RESPONSE STRATEGIES FOR STABILIZATION OF ATMOSPHERIC COMPOSITION

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Summary

A time scale of 100 years or more is characteristic for interactions between human

activities, resultant greenhouse-gas (GHG) emissions, changes in the atmospheric concentrations of GHGs, their influence on changes in the radiative balance of the planet, and, hence, climate change. The nature of these interactions is still highly uncertain, and the uncertainties in future socioeconomic development and technological progress make it impossible to predict precise quantitative levels of GHG emissions for the long-term future. Therefore, illustrative alternative pathways, called emissions "scenarios," are used to test the cost-effectiveness and synergies between various policies.

Of all the many available emissions reduction measures in the energy sector, agriculture and forestry, and industry, no one single measure will be sufficient for the timely development, adoption, and diffusion of mitigation options, sufficient to stabilize the atmospheric composition. Rather a combination of measures, a portfolio of the many "win-win" solutions available will most likely be adopted, an optimal mix of which will vary from country to country. This will include appropriate economic and regulatory frameworks for consumers and investors, which will promote cost-effective actions, leading-edge technologies, and "no-regrets" solutions.

Anthropogenic GHG emissions from many different sources have already altered the atmospheric composition and increased the atmospheric concentrations of GHGs significantly since the beginning of industrialization in the eighteenth century. Carbon dioxide from past emissions is currently responsible for more than 60% of the enhanced greenhouse effect that is due to human activities, methane contributes another 15%–20%, and nitrous oxide, chlorofluorocarbons, tropospheric ozone and other gases contribute the remaining 20%.

Future international agreements will complement recent efforts (e.g. FCCC, Kyoto Protocol) and will have to take a more long-term view. They will have to address the issues of providing the necessary financial resources to developing countries for controlling their rapidly increasing GHG emissions.

1. Introduction

One of the most profound challenges facing humanity today is the prospect that economic activities and the resultant emissions of gases will lead to global warming, with significant impacts on the ecosystem and on the way of life on this planet.

A time scale of 100 years or more is characteristic for interactions between human activities such as energy production and use, resultant greenhouse-gas (GHG) emissions, changes in the atmospheric concentrations of GHGs, their influence on changes in the radiative balance of the planet, and, hence, climate change. The nature of these interactions is still highly uncertain, and the uncertainties in demographic and economic development and technological progress make it difficult, if not impossible, to predict quantitative levels of GHG emissions and atmospheric concentrations for the long-term future. Therefore, instead of predictions, illustrative alternative pathways, what are called emissions "scenarios" are developed by the research community to illustrate the main relationships under given assumptions.

Despite the remaining uncertainties, the second assessment report (SAR) of the Intergovernmental Panel on Climate Change (IPCC) concluded in 1996 that the "balance of evidence suggests that there is discernible human influence on global climate." In particular, since complex systems (such as nature) sometimes experience sudden and chaotic changes it is reasonable to use the precautionary principle and to hedge actions against climate change now. Many kinds of policies are necessary to enable and to promote a large range of emissions reduction measures, and future response strategies will most likely adopt a portfolio of the many "win-win'' solutions available. This portfolio will include an appropriate economic and regulatory framework for consumers and investors that promotes cost-effective actions, leading-edge technologies, and "no-regrets" solutions.

Carbon dioxide (CO_2) from past emissions is currently responsible for more than 60% of the enhanced greenhouse effect that is due to human activities (SAR, 1996). The second most important anthropogenic greenhouse gas (GHG) is methane. Methane (CH_4) from past emissions currently contributes about 15%–20% of the enhanced GHG effect. Nitrous oxide (N_2O), chlorofluorocarbons (CFCs), tropospheric ozone and other gases contribute the remaining 20% of the enhanced greenhouse effect. These anthropogenic emissions have significantly altered the atmospheric composition. Whereas CO_2 levels have varied by less than 10% during the 10 000 years before industrialization, since 1800 these levels have risen by almost 30%. Also N_2O levels have risen by 15% during the same timeframe, whereas the rapid rise of CH_4 emissions started more recently than that of CO_2. The shorter atmospheric lifetime of CH_4, compared to CO_2, means that CH_4 emitted during the 1980s is expected to have had about 80% of the impact of the decade's CO_2 emissions, but only 30% over the 100-year period 1990–2109. The ozone precursors nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane hydrocarbons or volatile organic compounds (NMVOCs) are not GHGs themselves but are involved in a complex chain of reactions in the troposphere that lead to the production of ozone, an important GHG.

These emissions have already changed the global energy budget by about 2.5 watts per square meter, which is equal to about 1% of the net incoming solar energy content. Added up over the earth's entire surface, it amounts to an energy content of 950 billion tonnes of oil (Gtoe) annually, which is more than 100 times the world's current annual rate of commercial energy consumption (UNEP, 1999).

Recently, GHG emissions mitigation scenarios have been used to study cost-optimal strategies and cross benefits from individual emissions reduction measures, and to illustrate alternative future paths to stabilizing atmospheric GHG concentrations. These studies show that emissions reduction efforts will be needed both on the national and the international scale. A first example is the United Nations Framework Convention on Climate Change (UNFCCC) that was signed in 1992. It sets as a goal the stabilization of GHG concentrations in the atmosphere at a level that "does not interfere dangerously with the climate system." More concrete and binding quantitative targets are proposed in its Kyoto Protocol. To achieve these targets, financing actions and global cooperation on technologies may be of paramount importance.

The main purpose of this article is to discuss the main drivers for GHG emissions and possible cost-effective emissions reduction measures from the literature that aim to achieve a stabilization of atmospheric composition.

2. Greenhouse-Gas Emissions Drivers and Baseline Scenarios

To assess the usefulness and the costs of future GHG emissions reduction measures, one needs to understand the evolution of the drivers of these GHGs, and the nature of the links between the drivers and emissions. Usually, researchers create emissions scenarios (i.e. alternative future pathways) that describe the resultant future GHG emissions trajectories quantitatively. Baseline scenarios do not include specific climate policies, whereas mitigation scenarios aim to illustrate the outcome where climate policies are being introduced.

In any case, emissions scenarios will often adopt a long-term perspective (of the order of a century) because of the long-term nature of interactions between human activities, GHG emissions, and potential climate change. Taking into account the many uncertainties of a highly complex set of interactions, any scenario analysis will usually adopt a long view of a multiplicity of alternative future possibilities to assess response strategies for stabilizing atmospheric composition.

The first quantitative model assessments for the whole world were made in the 1970s to assess resource constraints. Then, from the end of the 1980s and in the 1990s, integrated global model assessments increasingly started to respond to new concerns about sustainability, local acidification, and GHG emissions. The heart of most of these models was the global energy sector, because of its prominent role as an emitter of GHGs. In the 1990s, such research work focused on the timing, location, and extent of responses necessary to stabilize atmospheric concentrations at a given level.

2.1. Energy-Related Carbon Dioxide Emissions and the Kaya Identity

Currently, the most important contributor to possible human-induced global warming is energy-related CO_2, which is emitted during energy production and use. Therefore, nearly all recent integrated assessment models quantify future CO_2 emissions under various assumptions of future development. To differentiate between the main drivers for energy-related CO_2 emissions, CO_2 emissions are often expressed with what is called the Kaya identity (Kaya, 1990) in terms of population, gross domestic product (GDP) per capita, energy intensity (primary energy per unit of GDP in a society), and carbon intensity (energy-related CO_2 emissions per unit of primary energy used):

$$CO_2 \text{ emissions} = \text{population} \bullet (\text{GDP per capita}) \bullet (\text{energy/GDP}) \bullet CO_2/\text{energy}) \qquad (1)$$

Component growth rates are additive in identity (1). For example, since the mid-nineteenth century, world energy-related CO_2 emissions have increased by about 1.7% per year. This growth rate can be roughly decomposed into a 1% growth in population, a 2% growth in GDP per capita, a 1% decline in energy intensity of world GDP, and a 0.3% decline in the carbon intensity of primary energy (SAR, 1996; Nakicenovic et al., 1993). In other words, in the past, population and average income have grown much faster than the energy efficiency has increased, than the economic structure has shifted, and than switching to less carbon-intensive energy fuels has proceeded (e.g. coal with the highest carbon content per unit of energy was replaced by oil, then by gas, and also by zero-carbon options such as wind.). This has led to ever-increasing energy-related global CO_2 emissions since the nineteenth century (see Figure 1). Most likely, this trend will continue in the twenty-first century, provided no human intervention in the form of climate policies will occur.

A set of GHG emissions scenarios was prepared for the first assessment report of the IPCC in 1990. In 1992, an updated version of these alternative emissions scenarios for 1990 to 2100 were published (Pepper et al., 1992). These IS92 scenarios have been used as preferred reference scenarios. The main drivers from the right-hand side of Equation (1) are presented for the IS92 scenarios in Table 1. For comparison, this table also provides the WEC-IIASA scenarios (Nakicenovic et al., 1998), and four selected scenarios from a more recent modeling effort by an international team (Nakicenovic (ed.), 2000).

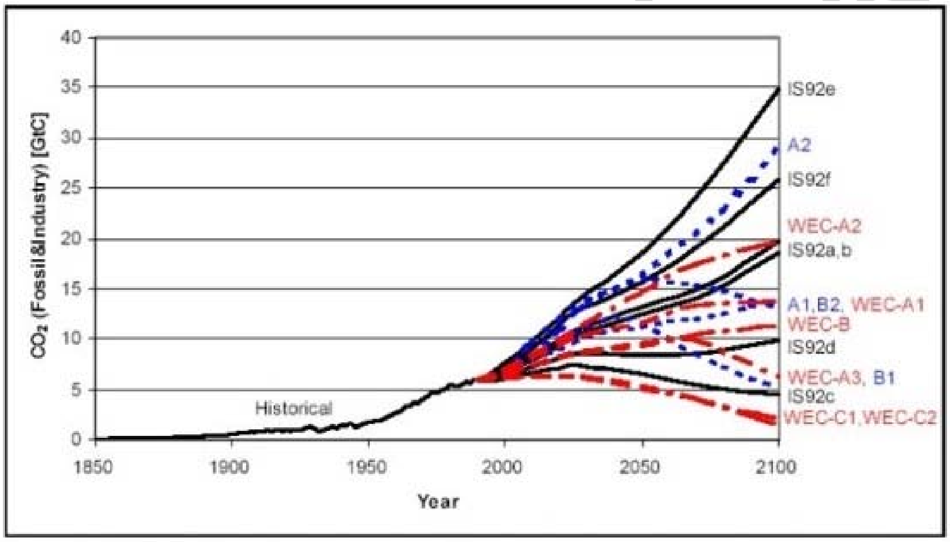


Figure 1. Global CO_2 emissions from fossil fuel combustion and cement production. The wide range of CO_2 trajectories for 1990–2100 is the result of three sets of future emissions scenarios (see Table 1)
(*Sources*: W.J. Pepper et al., *Emission Scenarios for the IPCC* (Washington, D.C.: U.S. EPA, 1992); N. Nakicenovic et al., *Global Energy: Perspectives* (Cambridge, U.K.: Cambridge University Press, 1998); N. Nakicenovic, ed. (2000))

In other words, Table 1 presents an overview of the possible relative importance of the various factors influencing future energy-related CO_2 emissions. The 16 scenarios in Table 1 cover a wide range of combinations of socioeconomic development possibilities, energy demand patterns, energy efficiencies, lifestyles, and technological progress in low-carbon technologies. Rapid economic growth (e.g. IS92e, A1 and B1) goes in parallel with rather fast energy intensity improvements, but not necessarily with rapid carbon intensity declines. Fast carbon intensity improvements due to fuel switching occur mainly in policy scenarios such as the WEC-IIASA C1, WEC-IIASA C2, and the IS92d. In any case, it seems clear from Table 1 that, contrary to in the past, economic growth (and technological progress) will be the main global driver of CO_2 emissions increases, and population increases will be of much less importance in the twenty-first century. For example, in the high economic growth case A1, global gross product increases by a factor of 26 from 1990 to 2100, whereas population increases in the worst (highest) case (IS92f) by a factor of only three.

Global long-term energy and emissions scenarios												
Scenario series	IS92 series[b]					WEC-IIASA[c]			Selected recent emissions scenarios[d]			
Scenario names	IS92a, IS92b	IS92c	IS92d	IS92e	IS92f	A1,A2,A3	B	C1,C2	A1	A2	B1	B2
Population (billion)												
1990	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3
2050	10.0	7.8	7.8	10.0	12.5	10.1	10.1	10.1	8.7	11.3	8.7	9.4
2100	11.3	6.4	6.4	11.3	17.6	11.7	11.7	11.7	7.1	15.1	7.1	10.4
Growth of gross world product per capita (% per year)												
1990–2050	1.5	0.8	1.7	2.1	1.3	1.6	1.0	1.1	2.8	1.0	2.3	1.8
1990–2100	1.6	0.9	1.8	2.3	1.4	1.7	1.3	1.4	2.7	1.3	2.2	1.6
Primary energy intensity[e] (% change per year)												
1990–2050	-0.9	-0.6	-0.7	-1.1	-0.9	-0.9	-0.8	-1.4	-1.5	-0.5	-1.8	-1.3
1990–2100	-1.0	-0.7	-0.8	-1.2	-1.0	-1.0	-0.8	-1.4	-1.3	-0.7	-2.2	-1.0
Carbon intensity[f] (% change per year)												
1990–2050	-0.5,-0.4	-0.8	-1.3	-0.5	-0.4	-0.6, -0.2, -0.9	-0.5	-0.9, -1.0	-0.5	-0.2	-0.3	-0.5
1990–2100	-0.4,-0.4	-0.8	-0.9	-0.4	-0.3	-0.7,-0.4,-1.4	-0.6	-1.0-1.8	-0.9	-0.1	-0.5	-0.5

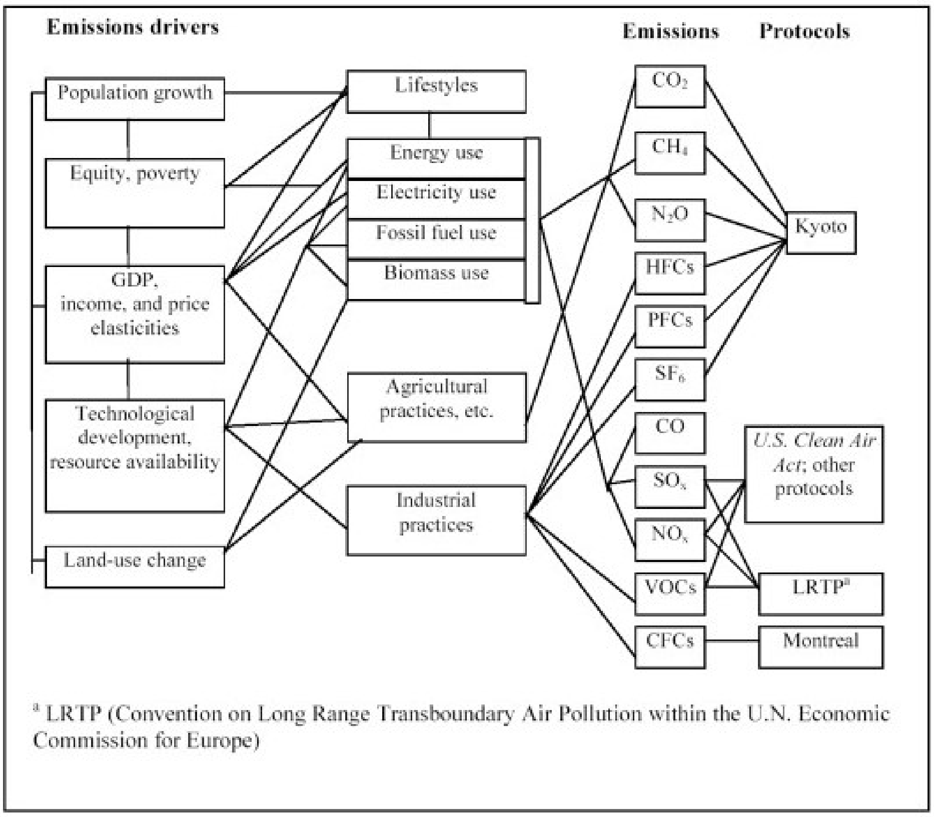
[a] Growth rates in this table were calculated as "exponential growth rates"
[b] Pepper et al., 1992.
[c] Nakicenovic et al., 1998.
[d] Nakicenovic, ed., 2000.
[e] Primary energy intensity: amount of energy used relative to GDP in an economy
[f] Carbon intensity: amount of CO_2 emissions per unit of primary energy used. This table refers only to energy-related CO_2.

Table 1. Overview of some long-term scenarios of energy development and GHG emissions for the twenty-first century
(*Sources*: W.J. Pepper et al., *Emission Scenarios for the IPCC* (Washington, D.C.: U.S. EPA, 1992); N. Nakicenovic et al., *Global Energy: Perspectives* (Cambridge, U.K.: Cambridge University Press, 1998); N. Nakicenovic, ed., (2000))

The energy-related CO_2 emissions resulting from the combination of drivers in Table 1 span a very wide range (see Figure 1). Whereas fossil dominated scenarios (IS92e, f, a, b, WEC-A2, A2, B2) show CO_2 emissions growing throughout the twenty-first century in a nearly linear fashion, some scenarios (A1, B1, WEC-C1, WEC-C2, WEC-A3, IS92c) show a peak (around 2030–2060) and a subsequent decline of emissions thereafter, due to fundamental changes in the energy system.

2.2. Scenario Driving Forces

Box 1 illustrates some of the interactions between socioeconomic development and the environment. Of course, Box 1 is a very simplified illustration of the complex network of multiple links; however, it may be useful as a roadmap across the following discussion of the multitude of drivers, different gases, and potential emissions reduction measures. First, the major driving forces of past and future anthropogenic GHGs are presented.



Box 1. Illustration of logical relationships between some emissions drivers and emitted gases: the greenhouse gases: CO_2, CH_4, N_2O, halocarbons (CFCs, HCFCs, HFCs), and other halogenated compounds (PFCs, SF_6); tropospheric ozone precursors: NO_x, CO, NMVOCs.

As discussed above, the most important contributor to human-induced global warming is energy-related CO_2, which is emitted during energy production and use. However, the absolute amount and the growth of CO_2 emissions are heterogeneously distributed, both in space and in time. Demographic developments, economic development, and technological progress are strongly interrelated. Therefore they can not be treated independent from each other. The interrelationships between the various drivers are discussed in the recent literature of economic growth theory, that draws on detailed statistical analyses of long-run country-level and regional data (see, e.g., Barro and Sala-I-Martin, 1995). Demographic trends are strongly correlated to social and economic development, and vice versa (Bloom et al., 1999). Resource endowment (Sachs and Warner, 1995), health provisions, education levels, and the relative distribution of wealth are all drivers of economic growth, and vice versa. Long-run per capita economic growth (Maddison, 1995) is strongly correlated to advances in knowledge and technological progress (Barro and Sala-I-Martin, 1995). Therefore, there are no simple linear relationships to be expected between these main driving forces (e.g. GHG emissions will not usually grow in a linear fashion with population on long timescales).

Historically, emissions of particulates and sulfur have been mitigated increasingly with increasing average income in a region, leading to the characteristic inverted U-shaped curves (environmnetal Kuznets curves) of sulfur emissions versus average income (see e.g., World Bank, 1992; Viguier, 1999). One might expect also that GHGs will pass through Kuznets curves. However, empirical experience does not yet support this view (Viguier, 1999). Interestingly, also, many energy systems models do not replicate Kuznets curves for GHGs in their projections for the twenty-first century (see, for example, Figure 1).

2.2.1. Population

World population has grown from three billion in 1960 to four billion in 1974, five billion in 1987 and six billion in 1999 (UN, 1998), with most of the growth in the developing countries (see Figure 2). Figure 2 also includes the 1998 United Nations (U.N.) median population projection, in which world population reaches 10.4 billion in 2100 (UN, 1998). The different gray shadings show the rapidly increasing population in today's developing countries, compared to a relatively stable population in today's industrialized countries. Around such "central" projections, some researchers have constructed probabilistic population scenarios (Lutz et al, 1997) that used fertility, mortality, and migration rate assumptions based on a survey of demographic experts. These indicate that it will be unlikely that the world population will double again in the twenty-first century. Important current demographic trends that influence GHG emissions are the phenomena of aging in the industrialized countries (MacKellar et al., 1995), and urbanization in the developing countries (HABITAT, 1996).

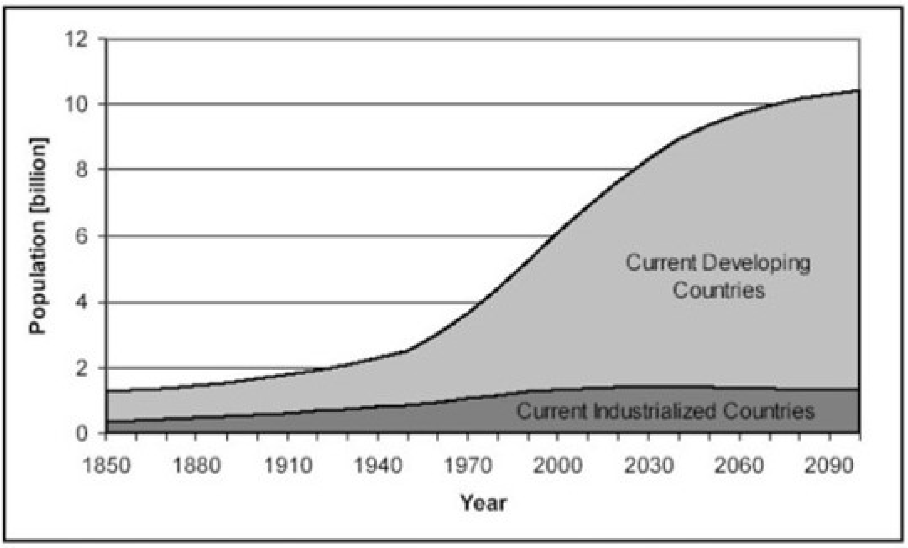


Figure 2. Historical world population from 1850 to 1998 and population projections to 2100 according to the 1998 United Nations median population projection (UN, 1998). The different gray shadings show the rapidly increasing population in today's developing countries since the mid-1950s, compared to a relatively stable population in today's industrialized countries
(*Source*: United Nations, *World Population Projections to 2150*, (New York: U.N. Department of Economic and Social Affairs Population Division, 1998))

2.2.2. Economic Development

There is widespread use of GDP as the most important indicator of development, and also as the main determinant of GHG emissions. However, GDP is an insufficient indicator for many reasons. For example, GDP does not adequately describe the income distribution and the status of poverty in a society. As an illustration, despite rising world GDP, it is estimated that 1.3 billion people live on less than US$1 per day at purchasing power parity (UNDP, 1997), and that nearly two billion people have no access to commercial energy services (i.e. they have no access to commercial energy services such as oil or electricity, but only to traditional biofuels, such as fuelwood, crop residues and animal dung) (World Bank, 1999). As described below this also has significant influence on GHG emissions.

Experience has shown that economic growth rates are often lower for economies at the technology and productivity frontier compared to those catching up (Maddison, 1995). However, the twentieth century saw widening income gaps throughout the world. For example, per capita GDP in Africa was reduced from 20% of that in the most affluent world region in 1870, to only 6% in 1990 (Maddison, 1995).

To construct emissions scenarios for the twenty-first century, one has to somehow deal with the large uncertainties in future economic growth perspectives. Manne and Richels (1994) report an export poll on uncertainty in future GDP projections. Among the major current trends, the globalization of markets and information networks will contribute to a rapid international diffusion of technologies that may in turn sustain accelerated productivity growth in the future. The direct relation between GDP and GHG emissions, however, is very complex (see Box 1 and Table 1). Just imagine that alternative high or low dematerialization futures might be realized at similar income levels.

2.2.3. Energy Technologies and Fossil Energy Resources

Rapid per capita economic growth increases capital turnover rates and provides increased room for demonstrating technological innovation. This in turn drives the availability of fossil fuels (see discussion below) and of new low-carbon energy technologies, which will decrease long-term prices and finally might fuel economic growth.

Fossil reserves are those occurrences of oil, gas, and coal that are recoverable with present technologies and at present market conditions (see, e.g. Masters et al., 1994). Mainly because of technological progress, the amount of remaining oil and natural gas reserves at any given time between 1945 and 1995 averaged 40 (to 60) times the amount of annual extraction of these reserves (Rogner, 1997). In other words, the amounts of remaining reserves were growing in a linear fashion with increasing amounts of extraction and use of oil and gas reserves because resources, which in comparison to reserves lack geological certainty or present economic feasibility, were continuously transformed into reserves. Therefore, there are numerous non-trivial links between technological development, market conditions, knowledge, energy demand, and CO_2 emissions. However, the above argument only holds on a long-term perspective. There have been (and will be) temporary and structural shortages that also resulted in volatile prices.

A recent WEC-IIASA study (Nakicenovic et al., 1998) estimates the sum of oil, natural gas, and coal reserves and resources (the fossil resource base) at approximately 5000 Gtoe (= $2.1 \cdot 10^{23}$ joules). This enormous amount would be enough for more than 100 years of global fossil energy use, leading to the equivalent of cumulative emissions of six to seven times the current atmospheric carbon content of 760 gigatonnes of carbon (GtC) (Nakicenovic et al., 1998). Therefore, it seems that only economic conditions and environmental constraints and not fossil resource availability constraints might limit fossil energy use and CO_2 emissions.

2.2.4. Land Use

The most important anthropogenic land-use emissions are CO_2 from deforestation, CH_4 from rice cultivation and enteric fermentation of cattle, and N_2O from the use of fertilizers (see discussion of sources below). Correlation analyses show that population is the most influential driving force in land-use emissions (Alcamo and Swart, 1998). Increasing population numbers and increasing food demand lead to larger numbers of cattle and larger rice production (i.e. CH_4 emissions) and more fertilized croplands (i.e. N_2O emissions). It remains to be seen how much of the increased food demand will be compensated for with increased crop and animal productivity.

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R.A. Roehrl has held a position as analyst in the Environmentally Compatible Energy Strategies (ECS) Project at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, since September 1997. He is co-author and modeler for the forthcoming Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC), and has also contributed to Chapter 2 of the draft third assessment report of the IPCC. His current work for Japanese and European contractors within the ECS Project focuses on the investigation of global energy supply and demand patterns, in particular on the impact of energy investment decisions, technology diffusion and emissions mitigation policies on worldwide development perspectives. His recent work for the Central Research Institute for the Electric Power Industry is related to issues of Eurasian electricity and gas grids.

Before joining IIASA, R.A. Roehrl participated in the trainee program of the European Commission in Brussels, Belgium, where he worked on R&D issues in the telecommunications sector (gigabit networks). His research experience includes a period of computational research work on Bose-Einstein-Condensation and Soliton Transmission at the Max Planck Institute for Quantum Optics in Garching, Germany. R.A. Roehrl studied physics, chemistry, and mathematics at the universities of Erlangen and Muenchen, Germany, and at Oxford University, U.K.