Ultra-Long Term Global Energy Supply/Demand Models And Simulation Analyses*

Kokichi Ito, Director / General Manager
Yasuhiro Murota, President, Shonan Econometrics
Yuji Morita, Manager, Oil Group
Mitsuhide Hoshino, Manager, Demand Forecast Research Group
Energy Data and Modelling Center
The Institute of Energy Economics, Japan

Abstract

There are concerns that the economic development of the developing countries will hasten global warming. That is to say, it is quite difficult to solve the North-South problem and the global warming problem simultaneously. But this paper shows that a potential exists for solving global warming in the long term by aggressively transferring technologies from the developed countries to the developing countries, and by accelerating development of the developing countries.

A model incorporating development stage theory is built and used to calculate regional population, economic growth, CO_2 emissions, and other factors (the world is divided into 12 regions). Results of the business as usual (BAU) case for 2100 indicate that world population will be about 11.7 billion (it was about 5.1 billion in 1990), GDP will be about US$225 trillion (1987 prices; GDP was about US$20 trillion in 1990), and CO_2 emissions will be about US$15.9 billion Tec (tons carbon equivalent; CO_2 emissions were about 5.9 billion Tec in 1990).

However, current study suggests there is a way to mitigate global warming. Combining various policy measures and options such as: (i) worldwide promotion of energy conservation (through technological progress in, and transferring technologies to, the current developing countries); (ii) worldwide acceleration of new energy source development (same means); (iii) cleaner use of fossil fuels (same means); and (iv) imposition and utilization of environmental taxes, will allow some options for stabilizing CO_2 emissions (for example, in the "new energy + energy conservation + carbon tax" case, CO_2 emissions will be 5.8 billion tons in 2100).

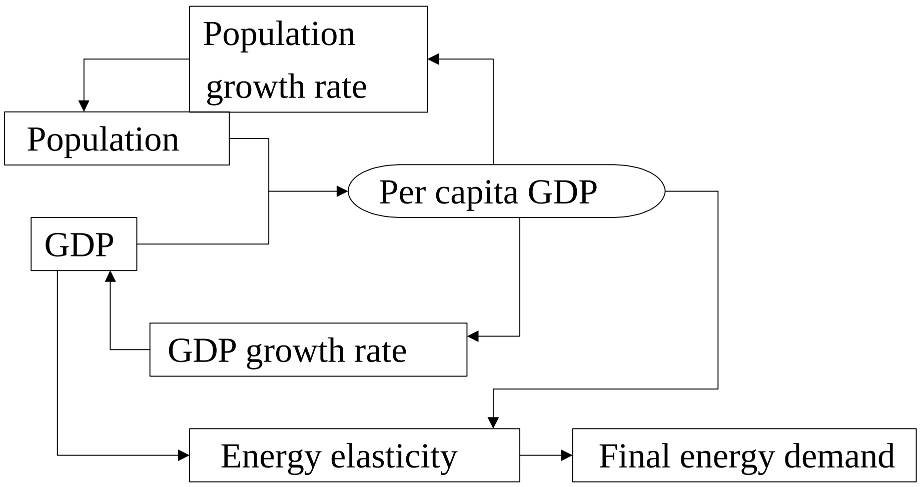
* This research was performed commissioned by NEDO.

1. The model's configuration and features

The main features of our model are described below.
(see Figure 1 for model configuration).

(1) Development stages, population, and energy consumption

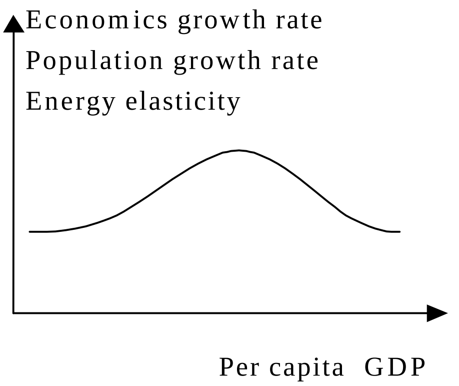
Our model expresses development stages by adopting per capita income as the indicator. The model assumes that the higher the per capita income, the more advanced the economic development stage. In our model, population, economic growth rates and energy elasticity are endogenously determined in line with the shifting economic development stage, which is expressed by per capita income.

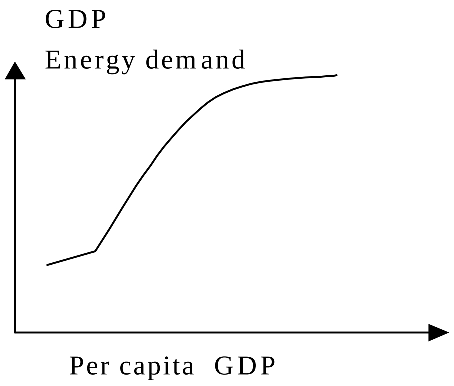


Heretofore models have treated population and economic growth rate as exogenous, in effect excluding problems including that of explosive population growth. Further, these models assumed no structural changes in the economy or extremely modest ones if any. Given the worldwide nature of the global warming problem, which will continue into the long-term future, we have been concerned with the serious limitations in hitherto available models. Incidentally, there is now some empirical research results that support the idea in our model. For example, Galli has recently shown that energy elasticity is a function of per capita income, and the function assumes an inverted-U shape.

(2) Determination of supply/demand for renewable (supply/demand, as well as costs)

Under a set of conditions for prices and a maximum ceiling for potential demand, as well as parameters for the ratio of annual investment to potential demand, the model allows one to determine actual demand for renewable energy sources in accordance with substitutability and cost competitiveness among energy sources, market size, and other factors.





(3) Analysis of price equilibrium path

In order to assure consistency between supply and demand for nonrenewable resources, particularly consistency between reserve levels and actual demand, there is also a routine to obtain equilibrium in the model.

(4) Incorporation of supply/demand for food, steel, automobile, and other commodities

In foreseeing the ultra-distant future, factors such as population, food, and energy problems are extremely important and interrelated. Thus there is a routine to calculate food supply/demand in the model. Further, the model explicitly incorporates steel production and automobile use, the former as a representative indicator for basic material production and the latter as an indicator for living standard and lifestyle. Since steel production and automobile use are factors that directly influence energy supply and demand, they be explicitly incorporated into the model.

(5) Consideration of land utilization

The model explicitly indicates interdependence or trade-off among population, food, and biomass (the last two factors may compete for limited arable land at a certain stage).

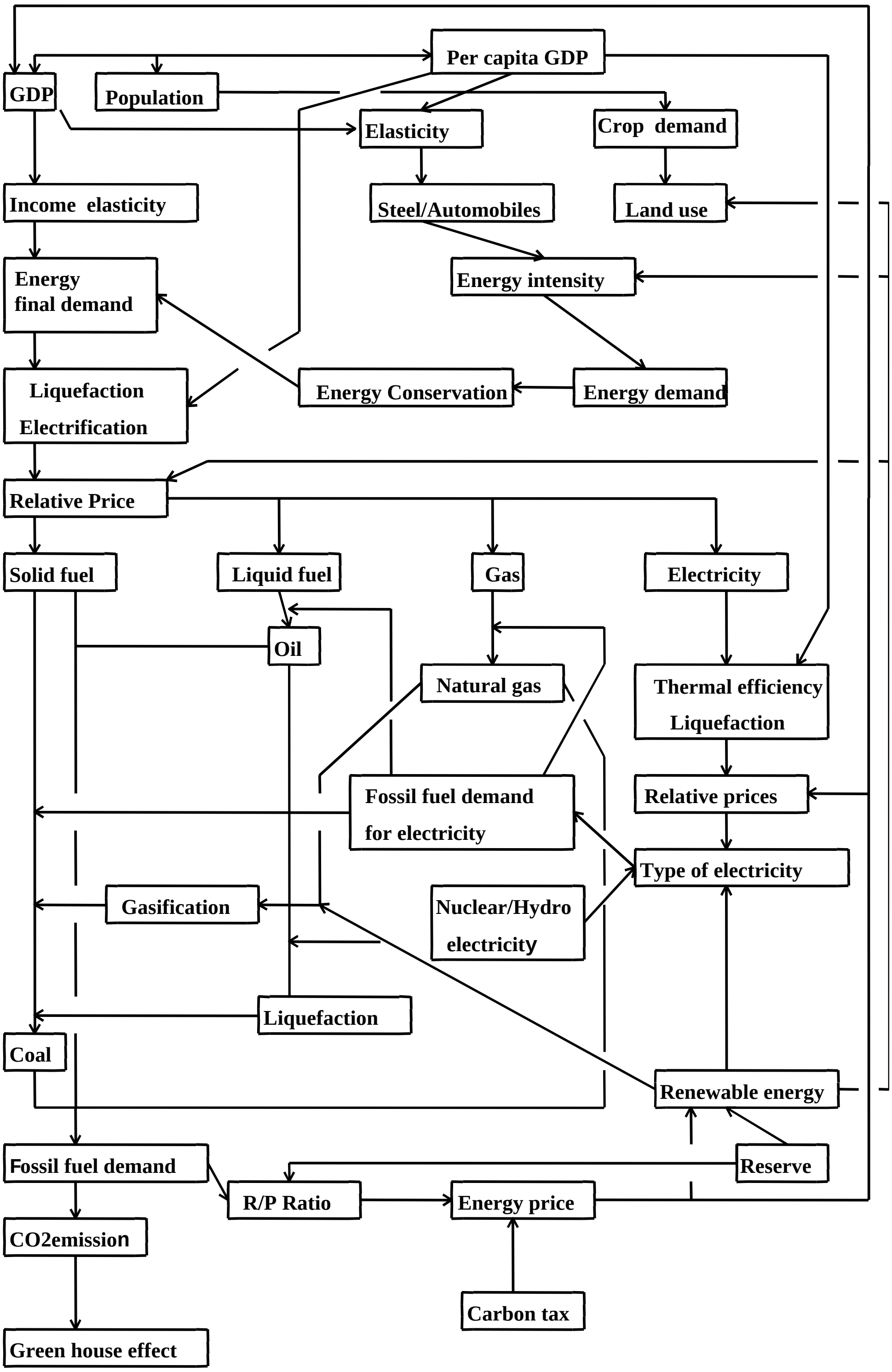
(6) Reflection of environmental taxes (carbon taxes) by geographical area

In order to reflect various energy price policy measures, the model allows the explicit treatment, by region, of environmental charges (or subsidies) and the like in accordance with that region's economic development stage.

(7) Adoption of the "Open Box Approach"

This means that the model should be easy to understand and clearly structured. Addressing global warming requires exchanging opinions among a variety of people from various sectors. For this purpose also, the meaning of simulation results, as well as the model structure, should be clearly understandable. In addition, the simulation-type model adopted here allows evaluation of various policies measures (for example, the effects of energy substitution, energy conservation, and carbon tax policies).

Fig.1 Flow chart of the model



2. Simulation Cases and Presuppositions

2-1. Simulation Cases

Simulation cases are summarized in Table 1.

Our first simulation was the business as usual (BAU) case, which basically assumes that current trends continue in terms of energy supply/demand, economic growth, and technical progress, without being subject to any particular environmental constraints. In terms of global warming, however, the BAU case is unacceptable judging from its implications for nonrenewable energy resources and CO_2 emissions. Whether or not we can achieve sustained economic development with lower CO_2 emissions depends upon accelerated energy conservation and substitution by non-fossil fuels. Imposition of carbon taxes is also a promising policy measure that relies on the market mechanism.

Thus, in addition to BAU, we performed four independent case studies, each representing a typical global environmental policy option: new energy acceleration, energy conservation, nuclear power expansion, and carbon taxes. Since the independent case study results are insufficient to reduce CO_2 emissions, we have performed analyses on additional cases combining the scenario elements of these four.

Table 1 Scenario cases in the Model

		Renewable	Conservation	Nuclear	Carbon tax
Reference	BAU: Business as usual				
Four scenario elements	A: Renewable Energy Promotion	O			
	B: Energy Conservation Progress		O		
	C: Nuclear Energy Expansion			O	
	D: CO_2Tax Introduction				O
Combi Nation	AC: Renewable+Nuclear	O		O	
	AB: Renewable+Conservation	O	O		
	ABC: Renewable+Conservation +Nuclear	O	O	O	
	ABD: enewable+Conservation+Tax	O	O		O

The BAU case

The BAU case basically assumes extrapolated trends in energy supply/demand, economic growth, and technical progress, and does not consider particular environmental constraints. In other words, it has no specific policy for solving global problems. BAU results can be used as a basis for considering various policy measures and other scenarios.

Major BAU scenario elements are as follows:

(1) Economy

The developed countries undergo relatively low growth, but the developing countries led by those in Asia continue high growth. As a whole, the world economy will grow steadily.

(2) Energy demand

Energy demand will keep growing especially in the developing countries, whose proportion will dominate world energy demand by the latter half of the 21st century. Further, the electrification of final demand in these countries will be accelerated.

(3) Resource endowments

There are various ways to see resource endowments, but current study adopts a rather conservative view.

(4) Primary energy demand

(FOSSIL FUELS)

By the latter half of the 21st century, world conventional oil and natural gas resources (i.e., those that can be exploited with current technology and market conditions) will approach depletion levels, accelerating the use of coal and unconventional oil and natural gas resources.

(RENEWABLES)

In terms of cost, it will be difficult for renewables to compete with fossil fuels during the first half of the 21st century. In the latter half of the 21st century, renewables will be used to some extent.

(NUCLEAR POWER)

Even though some countries will continue promoting nuclear power, others will move to curtail this energy source. On the whole, nuclear power will grow gradually.

A. New energy acceleration case

Investment, technical transfer, and other energy policy measures will be adopted to accelerate the use of new energy. More specifically:

(1) Financial support, including government subsidies to early pre-commercialization-stage R&D;

(2) Cost reduction in line with accelerated R&D;

(3) Enhanced cooperation among business, academic and government sectors to promote relevant projects;

(4) Worldwide acceleration in the use of renewables through technical cooperation for developing countries and other means.

B. Energy conservation case

To achieve economic development while restraining energy demand growth, it is essential for developing countries to actively introduce advanced technology, and at the same time to aim for economic growth led by high-added-value industries.

(1) Development of IT technology and the transfer of such technology to the developing countries for the purpose of establishing information-oriented industrial structures and the resulting improvement in energy intensities.

(2) Promotion of further energy conservation in the developed countries, and transfer of energy conservation technologies to the developing countries.

(3) Dissemination of innovative energy utilization technologies (fuel cells, combined cycle, micro gas turbines, and the like).

C. Nuclear power expansion case

Among non-fossil energy sources, nuclear power has the potential of large scale supply, but there certainly exist many constraints in addition to economic efficiency. Thus, BAU adopts relatively modest assumptions. The nuclear power expansion case assumes that worldwide expansion of nuclear power will be tolerated, and that the fast breeder reactor will begin full-blown commercial operation by the mid-21st century. Use of nuclear power in the current developed countries will grow moderately, with Japan in the lead. Nuclear power capacity will be added ambitiously in the current developing countries, with large Asian countries in the lead.

D. Carbon tax case

The carbon tax case assumes that carbon taxes will be instituted primarily in developed countries around 2010 with a rate of US$5/bbl (about US$40 per ton of carbon). Thereafter, carbon taxes will also be gradually instituted in the developing countries and by the latter half of the 21st century all countries will have imposed the same tax rate, which will be around US$20/bbl. Thereafter, the carbon tax rate will continue to grow and by 2100 all countries will have imposed the same tax rate of around US$20/bbl.

Through the price effect, imposition of carbon taxes is hoped to accelerate energy conservation and substitution towards renewables.

Compared with the BAU case, the above four cases indicate that CO_2 emissions will decline somewhat, but the reduction is not sufficient.
Thus, we performed cases studies combining scenario elements of these four.

AC. New energy acceleration + nuclear power expansion

The use of non-fossil new energy sources and nuclear power will be accelerated.

AB. New energy acceleration + energy conservation

In addition to the accelerated use of new energy sources, energy conservation will be promoted.

ABC. New energy acceleration + energy conservation + nuclear power expansion

Assumes the expanded use of nuclear power in addition to "new energy acceleration + energy conservation."

ABD. New energy acceleration + energy conservation + carbon taxes

The use of new energy sources and energy conservation will be further accelerated through an economic measure, i.e., carbon taxes.

2-2. Other presuppositions

Nuclear power and hydropower are exogenous variables since nuclear power is politically determined while reflecting various social factors, and the amount of future hydropower is presumably fixed.

All other energy sources are endogenously determined. To reflect the economic efficiency of exploration and development activities, investment value is chosen as the proxy. The model first determines "potential resource availability," which reflects investment value. For some energy sources, potential resource availability is exogenously given. Second, based on the "potential resource availability" thus far determined (or exogenously supplied), the model then calculates actual demand (i.e., supply) in accordance with the technical constraints and the oil price, which represents exploration costs (or secondary energy price such as electricity, which is determined by oil price).

An investment fund is secured through a mechanism that relies on a concept similar to that of "energy user charge." The investment fund accumulated during the current period is assumed to be allocated and invested in various energy exploration and development activities in the next period so as to secure energy resource availability. The level of "potential resource availability" will be determined in accordance with investment value. Further, based on the calculated R/P ratio for each reserve category, the representative energy price (such as oil) is defined as a declining function of the R/P ratio. Thus, a particular energy source will actually be demanded only when adequate investments are made and its cost becomes competitive with that of the representative energy price.

Concerning assumptions for fossil fuel resources, references were made to the Global Energy Perspective prepared jointly by IIASA and WEC, as well as the study results by Hans-Holger Rogner upon which the former is based.

For conventional oil and gas resource assessments, we adopted study results by the Petroleum Producers' Association, Japan (assessments are for end of calendar year 1995) as the base for current study. Fossil fuels are exhaustible resources, and their potential supply amount declines in accordance with the actual annual demand (i.e., supply), whereas the potential resource availability of renewables such as solar, geothermal, wind, and the like increase as oil price increases. The potential resource availability of each energy source under BAU is given below. Different sets of assumptions are made for the nuclear expansion and new energy acceleration cases.

Table 2 Assumptions for energy resource endowments

Fossil energy	Proven reserves	Undiscovered reserves	Total	1997 Production
Oil Conventional GBBL	920	630	1,550	
Unconventional		2,800	2,800	
Total	920(R/P 38yr.)	3,430	4,350	24.4
Gas Conventional Tcf	4,800	4,500	9,300	
Unconventional		15,600	15,600	
Total	4,800(R/P 60yr.)	20,100	24,900	8.1
Coal Gt	640(R/P 130yr.)	2,640	3,280	5

Nuclear	Installed capacity MKW			Generation TWh		
	1990 Record	2100	Rates %	1990 Record	2100	Rates %
BAU	344	580	0.5	1,990	3,800	0.6
Expansion		2,570	1.8		16,900	2.0

Hydro	1990 Record	2100	Rates% 2100/1990
Generation Twh	2,105	3,150	0.4

Solar	Large scale	On grid PV	World total 1997 TWh
Resources TWh/yr	505,000	34,560	14,000

Biomass, other renewables	Resources	Exploitable resources (Max.)
Biomass Biogas MTOE /yr	6,372 MTOE	540
Hydrogen		960
Methanol		1,905
Generation		1,239
Wind TWh /yr	48,000	4,256
Ocean Wave TWh /yr	7,200	500
Ocean thermal energy conversion	330	9
Tidal	150	24
Ocean current	440	5
Geothermal TWh /yr.	46,000	930

3. Results of the BAU case

Main results of BAU case are shown below.

Table 3 Summary of BAU case

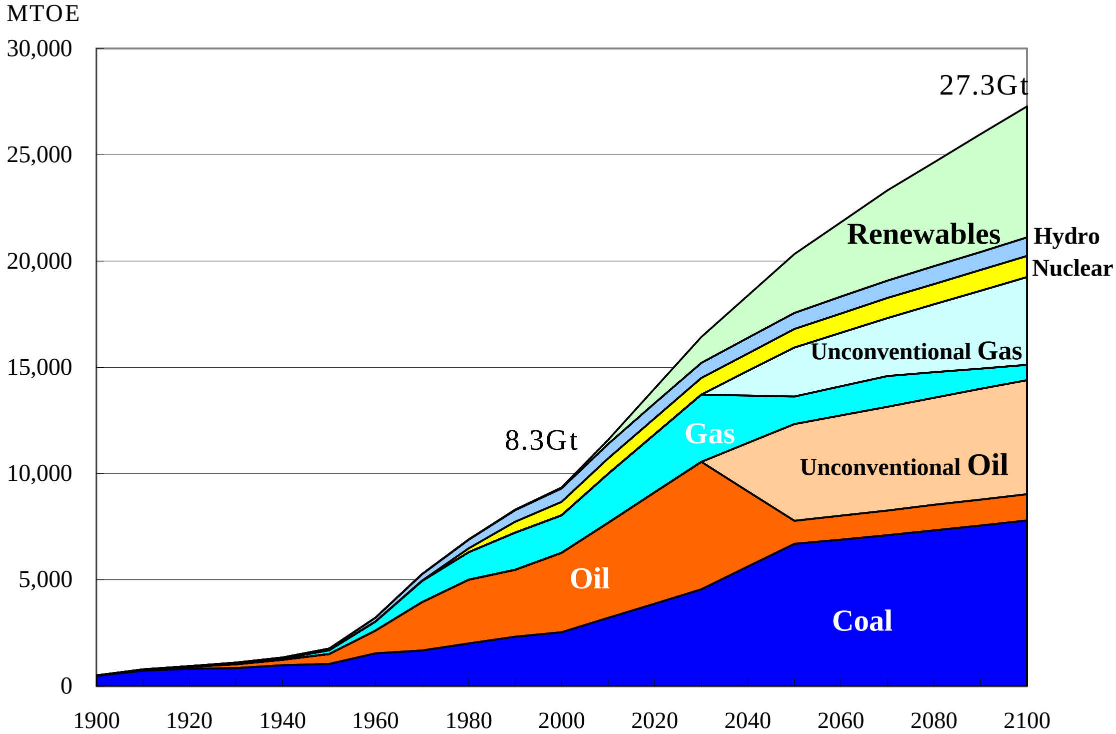
Population (billions)	1990 2050 2100	5.1 10.4 11.7
GDP (1990prices. US$ Trillion)	1990 2050 2100	20 92 225
GDP growth rates(%)	1990-2050 2050-2100	2.1 2.1
Per capita GDP(US$1000)	1990 2050 2100	4.0 8.9 19.2
Primary Energy Consumption (Gtoe)	1990 2050 2100	8.3 20.3 27.3
Primary energy intensity improvement (%/yr.)	1990-2050 2050-2100	1.0 1.1
Nuclear (Gtoe) (primary energy shares (%))	1990 2050 2100	0.51(6.2) 0.86(4.3) 0.99(3.6)
Renewables(Gtoe) (primary energy shares (%))	2050 2100	2.8(13.6) 6.2(22.6)
CO_2 emissions(Gcte)	1990 2050 2100	5.9 13.3 15.9
CO_2/TPES (Ct/toe)	1990 2050 2100	0.70 0.65 0.58

World population will be 11.7 billion in 2100, meaning an approximately two-fold increase over 1990. World GDP will grow by approximately 2% per year, from US$20 in 1990 to US$225 trillion in 2100 (1987 prices). As a result, per capita GDP will also grow, from US$ 4,000 in 1990 to US$19,000 in 2100. Many of the current developing countries will enter the ranks of the developed countries.

Primary energy consumption will significantly grow, from 8.3 billion tons oil equivalent (toe) in 1990 to 27.3 billion toe in 2100, meaning a more than three-fold increase. The proportion of renewables will increase to 23%, and the proportion of nuclear will grow somewhat. Despite the growth of these energy sources, CO_2 emissions will increase from 5.9 billion tce in 1990 to 15.9 billion tce, meaning an approximately 2.7 fold increase. CO_2 emissions per unit primary energy consumption will decline from 0.7 tce in 1990 to around

0.58 tce in 2100.

Fig.2 Primary Energy Consumption



The composition of primary energy sources (see Figure 3) indicates that the production of conventional oil will peak after 2030, and the production of new or unconventional oil begins around that time. However, in the reserve-rich Middle East region the production of conventional oil will continue to satisfy demand within the region. The production of conventional gas will peak after 2030 following the peak of oil, and the production of new or unconventional gas begins around that time.

Judging from current moves for decarbonization, one might think that coal consumption would be restrained, but BAU case simulation results indicate otherwise: consumption of coal, which has plentiful reserves, will start to increase around the time when conventional oil and gas reach their production peaks.

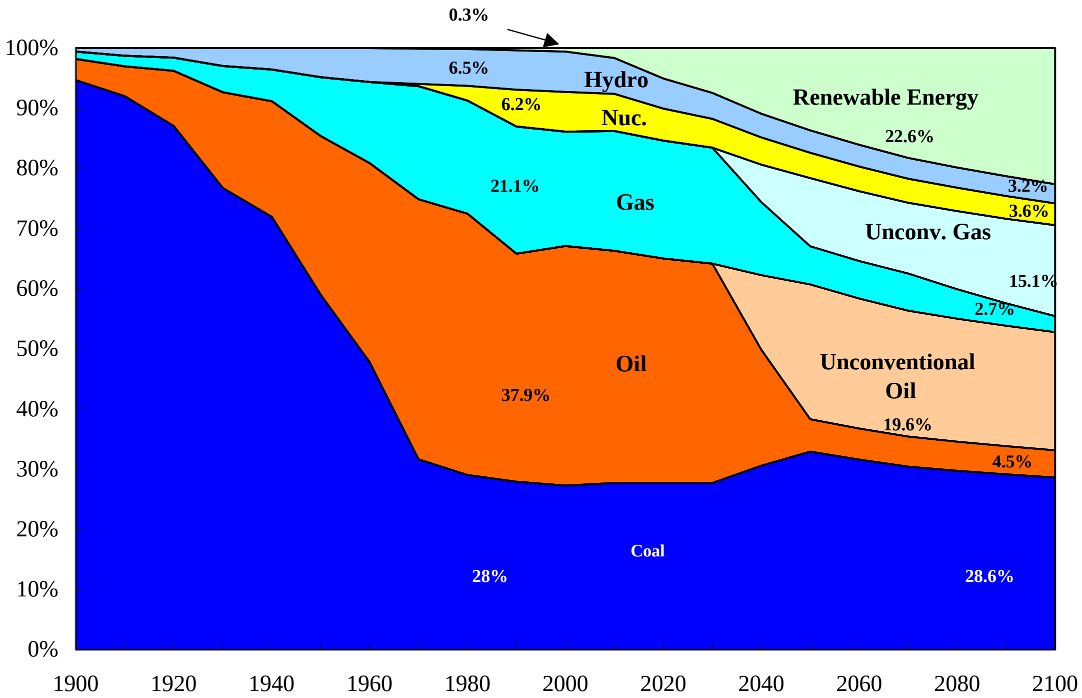
There are two factors affecting this increasing trend in coal consumption. First, it is difficult for some coal producing countries such as China and India to restrain coal consumption given their scarcity of conventional oil and gas. Second, the abundance of coal resources, coupled with progress in coal liquefaction and gasification technologies, will enable coal to compete with other energy sources in terms of price as well as end-use technical aspects. In terms of proportion, coal currently accounts for around 27% in the world total primary energy, but that proportion will grow to around 33% in 2050. Even in 2100, when massive amounts of new energy will be used, coal will presumably maintain its current proportion.

On the other hand, the proportions of oil will have declined so that in 2100 they will have dropped from their current 40% to 24%. Gas will remain more or less the same, but increase in terms of final demand. On the other hand, current proportion of renewables is 0.3%, but starting around 2030 their use will accelerate, and their proportion will be as large as 22.6% in 2100. Among renewables, utilization of biomass and solar energy will be prominent. Other renewables include geothermal, tidal, wind, and the like, but their amounts will remain at low levels.

Compiling BAU results for the current developed countries (current OECD countries, including Japan) and for the current developing countries shows that the proportion of OECD countries in world population will decline from 16% in 1990 to 8% in 2100. For GDP, the developed countries' proportion will decline from 69% in 1990 to 25% in 2100, and the proportion of the developing countries will be 75%. For primary energy consumption, the proportion of current OECD countries will decline from 50% to 21%, while that of the current developing countries will increase. As a result, in terms CO_2 emissions, the proportion of the developing countries will increase to 81%.

Thus, it is no exaggeration to state that the global warming problem is indeed the energy problem of the developing countries. Therefore, in considering measures to tackle global warming, international cooperation including technical transfer to the developing countries, and related institution building that includes, but is not limited to, the clean development mechanism (CDM) are extremely important.

Fig.3 Primary Energy Shares



Japan's proportion in world GDP was 14% in 1990, but it will decline to 3% in 2100. For primary energy consumption and CO_2 emissions, Japan's proportion will decline from 5.2% to 2.3%, and from 5.0% to 1.9%, respectively. Even if Japan restrains its CO_2 emissions, the effects will be insignificant in view of the global nature of the problem. Here again, it will be essential for Japan to formulate and implement global policy measures focusing on cooperation with developing countries.

Table 4 Developed & developing countries shares in the world(%)

		1990	2100
Population	Developed	16	8
	Developing	84	92
GDP	Developed	69	25
	Developing	31	75
Primary energy consumption	Developed	50	21
	Developing	50	79
CO_2 emissions	Developed	48	19
	Developing	52	81

Table 5 Japanese shares in the world(%)

	Record		Forecast					
	1975	1990	2000	2010	2030	2050	2070	2100
GDP	11.0	14.1	12.8	11.3	9.0	6.7	4.8	3.0
Population	2.8	2.4	2.1	1.8	1.4	1.1	1.0	0.8
Primary energy Consumption	5.4	5.2	5.4	4.6	3.5	2.9	2.6	2.3
Coal	3.3	3.1	2.5	1.9	1.2	1.7	1.5	1.3
Oil	8.4	7.6	6.9	5.7	4.4	4.4	3.8	3.0
Gas	1.1	2.7	3.4	3.0	2.7	3.7	3.7	2.9
Nuclear	6.1	9.4	15.0	15.9	15.2	14.6	13.8	13.3
Hydro	5.6	4.4	4.3	4.3	4.3	4.4	4.0	3.8
Renewables	0.0	7.1	3.3	2.5	1.9	1.4	1.3	1.1
CO_2 emissions	5.5	5.0	4.6	3.8	2.8	2.4	2.2	1.9

Table 6 BAU case summarized

GDP,Population etc

	1990	2000	2010	2030	2050	2070	2100	90/00	00/10	10/30	30/50	50/70	70/00
GDP(1987 price, US$ billion)	20,171	26,966	35,978	58,785	92,283	139,353	224,765	2.9	2.9	2.5	2.3	2.1	1.6
Population (million)	5,083	6,125	7,136	8,689	10,350	10,893	11,691	1.9	1.5	1.0	0.9	0.3	0.2
Per capita GDP (US$ 1,000)	4.0	4.4	5.0	6.8	8.9	12.8	19.2	1.0	1.4	1.5	1.4	1.8	1.4
Final Energy Demand	5,555	6,348	7,756	10,832	13,216	14,852	17,376	1.3	2.0	1.7	1.0	0.6	0.5
TPES/GDP (toe/US$)	412	347	322	279	220	167	121	-1.7	-0.7	-0.7	-1.2	-1.4	-1.1
TPES/person(toe)	1.6	1.5	1.6	1.9	2.0	2.1	2.3	-0.7	0.6	0.8	0.2	0.4	0.3

Final energy demand (Mtoe)

	1990	2000	2010	2030	2050	2070	2100	90/00	00/10	10/30	30/50	50/70	70/00
Solid	1,035	1,144	1,439	2,073	2,431	2,511	2,724	1.0	2.3	1.8	0.8	0.2	0.3
Liquid	2,606	3,012	3,523	4,806	5,723	6,290	7,170	1.5	1.6	1.6	0.9	0.5	0.4
Gas	1,055	1,114	1,394	1,876	2,343	2,691	3,349	0.6	2.3	1.5	1.1	0.7	0.7
Electricity	859	1,078	1,399	2,077	2,720	3,360	4,134	2.3	2.6	2.0	1.4	1.1	0.7
Total	5,555	6,348	7,756	10,832	13,216	14,852	17,376	1.3	2.0	1.7	1.0	0.6	0.5
(Percentage share)													
Solid	18.6	18.0	18.6	19.1	18.4	16.9	15.7						
Liquid	46.9	47.5	45.4	44.4	43.3	42.4	41.3						
Gas	19.0	17.6	18.0	17.3	17.7	18.1	19.3						
Electricity	15.5	17.0	18.0	19.2	20.6	22.6	23.8						

Primary energy supply (Mtoe)

	1990	2000	2010	2030	2050	2070	2100	90/00	00/10	10/30	30/50	50/70	70/00
Coal	2,324	2,551	3,211	4,556	6,692	7,093	7,799	0.9	2.3	1.8	1.9	0.3	0.3
Oil	3,148	3,719	4,476	5,983	1,094	1,171	1,241	1.7	1.9	1.5	-8.1	0.3	0.2
Inconventional Oil	0	0	0	0	4,554	4,882	5,359	0.0	0.0	0.0	0.0	0.3	0.3
Gas	1,754	1,779	2,306	3,170	1,289	1,438	724	0.1	2.6	1.6	-4.4	0.5	-2.3
Unconventional Gas	0	0	0	0	2,305	2,736	4,120	0.0	0.0	0.0	0.0	0.9	1.4
Nuclear	513	618	717	789	864	936	990	1.9	1.5	0.5	0.5	0.4	0.2
Hydro	543	627	690	705	756	816	873	1.4	1.0	0.1	0.3	0.4	0.2
Renewables	28	54	189	1,223	2,773	4,245	6,167	6.8	13.3	9.8	4.2	2.2	1.3
Total	8,310	9,349	11,588	16,426	20,326	23,316	27,273	1.2	2.2	1.8	1.1	0.7	0.5
(Percentage share)													
Coal	28.0	27.3	27.7	27.7	32.9	30.4	28.6						
Oil	37.9	39.8	38.6	36.4	5.4	5.0	4.5						
Inconventional Oil	0.0	0.0	0.0	0.0	22.4	20.9	19.6						
Gas	21.1	19.0	19.9	19.3	6.3	6.2	2.7						
Unconventional Gas	0.0	0.0	0.0	0.0	11.3	11.7	15.1						
Nuclear	6.2	6.6	6.2	4.8	4.3	4.0	3.6						
Hydro	6.5	6.7	6.0	4.3	3.7	3.5	3.2						
Renewables	0.3	0.6	1.6	7.4	13.6	18.2	22.6						

CO2 emissions

	1990	2000	2010	2030	2050	2070	2100	90/00	00/10	10/30	30/50	50/70	70/00
CO2 emissions (Mtoe)	5,853	6,553	8,120	11,168	13,269	14,327	15,855	1.1	2.2	1.6	0.9	0.4	0.3
Per capita CO2 emissions (toe)	1.2	1.1	1.1	1.3	1.3	1.3	1.4	-0.7	0.6	0.6	0.0	0.1	0.1
CO2 emissions/TPES (tce/t	0.70	0.70	0.70	0.68	0.65	0.61	0.58	0.0	0.0	-0.2	-0.2	-0.3	-0.2

Renewables(Mtoe)

	1990	2000	2010	2030	2050	2070	2100	90/00	00/10	10/30	30/50	50/70	70/00
Solar													
On grid	0.0	0.0	6.9	96.5	261.7	502.1	881.0	0.0	0.0	14.1	5.1	3.3	1.9
Large Scale	0.0	0.0	0.0	106.4	389.9	734.3	998.4	0.0	0.0	0.0	6.7	3.2	1.0
PV system	0.0	0.0	0.0	58.5	339.2	682.9	938.5	0.0	0.0	0.0	9.2	3.6	1.1
Thermal	0.0	0.0	0.0	47.9	50.7	51.4	59.9	0.0	0.0	0.0	0.3	0.1	0.5
Solar Total	0.0	0.0	6.9	202.9	651.6	1236.4	1879.4	0.0	0.0	18.4	6.0	3.3	1.4
Boomass	18.7	36.7	127.9	828.1	1797.0	2613.7	3868.0	14.4	13.3	9.8	3.9	1.9	1.3
Wind	0.9	5.7	29.5	130.7	238.6	296.7	309.4	20.4	17.8	7.7	3.1	1.1	0.1
Geothermal	8.3	11.7	21.2	45.5	58.9	64.8	70.9	3.5	6.1	3.9	1.3	0.5	0.3
Ocean	0.1	0.1	3.8	15.8	26.7	33.0	38.9	-0.2	39.0	7.4	2.6	1.1	0.6
Renewables Total	28.0	54.3	189.2	1223.1	2772.8	4244.6	6166.6	11.1	13.3	9.8	4.2	2.2	1.3

4. Comparison of cases

We shall now examine various case study results and compare them with BAU (see Table 7).

Table 7 Comparison of case study results(2100)

	BAU	Renewable	Nuclear	Conservation	Carbon tax	Renewable + Conservation	Renewable + Nuclear	Renewable Conservation Tax	Renewable Conservation Nuclear
GDP(1987prices, US$ billion)	224,765	224,792	225,180	227,382	221,943	227,869	226,501	224,226	227,869
Poplation(million)	11,691	11,691	11,690	11,679	11,719	11,685	11,694	11,713	11,685
Per capita GDP (US$ 1,000)	19.2	19.2	19.3	19.5	18.9	19.5	19.4	19.1	19.5
TPES/GDP(toe/US$)	121.4	121.4	123.9	85.8	112.9	85.4	126.4	80.5	87.6
TPES/person(toe)	2.3	2.3	2.4	1.7	2.1	1.7	2.4	1.5	1.7
Final energy demand (Mtoe)									
Solid	2,724	2,726	2,750	1,891	2,468	1,905	2,827	1,701	1,905
Liquid	7,170	7,175	7,239	5,051	6,443	5,088	7,440	4,505	5,088
Gas	3,349	3,352	3,381	2,399	2,982	2,413	3,470	2,116	2,413
Electricity	4,134	4,137	4,173	2,992	3,679	3,009	4,283	2,636	3,009
Total	17,376	17,390	17,543	12,333	15,571	12,415	18,019	10,958	12,415
(Percentage share)									
Solid	15.7	15.7	15.7	15.3	15.8	15.3	15.7	15.5	15.3
Liquid	41.3	41.3	41.3	41.0	41.4	41.0	41.3	41.1	41.0
Gas	19.3	19.3	19.3	19.5	19.1	19.4	19.3	19.3	19.4
Electricity	23.8	23.8	23.8	24.3	23.6	24.2	23.8	24.1	24.2
Total	100	100	100	100	100	100	100	100	100
Primary energy consumption (Mtoe)									
Coal	7,799	6,197	6,558	4,903	5,987	3,865	5,411	3,099	3,013
Oil	1,241	348	1,210	848	777	4	328	0	183
Unconventional Oil	5,359	2,567	4,626	3,180	3,995	1,478	2,220	1,350	974
Gas	724	721	729	491	720	490	744	482	488
Unconventional Gas	4,120	4,024	3,470	2,569	3,824	2,552	3,544	2,330	1,951
Nuclear	990	990	4,344	972	972	972	4,344	972	4,328
Hydro	873	873	873	813	873	813	873	813	813
Renewables	6,167	11,388	6,094	5,740	8,166	9,238	11,067	9,137	8,334
(Large Scale solar)	998	5,754	979	879	2,913	4,125	5,552	3,897	3,587
Total	27,273	27,106	27,903	19,516	25,315	19,412	28,532	18,184	20,083
(Percentage share)									
Coal	28.6	22.9	23.5	25.1	23.7	19.9	19.0	17.0	15.0
Oil	4.5	1.3	4.3	4.3	3.1	0.0	1.2	0.0	0.9
Unconventional Oil	19.6	9.5	16.6	16.3	15.8	7.6	7.8	7.4	4.9
Gas	2.7	2.7	2.6	2.5	2.8	2.5	2.6	2.7	2.4
Unconventional Gas	15.1	14.8	12.4	13.2	15.1	13.1	12.4	12.8	9.7
Nuclear	3.6	3.7	15.6	5.0	3.8	5.0	15.2	5.3	21.5
Hydro	3.2	3.2	3.1	4.2	3.4	4.2	3.1	4.5	4.0
Renewables	22.6	42.0	21.8	29.4	32.3	47.6	38.8	50.3	41.5
(Large Scale solar)	3.7	21.2	3.5	4.5	11.5	21.2	19.5	21.4	17.9
Total	100	100	100	100	100	100	100	100	100
CO2 emissions (Mtce)	15,855	11,238	13,633	9,878	12,409	6,787	9,900	5,786	5,331
Per capita CO2 emissions (tce)	1.36	0.96	1.17	0.85	1.06	0.58	0.85	0.49	0.46
CO2 emissions/TPES(tce/toe)	0.56	0.40	0.47	0.48	0.46	0.34	0.34	0.28	0.25

(1) New energy acceleration

	2050	2100
New energy (Gt)		
BAU	2.7(13.6%)	6.2(22.6%)
Renewable	4.2(20.7%)	11.9(42.0%)
CO_2 emissions(Gtce)		
BAU	13.3	15.9
Renewable	12.0	11.2

Large-scale solar will play the leading role in the accelerated use of new energy sources, but the use of wind and wave energy will also be accelerated. As a whole, new energy will account for 42% of world primary energy, thereby inducing decarbonization and reducing CO_2 emissions by 4.7 billion tce (30%) over BAU.

Table 8 Comparison of case study results: Renewables in 2100

	BAU	Renewable	Nuclear	Conservation	Carbon tax	Renewable + Conservation	Renewable + Nuclear	Renewable Conservation Tax	Renewable Conservation Nuclear
Solar	1,879	6,636	1,861	1,755	3,795	4,998	6,427	4,770	4,403
On grid	881	882	882	877	882	873	875	873	816
Large Scale	998	5,754	979	879	2,913	4,125	5,552	3,897	3,587
PV system	939	5,409	921	826	2,738	3,877	5,218	3,663	3,372
Thermal	60	345	59	53	175	248	333	234	215
Biomass	3,868	3,872	3,812	3,562	3,949	3,354	3,757	3,480	3,123
Wind	309	700	311	316	313	710	705	711	649
Geothermal	71	72	71	70	71	69	70	69	64
Ocean total	39	108	39	38	39	107	109	108	96
Wave	36	105	36	35	36	104	106	105	93
Ocean Thermal Energy Conv.	0.7	0.7	0.7	0.7	0.7	0.5	0.5	0.5	0.4
Tidal	1.7	1.7	1.7	1.8	1.8	1.8	1.7	1.9	1.7
Ocean Current	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Renewables total	6,167	11,388	6,094	5,740	8,167	9,238	11,067	9,137	8,334

(2) Energy conservation

	2050	2100	1990-2100 Annual energy improvement rates
Primary energy consumption (Gt)			
BAU	20.3	27.3	-1.1%
Conservation	16.0	19.5	-1.4%
CO_2 emissions (Gtce)			
BAU	13.3	15.9	
Conservation	9.7	9.9	

Under this case, progress in energy conservation technologies and the shift towards a less energy-intensive industrial structure will decrease energy elasticity particularly in developing countries. In view of energy savings, this case represents a 0.3% improvement in the annual average growth rate. Primary energy consumption in 2100 will be 30% lower than BAU. CO_2 emissions will be approximately 6 billion tce (38%) lower than BAU.

(3) Nuclear power expansion

	2050	2100
Installed capacity(MKW)		
BAU	510	580
Nuclear expansion	1,180	2,570
CO_2 emissions(Gtce)		
BAU	12.8	15.4
Nuclear expansion	11.9	13.1

In 1990 nuclear power generation capacity was 344 million kW and the nuclear proportion of total kWh generation was 18.3%. The proportion of nuclear of total electric power will decline to 6.9% in 2100 under BAU, whereas it will increase to 30.2% under the nuclear power expansion case. Although nuclear power expansion will reduce fossil fuel consumption for power generation, its contribution to the primary energy mix is not so large. As a result, nuclear's reduction of CO_2 emissions would be relatively small, at 2.3 billion tce over BAU.

(4) Carbon tax case

	2050	2100	1990-2100 Annual energy improvement rates
Primary energy consumption (Gt)			
BAU	20.3	27.3	-1.1%
Carbon tax	19.6	25.3	-1.2%
CO_2 emissions (Gtce)			
BAU	12.8	15.9	
Carbon tax	11.7	12.4	

Imposition of carbon taxes will have two effects. First is a price effect leading to energy conservation. Primary energy demand under the carbon tax case will be 7% less than BAU in 2100. The carbon tax case represents 0.1% annual improvement over BAU in view of energy savings.

Second, since carbon taxes are levied in accordance with the carbon content of each energy source, this case is advantageous to renewables. Renewables will increase to 4.3 billion toe in 2050, and to 8.8 billion toe in 2100. CO_2 emissions will be curtailed by 3.5 billion tce (22%) over BAU.

(5) Combined cases

Since the reduction in CO_2 emissions over BAU is not sufficient under the four independent cases, we have combined these cases and performed a number of simulation studies.

The figure below compares primary energy demand and CO_2 emissions under the following combinations: new energy acceleration + nuclear power expansion; new energy acceleration + energy conservation; new energy acceleration + energy conservation + nuclear power expansion; and new energy acceleration + energy conservation + carbon tax.

Fig.4 Primary Energy Consumption, Share of Renewables, CO_2 emissions in 2100

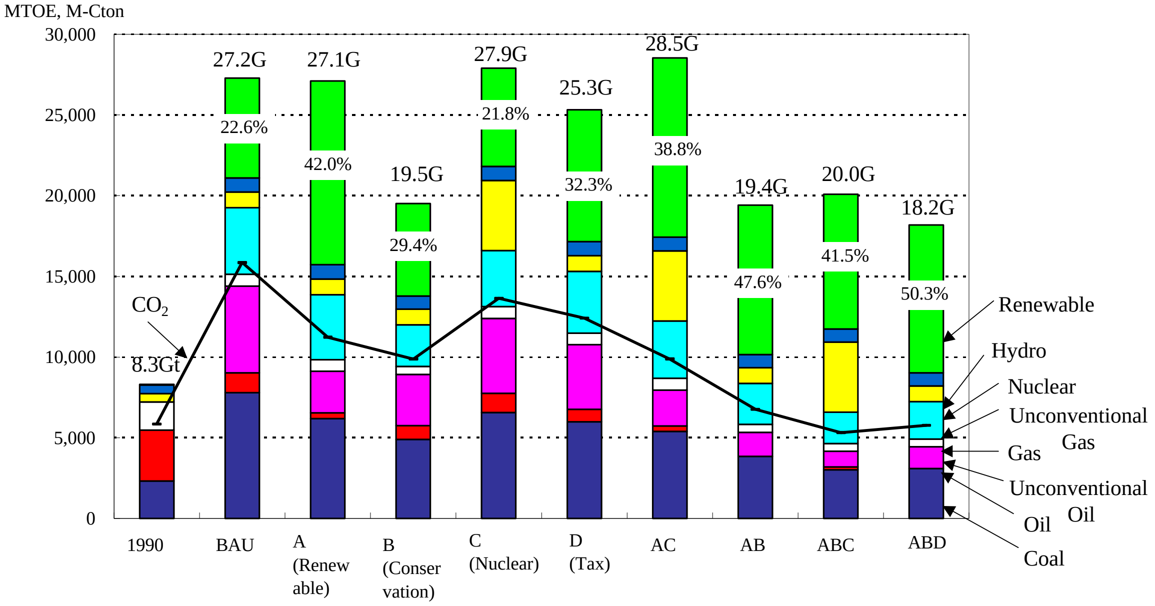


Fig.5 Primary Energy Consumption

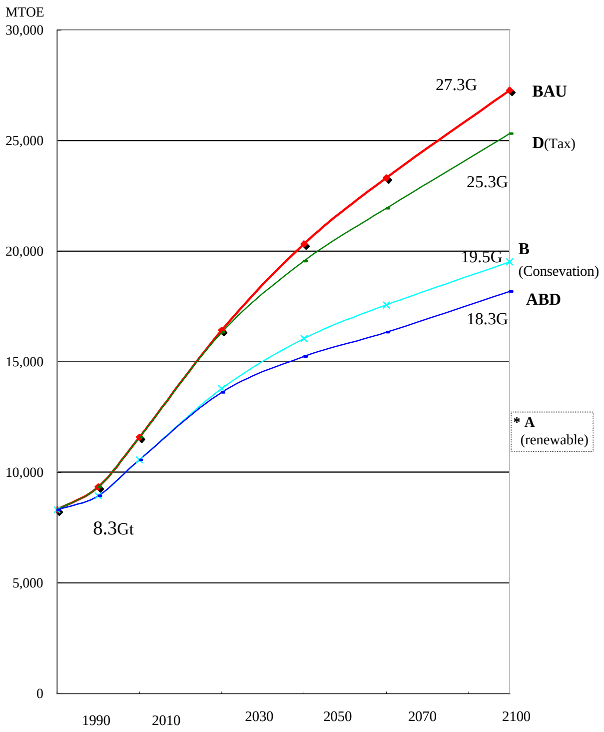
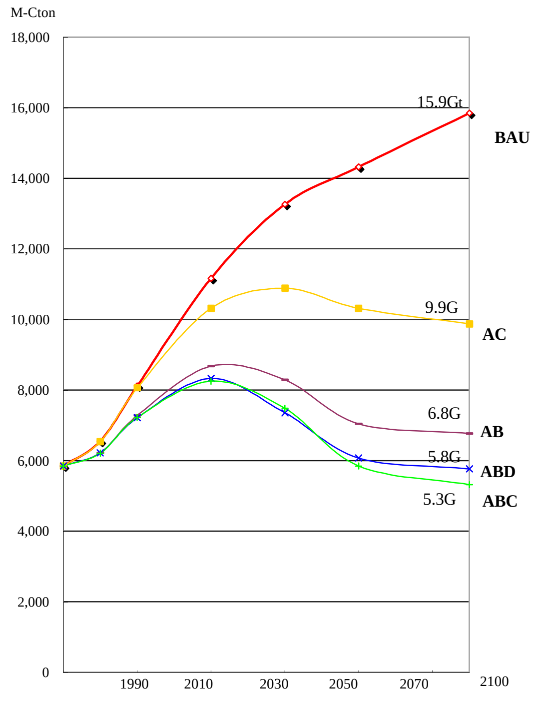


Fig.6 CO_2 emissions



5. Conclusion

Through simulation analyses we have shown the implications of various measures in restraining global warming. It is not the intent of this study to offer future predictions. Instead, it consistently theorizes factors such as economic growth, population, energy demand, fossil fuel reserves, potential renewable resource availability, costs of renewables and other factors, and econometrically illustrates future situations in order to indicate future options and possibilities. Considering the uncertainties associated with each factor, the model's solutions should be interpreted with some leeway. However, study results seem to imply that there are no simple and decisive measures for global warming, and that combinations of various measures is essential. Such measures may include, but are not limited to:

(1) Promotion of energy conservation in developed countries, along with transfer of energy conservation technologies to developing countries in order to promote energy conservation on a world scale (in this context, CDM, emissions trading schemes, and the like also warrant attention).

(2) Government leadership in establishing the positive cycle of "mass production and price reduction" in order to accelerate the development, and encourage utilization, of new and renewable energy sources. Many new and renewable energy sources, including large-scale solar, have massive resource potential. However, a long lead time is required to bring these sources on line. In terms of cost, these energy sources are not competitive with conventional energy sources at this moment. Efforts are needed in three areas in order to realize major cost reductions: (i) accelerated technical development for cost reduction; (ii) public sector support for investment in order to induce market entry at an earlier stage; and (iii) cooperation among business, academia, and government for promoting relevant projects. Once market conditions are made conducive to entry, the market mechanism should gradually assume the role hitherto assumed by the public sector.

(3) Introduction of environmental charges. Environmental charges are effective market-based measures to adequately allocate environmental conservation costs, and to accelerate energy conservation and decarbonization.

(4) Cleaner utilization of fossil fuels. Since coal reserves are abundant and distributed world-wide, cleaner utilization of this resource (including clean coal and technology to fix CO_2) is a realistic measure.

Japan is not only a country with ample experience and resources in terms of energy conservation and environmental protection technologies, but also a large economic power. Japan should and can play a leading role in the area of energy conservation and environmental protection. By doing so, this country can contribute to solving world environmental problems for a long time. This path also leads Japan toward sustainable development. Sooner or later, fossil fuel resources may dwindle. However, technology is an asset that will be with us always and never run out.

For questions, please contact info@tky.ieej.or.jp