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Global warming related carbon dioxide abatement proposals

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Abstract— The relationship between man-made CO_2 emission and atmospheric CO_2 concentration has been established. The factors that affect CO_2 reduction allotment and the impacts on future energy demand and supply were discussed, in order to help energy policy makers both in developed countries and in developing countries for understanding the fundamental constraint on energy sector resulted from global warming related CO_2 reduction, and hopefully in finding a common objective starting point to deal with global warming negotiation in energy sector, and to investigate the optimum stabilization goal and process acceptable to all sovereign countries that based on equity and applicability.

Keywords: global warming; carbon dioxide abatement; optimum CO_2 stabilization.

1 Introduction

Since the 1985 scientists' Villach meeting on global warming and its consequent climate change, tremendous international efforts have been done to study global warming and establish the action plan against it in an unprecedentedly short period (Houghton, 1990).

At present, developed countries account for 2/3 of the total CO_2 emission. But the situation might be reversed in a not too distant future. Developing countries might contribute at least 60% of the world CO_2 emission within 20 years due to the multiplied effect of rapid population and economic growth. This necessarily brings about a serious constraint on fossil fuel consumption and consequently on the whole energy sector. In this paper, an optimum stabilization path is proposed.

2 Man-made CO_2 emission and atmospheric CO_2 concentration

The main natural factors that affect the carbon cycle are mass transfer between the atmospheric CO_2 and the ocean surface water, uptake by photosynthesis and release by respiration (Houghton, 1990).

The material balance for the atmospheric CO_2 is given as follows:

$$\frac{M.W.(CO_2)}{M.W.(\text{air})} \times \int_{h=0}^{h=H} \rho(\text{h}) \times 4\pi(r+h)^2 \mathrm{d}h \times \frac{\mathrm{d}c}{\mathrm{d}t} = i - o \ , \tag{1}$$

where, C is atmospheric CO_2 concentration, ppmv; H is upper atmospheric limit, km; $M.W.(CO_2)$ is molecular weight of CO_2, g/gmol; $M.W.$(air) is molecular weight of air, g/gmol; r is radius of the earth, km; h is height from the earth surface, km; i is input of CO_2 into the atmosphere, bil.ton C/a, such as fossil fuel combustion, Cement manufacturing, land use change, volcanic eruption, and so on; o is ouput of CO_2 from the atmosphere, bil.ton C/a, such as absorption by ocean, uptake by terrestrial ecosystem; t is time, year; ρ_{air} is density of air, kg/m^3.

Assuming air density changes linearly and integrating the pre $-\frac{\mathrm{d}c}{\mathrm{d}t}$ term of Equation (1) from $h=0$ to $h=60$ km, we get the following expression and the numerical estimate of M as 2.39 bil.ton C/ppm.

$$M \times \frac{\mathrm{d}c}{\mathrm{d}t} = i = o, \tag{2}$$

where, M is carbon equivalent mass per unit change of atmospheric concentration, bil. ton C/ppm.

Since the natural emission also contributes to the CO_2 influx into the atmosphere, and there exists a natural disturbance term like volcanic eruption, the equation can be reconceptualized as follows:

$$M \times \frac{\mathrm{d}c}{\mathrm{d}t} = i^{*} - An \ , \tag{3}$$

where, i^{*} is man made emission; An is apparent natural absorption. An is defined as the difference between man-made emission and the increment in atmospheric CO_2.

To decrease the impact of the natural disturbance term, the above equation can be better expressed as an integrated form for the internal $t=t_0$ to $t=t_1$ with the assumption of constant natural absorption:

$$An = \frac{1}{t-t_0} \left\{ \int_{t_0+1}^{t} i^{*} \mathrm{d}t - M\left[\mathrm{C}(t) - \mathrm{C}(t_0) \right] \right\} . \tag{4}$$

Applying the data from "Energy Statistics Yearbook 1989" (UN,1990) to the derived expression, the apparent natural absorption An and the remaining ratio R of man-made CO_2 emission have been estimated since 1959.

Table 1 Apparent natural absorption and remaining ratio

	1959–1965	1965–1970	1970–1975	1975–1980
Accumulated CO_2 emission, btc	16.921	18.228	22.584	25.553
$C(t)-C(t_0)$, ppm	4.31	5.1	5.5	7.39
$M[C(t)-C(t_0)]$, btc	10.3009	12.189	13.145	17.6621
An, btc	1.1034	1.2078	1.8878	1.6451
R	0.6088	0.6687	0.582	0.6912

	1980–1985	1985–1988	Total
Accumulated CO_2 emission, btc	25.83	17.344	126.46
$C(t)-C(t_0)$, ppm	7.25	5.35	34.9
$M[C(t)-C(t_0)]$, btc	17.3275	12.7865	83.411
An, btc	1.7005	1.5192	1.484448[1]
R	0.6708	0.7372	0.659584[1]

$M=2.39$ btc(billion ton carbon) 1: average value

Three observations can be obtained from Table 1. First, the rate of increase in atmospheric carbon concentration has been accelerated along with increased fossil fuel consumption since the atmospheric CO_2 concentration was directly measured in 1959. Second, approximately 60%–70% of man-made CO_2 emission has been apparently added to the atmosperic carbon dioxide. Third, in relation to the second observation, the apparent natural CO_2 absorption capacity can be estimated as 1–2 bil. ton carbon per year for the past three decades.

From the above postulated CO_2 material balance, we may reasonably assume there would be a direct relationship between atmospheric CO_2 concentration and accumulated man-made CO_2 emission.

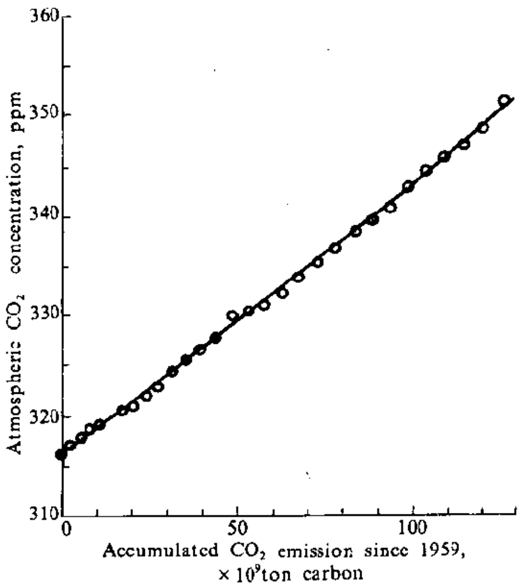

Fig.1 Accumulated CO_2emission vs. atmospheric CO_2 concentration

Accumulated man-made CO_2 emission (mil. ton C) vs. atmospheric CO_2 concentration (ppm) data since 1959 were fitted by various regression equation(Fig.1).

As shown in Table 2, the exponential regression fits excellently the data since 1959.

Table 2 Regression results

Type	Equation	R - square
Lin	$315.8806+0.0027\ X$	0.9983
Exp	$316.1523 \cdot \exp(8.1290E-6X)$	0.9988
Log	$255.5415+9.1429 \cdot \ln X$	0.7951
Pwr	$263.4011 \cdot X^{0.0276}$	0.8039

3 Setting the global goal and its fair distribution

3.1 Setting the goal

If possible, CO_2 emission should be conceptually equal to or less than natural absorption capacity. The stabilization path should be a technologically-economically feasible one without sacrificing the economic growth especially in the developing countries.

The apparent natural absorption is defined as the difference between man-made CO_2 emission and atmospheric CO_2 increase. It is estimated to be in the range of 1.2 to 1.9 bil.ton carbon per year. Therefore, idealistically the current level of 6 bil.ton carbon should be reduced to approximately 1/3 of the present level. But, it would be a good idea to hold even this tentative goal until we finish reviewing the long term impact on future energy supply of the major proposed scheme to stabilize CO_2 emission in the next section.

3.2 Review on the major proposed scheme to stabilize CO_2 emission

Whatever the reduction level, it is most critical how to distribute the burden between the sovereign countries.

Being the most fair single criterion, population prorated apportioning is unlikely to be practicable. From the point view of developed countries, the current emission or a GDP-based allocation is more acceptable than the sole population-based allocation. No doubt, a criterion is much more favorable to a specific country than the other.

Therefore, this is a necessary step to identify the factors affecting each individual country's interest explicitly. Only after we clearly understand the short-term and long-term implications on each individual country's interest, we could start the meaningful negotiation to reduce the CO_2 emission on a global scale.

If we define $X(t)_i$ as country i's BAU(business as usual) carbon emission in year t, $X(t)_i$ can be given as follows:

$$X(t)_i = P(t)_i \times \text{GDP}(t)_i \times E(t)_i \times C(t)_i \ , \tag{5}$$

where population: $P(t)_i = (1+a)P(t_o)_i$, mil.; per capita GDP: $\text{GDP}(t)_i = (1+b)\text{GDP}(t_o)_i$, US$; energy use per GDP: $E(t)_i = (1+c)E(t_o)_i$, TOE/US$ 1000; carbon intensity: $C(t)_i = (1+d)C(t_o)_i$, ton carbon/TOE in energy mix.

Then global carbon emission $Y(t)$ is the sum of emissions from all the countries.

$$Y(t) = \Sigma X(t)_i \ , \tag{6}$$

where i is country code; t_o is reference year; t is target year.

To give practical insight for the underlying the differencc between alternatives, all the countries (regions) are categorized as three groups: group A, developed countries including OECD, Eastern Europe and the former Soviet Union; group B1, NIES (newly industrializing economic states) including Brazil, Mexico, Korea, Taiwan, Singapore and Hong Kong; group B2, other developing countries.

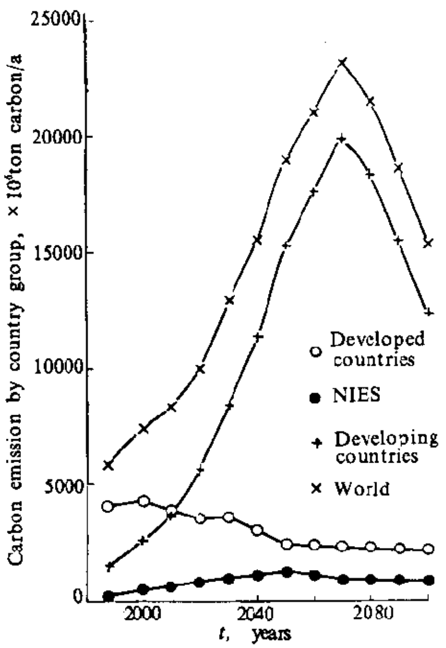

Fig.2 Carbon emission by country group

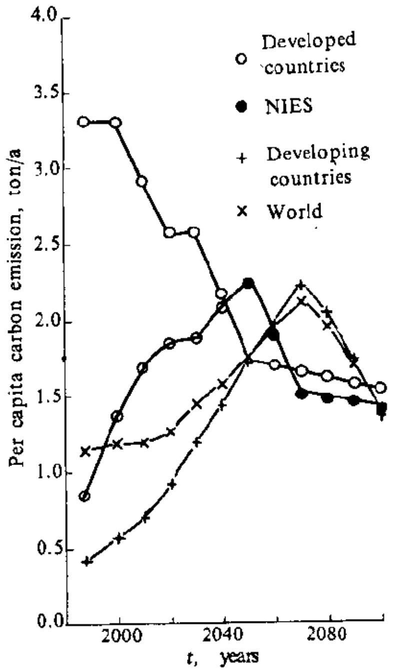

Fig.3 Per capita carbon dioxide emission

The carbon dioxide emission from the energy sector was estimated up to the end of 21st century based on the above assumption.

Fig.2 and Fig.3 show the results of our proposed model simulation.

This implies that even though developed countries consist about 60% of global emission at the moment, developing countries would consist the majority of CO_2 emission in the near future.

But in terms of per capita emission, parity would be achieved only after the mid 21st century.

Alternative I: stabilization based on current emission

$$DX = \text{amount of sacrifice at year } t = X(t)_i - X(t_o)_i$$
$$= [(1+a)(1+b)(1+c)(1+d)-1]P(t_o)_i \cdot \text{GDP}(t_o)_i \cdot E(t_o)_i \cdot C(t_o)_i$$

Accumulated sacrifice can be obtained from integration of DX for the interval of t_o and t.

$$X = \int_{t_o}^{t} DX\mathrm{d}t$$

$$= \int_{t_o}^{t} \{[(1+a)(1+b)(1+c)(1+d)-1]P(t_o)_i \times \text{GDP}(t_o)_i \times E(t_o)_i \times C(t_o)_i\}\mathrm{d}t. \quad (7)$$

It is obvious from Table 3 that developing countries would sacrifice their future CO_2 emission far more than developed countries by the current emission level based stabilization

Table 3 Determining factors estimation

Factor	2000			2010		
	A	B1	B2	A	B1	B2
$1+a$, population growth	1.0579	1.2184	1.2727	1.0879	1.3674	1.4683
$1+b$, economic growth	1.3767	1.7959	1.5645	1.797	2.6583	2.2717
$1+c$, energy intensity	0.823	0.895	0.8677	0.646	0.79	0.7354
$1+d$, carbon intensity	0.8796	0.9902	1	0.759	0.9394	1
Factor	**2030**			**2050**		
	A	B1	B2	A	B1	B2
$1+a$, population growth	1.1504	1.7221	1.9544	1.1504	1.8914	2.4614
$1+b$, economic growth	2.1927	4.7548	4.9775	2.6755	8.101	8.903
$1+c$, energy intensity	0.581	0.579	0.6619	0.523	0.521	0.5956
$1+d$, carbon intensity	0.6071	0.7994	0.8619	0.3721	0.6228	0.7727

It is well attributed to the fact that developing countries' future economic and population growth potentials would be much higher than those of developed coutries'. Therefore, if we decide to stabilize CO_2 emission based on current level, it follows that developing coutries' future economic growth would be seriously limited due to energy supply shortage.

There is another important aspect, namely, the huge potential gap of future CO_2 emission sacrifice between developing countries and developed countries. Developed countries would be able to reduce energy intensity and carbon intensity far more than developing countries due to their high technology-based industrial structure.

Alternative Ⅱ GDP-based allocation

$$X(t_o)_i = Y(t_o)/[\Sigma \mathrm{GDP}(t_o)_i \times P(t_o)_i] \times \mathrm{GDP}(t_o)_i \times P(t_o)_i \ , \tag{8}$$

$$DX = [(1+a)(1+b)(1+c)(1+d) \times E(t_o)_i \times C(t_o)_i - Y(t_o)/\sum \mathrm{GDP}(t_o)_i \times P(t_o)_i] \times_i \mathrm{GDP}(t_o)_i \times P(t_o)_i \ . \tag{9}$$

The amount of future CO_2 emission sacrifice is determined by the difference between current carbon output per GDP multiplied by the growth potential factors and current world average carbon output per GDP.

Alternative Ⅲ : Population-prorated apportioning

$$DX = [(1+a)(1+b)(1+c)(1+d) \times \mathrm{GDP}(t_o)_i \times E(t_o)_i \times C(t_o)_i \frac{\sum X(t_o)_i}{\sum P(t_o)_i}] \times P(t_o)_i \ . \tag{10}$$

Similarly, the amount of future CO_2 emission sacrifice is determined by the difference between current carbon output per capita multiplied by the growth potential factors and cuurrent world average per capita CO_2 emission.

Developed countries obviously would be benefited from GDP or present level-based apportioning, but even in the case of population prorated apportioning developed countries would face the least impact on their future energy supply once they pay a drastic short term restructuring cost. Even in the most favorable case of population prorated apportioning developing countries surprisingly might become the biggest loser eventually due to their strong population growth and relatively inferior energy and carbon intensity.

3.3 Eligible stabilization path

It is quite certain from Fig.2 that any attempt to stabilize global CO_2 emission at 1988 level or ever below looks like impractical. It is also clear that any one of the discussed allocation methods cannot be acceptable to certain countries. There is a serious conflict of interests. Thus, the pathway to achieve stabilization of CO_2 emission should be flexible and self-designed, reflecting each individual country's particular situation.

Fig. 4 represents the suggested path to achieve stabilization of CO_2 emission level approximately equal to the 2/3 of the 1988 level until the end of 21st century, conceptually equal to the natural absorption level.

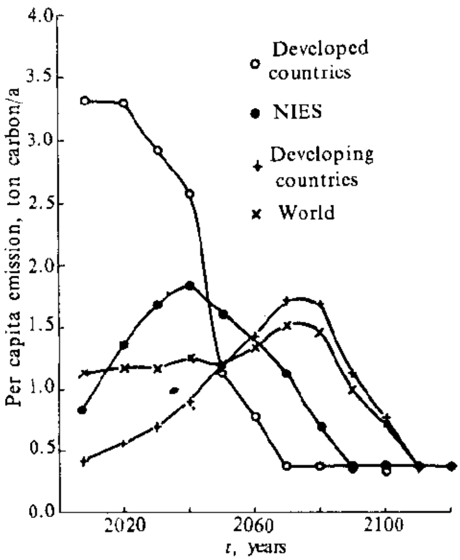

Fig.4 Suggested emission stabilization path

Here the natural absorption rate of CO_2 was assumed to be increased by 2 bil.ton carbon per year through reforestation. It was estimated that an equivalent amount of 539.5 mil. ha of temperate zone forestry was necessary to raise the natural absorption rate by 2 bil. ton carbon per year, where the unit absorption capacity was assumed as 1.5 ton carbon per hactre per year (World Resources Institute, 1991). It means global forest area should be increased by 13.32% comparing with 1988's 4.049 bil.ha.

Basically, all the countries should reach the same per capita CO_2 emission ultimately, but has different time table to get there according to each country's development stage.

Developed countries would reduce their per capita CO_2 emission to the 1988 world average per capita until 2030, and further reduce to the 1/3 of 1988 level until 2050, and thereafter maintain the total emission.

Developing countries would reduce their per capita CO_2 emission to the 1988 world average per capita emission until 2070, and further reduce to the 1/3 of 1988 level until 2090. Among developing countries, some countries like NIES might reduce their per capita emission to the 1988 world average level until 2050, and further reduce to the 1/3 of 1988 level until 2070, and similarly keep the total emission thereafter.

4. Exponential regression result application

According to the derived relationship between the accumulated man-made CO_2 emission and atmospheric CO_2 concentration, the future carbon emission budget to allow atmospheric CO_2 concentration to reach a certain level, or the atmospheric CO_2 concentration resulted from the proposed path can be estimated (Fig.5).

Adopting this path, it may be expected that the global CO_2 emission decreases to approximately 2/3 of 1988 level until the end of next century and atmospheric CO_2 concentration would reach approximately three times of preindustrial revolution level (3 × 278 ppm)

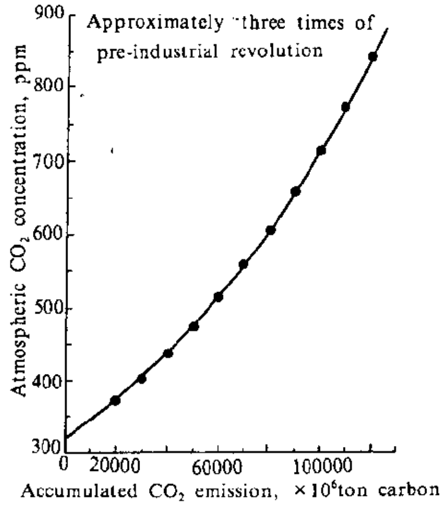

Fig. 5 Projection of CO_2 concentration as a function of accumulated emission

5 Discussion

It seems almost impossible to stabilize CO_2 emission approximately at a level of 1988's 6 bil. ton carbon per year in the near future. Only the developed countries would be able to lower the total CO_2 emission down to 1988's level until the middle of 21st century.

Developing countries, mainly due to their economic growth, can not but increase CO_2 emission more than 5 times than 1988's level until 2070. This is nothing but a reflection of today's world which majority of mankind just marginally survive on less than a 1/10 of developed countries' per capita income.

Provided that population growth could reach a standstill until the end of 21st century and economic growth would continue to achieve better living standards, the possible way to reduce the total CO_2 emission would be to lower the carbon intensity in energy mix and to enhance the overall efficiency of energy.

In relation to the overall energy efficiency, it should be recognized that even though industrial structure change toward a less energy intensive and high-value-added industry must be critical to improve an individual country's overall energy efficiency in terms of consumed energy per unit GDP, it could not contribute to reduce the global CO_2 emission as long as the production technology itself remains the same. In other words, if an energy intensive industry moves from a developed country to a developing country without improving the technology, it would be a just redistribution rather than a real reduction in CO_2 emission.

At the moment, energy conservation has quite good potential to decrease total energy demand. Probably energy conservation must have a certain limit imposed by physical law and be saturated as time goes by. That is why material recycling is crucial to minimize total energy demand of a society and consequently to enhance the overall energy efficiency. Especially the energy intensive raw materials such as iron, non-ferrous metals, glass, paper, and plastics should be recycled as much as possible. A drastic change in energy supply for next couple of decades is inevitable to stabilize the CO_2 emission until the end of 21st century.

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