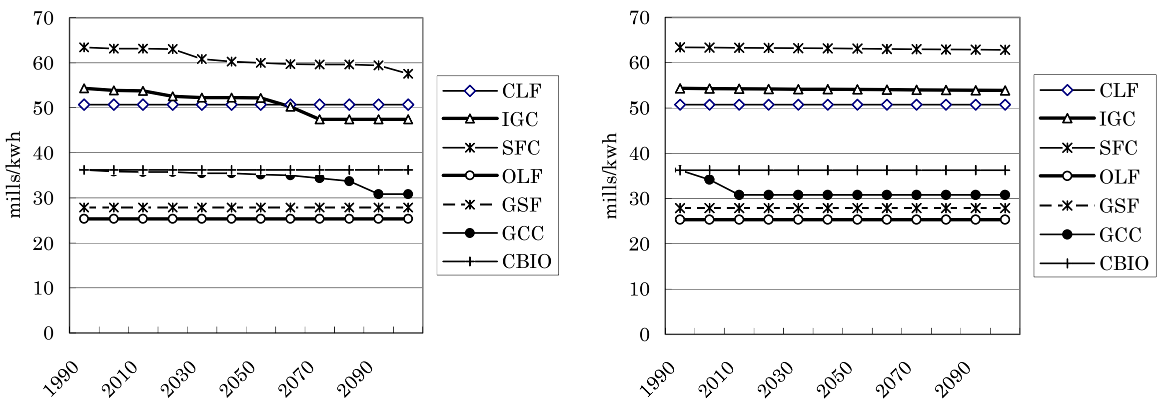


(a) BAU case (b) carbon control case

Figure A-5 Endogenous cost change profiles of windpower and solar PV

We can see that the costs of renewables in carbon control case approach their minimum values earlier than those in BAU. It should be noted that the implemented capacity of solar power deterministically depends on the assumptions of the cost curve since the theoretical supply capacity of PV is high.

Figure A-6(a) and (b) compare the price change patterns of fuel based power generation technologies. In BAU case, since fossil fuel is mainly used in the power generation, costs of advanced technologies decrease as they are implemented. However, in carbon control case, since fuel based generation plants are replaced by nuclear power and other carbon free technologies, cost reduction does not appear clearly except for GCC.



(a) BAU case (b) carbon control case

Figure A-6 Endogenous cost changes of fuel based power generation plants in BAU and carbon control cases; costs of conventional plants i.e., coal fired plant (CLF), oil fired plant (OLF), gas fired plant (GSF) and biomass power plant (CBIO), are constant

Although the results described here are preliminarily and far more technology options including carbon sequestration options should be assessed on the model. However, the above three points will contribute to the next studies.

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Appendix-3 GAMS source in STAGE-3

```
* T simulation periods and RNW indicates renewable options
* M (=5) indicates piecewise linear sections
* PR_R represents the production cost

binary variable DLT(M,T, RNW) ;

equations
   DLT_C(T, RNW)
   SECT_C(M,T, RNW)
   SECT_C1(T, RNW)
;

DLT_C(T, RNW).. sum(M, DLT(M,T, RNW))=E=1;

SECT_C(M+1,T, RNW)..
      LMD(M+1,T, RNW) =L= DLT(M,T, RNW)+DLT(M+1, T, RNW);

SECT_C1(T, RNW)..
      LMD("1", T, RNW) =L= DLT("1", T, RNW);

model CO2_MIP /all/;

DLT.L(M,T,RNW)=0;
loop(M,
   DLT.L(M,T,RNW)
   $( (CUM_R.L(T, RNW) GE X_SCT(M,RNW))AND((CUM_R.L(T, RNW) LT X_SCT(M+1,RNW))))
      =1;
);

DLT.L("5",T,RNW)$(CUM_R.L(T, RNW) GE X_SCT("5",RNW))=1;

LMD.L(M,T,RNW)=0;
Loop(M,
     LMD.L(M,T,RNW)$(DLT.L(M,T,RNW) GE 1)
      =1.0-(CUM_R.L(T, RNW)-X_SCT(M,RNW))/(X_SCT(M+1, RNW)-X_SCT(M,RNW));
);
Loop(M,
     LMD.L(M+1,T,RNW)$(DLT.L(M,T,RNW) GE 1)
      =(CUM_R.L(T, RNW)-X_SCT(M,RNW))/(X_SCT(M+1, RNW)-X_SCT(M,RNW));
);

PR_R.L(TR, RNW) = sum(M, P_SCT(M, RNW)*LMD.L(M,TR, RNW));

          SOLVE CO2_MIP MAXIMIZING UTILITY USING MINLP;
```