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CAN ADVANCES IN SCIENCE AND TECHNOLOGY PREVENT GLOBAL WARMING?

A Critical Review of Limitations and Challenges

MICHAEL H. HUESEMANN
Pacific Northwest National Laboratory, Marine Sciences Laboratory, Sequim, WA 98382, USA
(Tel: +1-360-681-3618, Fax: +1-360-681-3699; E-mail: michael.huesemann@pnl.gov)

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Abstract. The most stringent emission scenarios published by the Intergovernmental Panel on Climate Change (IPCC) would result in the stabilization of atmospheric carbon dioxide (CO_2) at concentrations of approximately 550 ppm which would produce a global temperature increase of at least 2 °C by 2100. Given the large uncertainties regarding the potential risks associated with this degree of global warming, it would be more prudent to stabilize atmospheric CO_2 concentrations at or below current levels which, in turn, would require more than 20-fold reduction (i.e., ≥95%) in per capita carbon emissions in industrialized nations within the next 50–100 years. Using the Kaya equation as a conceptual framework, this paper examines whether CO_2 mitigation approaches such as energy efficiency improvements, carbon sequestration, and the development of carbon-free energy sources would be sufficient to bring about the required reduction in per capita carbon emissions without creating unforeseen negative impacts elsewhere. In terms of energy efficiency, large improvements (≥5-fold) are in principle possible through aggressive investments in R&D and the removal of market imperfections such as corporate subsidies. However, energy efficiency improvements per se will not result in a reduction in carbon emissions if, as predicted by the IPCC, the size of the global economy expands 12–26-fold by 2100. Terrestrial carbon sequestration via reforestation and improved agricultural soil management has many environmental advantages, but has only limited CO_2 mitigation potential because the global terrestrial carbon sink (ca. 200 Gt C) is small relative to the size of fossil fuel deposits (≥4000 Gt C). By contrast, very large amounts of CO_2 can potentially be removed from the atmosphere via sequestration in geologic formations and oceans, but carbon storage is not permanent and is likely to create many unpredictable environmental consequences. Renewable energy can in theory provide large amounts of carbon-free power. However, biomass and hydroelectric energy can only be marginally expanded, and large-scale solar energy installations (i.e., wind, photovoltaics, and direct thermal) are likely to have significant negative environmental impacts. Expansion of nuclear energy is highly unlikely due to concerns over reactor safety, radioactive waste management, weapons proliferation, and cost. In view of the serious limitations and liabilities of many proposed CO_2 mitigation approaches, it appears that there remain only few no-regrets options such as drastic energy efficiency improvements, extensive terrestrial carbon sequestration, and cautious expansion of renewable energy generation. These promising CO_2 mitigation technologies have the potential to bring about the required 20-fold reduction in per capita carbon emission only if population and economic growth are halted without delay. Therefore, addressing the problem of global warming requires not only technological research and development but also a reexamination of core values that equate material consumption and economic growth with happiness and well-being.

Keywords: climate change mitigation, carbon emission reductions, carbon sequestration, economic growth, energy efficiency, Kaya equation, nuclear energy, population stabilization, renewable energy

1. The Technological Challenge of Global Warming

In its latest assessment report, the Intergovernmental Panel on Climate Change (IPCC, 2001a, b) considered various CO_2 emission scenarios that would lead to stabilization of atmospheric CO_2 concentrations at levels ranging from 550 ppm to greater than 1000 ppm (see Table I). An increase of the atmospheric CO_2 concentration above 1000 ppm due to the continued use of fossil fuels and unlimited economic growth (Table I) would result in a global temperature increase of at least 4 °C (7 °F) by 2100 (Watson et al., 2001) which is very substantial considering that during the warmest period of the past 200 million years the mean temperature was only 6–9 °C (11–16 °F) higher than today. Even the most aggressive emission reduction scenario published in the IPCC's Summary for Policymakers (IPCC, 2001a) will result in a stabilization of the atmospheric CO_2 concentration at approximately 550 ppm which will increase global temperatures by at least 2 °C (3.6 °F) by 2100 (Table I). Additional warming is expected after 2100 even if the global CO_2 concentration has been stabilized at 550 ppm. The predicted range of temperature increase at equilibrium is 2–5.2 °C (3.6–9.4 °F) (Watson et al., 2001).

Given that all IPCC emission scenarios including the most stringent one (i.e., stabilization at 550 ppm) would lead to significant global temperature increases which, in turn, would most likely cause a wide range of serious consequences such as catastrophic weather events, unprecedented decreases in ocean pH (Caldeira and

TABLE I

Estimated atmospheric CO_2 concentrations, annual and cumulative (1990–2100) carbon emissions, world population, Gross World Product (GWP), per capita affluence, primary energy use, and energy intensity in 2100 for the two worst (A1FI and A2) and two best (A1T and B1) IPCC scenarios relative to 1990 reference values

	Reference case	Highest CO_2 concentration	Highest C emissions	Lowest CO_2 concentration	Lowest C emissions
Scenario	1990	A1FI (2100)	A2 (2100)	B1 (2100)	A1T (2100)
CO_2 concentration (ppm)[a]	353	970 (2.7)	856 (2.4)	549 (1.5)	582 (1.6)
Annual C emissions (Gt per year)[a]	7.1[b]	28.2 (4.0)	29.1 (4.1)	4.2 (0.6)	4.3 (0.6)
Cumulative C emissions (Gt C)[b]	NA	2189	1862	983	1068
World population (billion)[b]	5.3	7.1 (1.3)	15.1 (2.8)	7.0 (1.3)	7.0 (1.3)
GWP (10^{12} 1990 US$ per year)[b]	21	525 (25)	243 (12)	328 (16)	550 (26)
Per capita affluence (1990 US$)	4000	74,000 (18)	16,000 (4)	47,000 (12)	78,000 (19)
Primary energy use (EJ per year)[b]	351	2073 (5.9)	1717 (4.9)	514 (1.5)	2021 (5.7)
Energy intensity (10^6 J/US$)[b]	16.7	3.0 (1/5.6)	5.9 (1/2.8)	1.4 (1/12)	2.3 (1/7.2)

Values in parentheses indicate change relative to 1990.

[a] IPCC (2001d), SRES Tables.

[b] IPCC (2001c), Tables SPM-1a, SPM-2a, and SPM-3a.

Wickett, 2003), rise in sea level, a permanent collapse of the thermohaline ocean circulation (Broecker, 1997; Manabe and Stouffer, 1993; NRC, 2002; Stocker and Schmittner, 1997), irreversible ecosystem damage, and species extinction (IPCC, 2001a, b), it appears that the declared goal by the UN Framework on Climate Change to "achieve . . . stabilization of greenhouse-gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" will be automatically violated (Houghton, 1997; Kauppi, 1995; O'Neill and Oppenheimer, 2002). Considering that the consequences of global warming are not only highly unpredictable but also potentially devastating to human civilization and the environment, it is not clear why the IPCC did not follow the precautionary principle by considering scenarios that would lead to stabilization of CO_2 at or below present levels (i.e., 350 ppm). Given the unpredictability of global climate change, it would be far more prudent to stabilize the atmospheric CO_2 concentration at the lowest possible level in order to minimize potential risks.

It is likely that stabilization at 350 ppm was considered impractical by the IPCC for both economic and political reasons, as large and immediate CO_2 emission reductions would be required. In order to maintain CO_2 concentrations at 1990 levels of ca. 350 ppm, it will be necessary, beginning in 2005, to reduce global anthropogenic carbon emissions from 7.1 Gt per year (1990 levels) to zero by 2060, with long-term stabilization of emissions at around 1 Gt per year (Wigley et al., 1996). Modeling results by Walker and Kasting (1992) suggest even more drastic emission reductions: in order to maintain atmospheric CO_2 concentrations indefinitely below 500 ppm, a 25-fold reduction in the current fossil fuel combustion rate would be required, even if all forest clearance were to be immediately discontinued. Considering that total US greenhouse gas emissions have not stabilized but are increasing at a significant rate (i.e., ca. 14% during the 1990s (U.S. EPA, 2002)), it is not surprising that the IPCC ignored more stringent scenarios such as stabilization of atmospheric CO_2 concentrations at or below present levels.

It is the purpose of this paper to determine whether atmospheric CO_2 concentrations can, at least in principle, be stabilized at 350 ppm with the help of innovative science and technology so that climate change and its associated consequences may be prevented to the greatest possible extent. As indicated earlier, long-term stabilization of atmospheric CO_2 at ca. 350 ppm would require a reduction of global carbon emissions to 1 Gt per year (or less) within the next 50 years (Wigley et al., 1996). All major projections by the UN, World Bank, and the U.S. Census Bureau predict that world population will have reached 9.5 billion (central case) by 2050 (Gaffin, 1998). If equity principles are incorporated in the process of sustainable development as recommended by the World Commission on Environment and Development (1987), each of the 9.5 billion people living on the planet in 2050 should be allocated an equal share of carbon emissions which translates into allowable per capita emissions of ca. 0.1 tons per year (Graedel and Klee, 2002). Given that 6.6 tons of carbon equivalents are currently produced per person in the United States (Graedel and Klee, 2002), it follows that a 66-fold reduction (or

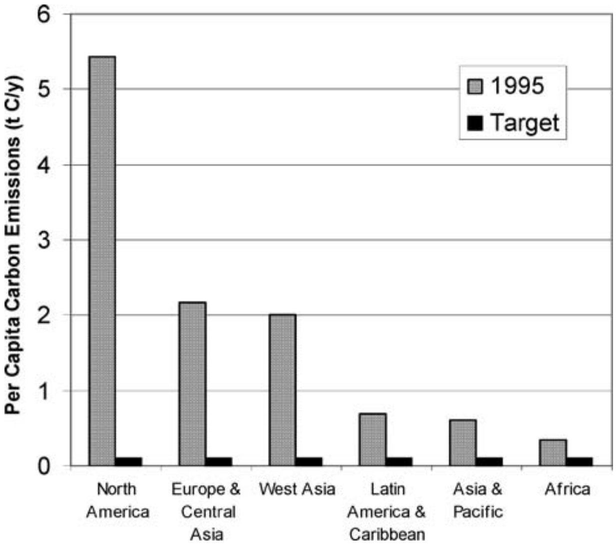

Figure 1. Per capita carbon emissions (tons per year, 1995) in different world regions compared to the emission target required to stabilize atmospheric CO_2 at 350 ppm (United Nations Environment Programme, 2000).

equivalently a 98.5% decrease) in greenhouse gas emissions will be required to achieve a globally sustainable rate of 0.1 tons per year.

Although Europe and parts of Asia are far more energy efficient than the United States, significant emission reductions will be needed there as well. As shown in Figure 1, per capita carbon emissions in Europe, Central and West Asia will have to be reduced approximately 20-fold (or 95%) from ca. 2 tons per year to achieve the sustainable per capita goal of 0.1 tons per year. Even in the least-developed countries of Africa, average per capita carbon emissions would still have to be reduced more than threefold, i.e., from 0.34 to 0.1 tons of carbon per year. In summary, per capita carbon emissions in industrialized nations need to be reduced by at least 95% within the next 50 years in order to stabilize atmospheric CO_2 concentrations at 350 ppm so that global warming may be avoided to the greatest possible extent.

Can science and technology advance fast enough in the next 50–100 years to produce such drastic reductions (>95%) in per capita carbon emissions? In order to answer this question, it is useful to review the so-called “Kaya” equation which presents the magnitude of net carbon emissions to the atmosphere (Net C) as a function of multiple driving forces (Gruebler et al., 1993b; Halmann and Steinberg, 1999; Hoffert et al., 1998; Nakicenovic et al., 1998a):[1]

$$\mathrm{Net\,C} = P\left(\frac{\mathrm{GDP}}{P}\right)\left(\frac{E}{\mathrm{GDP}}\right)\left(\frac{C}{E}\right) - S \tag{1}$$

where P is the size of the human population, GDP/P the per capita gross domestic product, often referred to as "affluence," E/GDP the energy required per gross domestic product, also called energy intensity, which is the inverse of energy efficiency (see later), C/E the carbon emitted per unit energy generated, i.e., the carbon intensity of the fuel mix used to drive the economy, and S the natural and induced removal of carbon as CO_2 from the atmosphere, also referred to as carbon sequestration. In short, the Kaya equation indicates that the size of total carbon emissions is the product of a nation's population, its per capita economic output, its energy utilization efficiency, and the carbon quality of the fuel used, minus any carbon that is sequestered in terrestrial biomass, geologic formations, or oceans.

Given that drastic reductions in total carbon emissions are required by the end of this century, it is clear from Equation (1) that significant changes in the contributing factors will be necessary. It is the objective of this paper to evaluate whether innovations in technology such as improved energy efficiency, greater carbon sequestration, and a shift to low-carbon fuels will be sufficient to bring about a 95% reduction in annual per capita carbon emissions in industrialized nations within the next 50–100 years.

Before proceeding with the analysis of different climate change mitigation options, it should be noted here that the present author is not a specialist in any of the particular areas covered in this paper. Consequently, this paper should not be viewed as the latest in-depth state-of-the-art review of individual climate change mitigation technologies. Instead, utilizing primarily data from the peer-reviewed literature and drawing insights from different disciplines, this paper was written as a conceptual 'think piece' to invite a large-scale analysis of the various climate change mitigation options. Finally, although drastic reductions in per capita carbon emissions will most certainly increase the cost of energy for consumers, the potential adverse economic impacts of different technologies will not be addressed in this paper. Rather, the main focus of this analysis is on the scientific and technological limitations of various climate change mitigation technologies as well as their potential environmental risks and public acceptance issues.

2. Improving Energy Efficiency

Efficiency is the extent to which a certain energy or material "input" is converted to a desired "output," i.e., efficiency = output/input. As numerous steps are involved in the conversion of primary energy into useful economic activities, various types of energy efficiencies can be defined. Primary energy (e.g., coal, oil, uranium, biomass) is converted into secondary or final energy (e.g., electricity, gasoline, ethanol) which is transformed into various forms of useful energy (e.g., work, heat, light emission) which, in turn, delivers a multitude of energy services (e.g., moving a vehicle, operating a machine, warming or cooling a room, providing space illumination) that, when contributing to economic activity, constitute in the aggregate the gross domestic product (GDP) (Jochem, 2000; Nakicenovic and Gruebler, 1993). The overall efficiency (ε) of converting primary energy into GDP can then be defined as the product of supply-side efficiency ($\varepsilon_{\mathrm{ss}}$) and end-use efficiency ($\varepsilon_{\mathrm{eu}}$):

$$\begin{aligned}\varepsilon = \varepsilon_{\mathrm{ss}} \cdot \varepsilon_{\mathrm{eu}} &= \left(\frac{\text{useful energy}}{\text{primary energy}}\right)\left(\frac{\text{GDP}}{\text{useful energy}}\right)\\ &= \frac{\text{GDP}}{\text{primary energy}} = \frac{1}{\text{energy intensity}} \qquad (2)\end{aligned}$$

Energy intensity, which is the inverse of energy efficiency (ε), is the amount of primary energy required to generate economic activity (GDP). Historical data indicate that globally energy intensity has decreased at a rate of ca. 1% per year in the last century (Jochem, 2000; Nakicenovic et al., 1998b; Nakicenovic and Gruebler, 1993; Pepper et al., 1998) and is currently converging toward 0.25–0.5 tons of oil equivalent per US$ 1000 (1980) in most nations (Nakicenovic, 1996; Nilsson, 1993).

The key question, in terms of averting global warming, is how much further can energy intensity be reduced, or equivalently, overall energy efficiency be increased? If the historical efficiency improvement rate of 1% could be maintained for the next 100 years, energy intensity would drop almost threefold (i.e., ca. 270%) by 2100. This tripling in overall energy efficiency, although impressive, would not be sufficient to meet the low CO_2 concentration and emission targets of scenarios B1 and A1T in Table I, where 7.2- to 12-fold efficiency improvements are required by 2100. The question is how realistic is it to expect an order of magnitude decrease in energy intensity? If there were no economic, social, and political barriers (see later), an instantaneous replacement of the current energy system by the best available technology would result in an overall efficiency increase of only 60% (Nakicenovic and Gruebler, 1993). Clearly, major technological breakthroughs will be required to obtain the necessary 10-fold (or 1000%) improvement in energy efficiency within the next century.

What is the maximum achievable potential for global energy efficiency improvements? The potential for increasing the supply-side efficiency ($\varepsilon_{\mathrm{ss}}$), which is currently around 37% at the global level (Jochem, 2000), is relatively small. According to a theoretical analysis by Jochem (1991), $\varepsilon_{\mathrm{ss}}$ could be increased up to twofold, and further improvements are thermodynamically impossible because Carnot efficiency limits will have been reached (Balzhiser et al., 1972). Given the limited potential for increasing supply-side efficiency ($\varepsilon_{\mathrm{ss}}$), large improvements in end-use efficiency ($\varepsilon_{\mathrm{eu}}$) will be required to produce a substantial decline in energy intensity in the next 100 years. The maximum thermodynamically achievable improvements in $\varepsilon_{\mathrm{eu}}$ are not precisely known, but estimates range from 10-fold (Nakicenovic et al., 1998b) to 50-fold (Nakicenovic and Gruebler, 1993). Although the higher estimate may well reflect unrealistic techno-optimism, it should, however, given historical trends, be in principle possible to increase the overall efficiency (ε) at least fivefold by 2100 via promotion of aggressive research and development and widespread technology diffusion.

Why has this potential for efficiency improvement not already been exploited, especially when many technological changes could be implemented at no additional cost (Lovins and Lovins, 1991)? The reasons for inaction are numerous and include absence of energy efficiency incentives (Sioshansi, 1991), lack of consumer information (Rosenfeld et al., 1997), insufficient capital to implement innovative technologies and the desire to minimize initial costs, unpopularity among politicians because most energy efficiency investments remain invisible and do not enhance their public image (Jochem, 2000), slow diffusion of new technologies (Nakicenovic and Gruebler, 1993), and general inertia to change, i.e., high transaction costs (Von Weizsacker et al., 1998). However, perhaps the primary reason for not realizing theoretically achievable efficiencies are market imperfections which are created when the cost of energy is kept artificially low by subsidies or by externalizing environmental and national security costs, thereby encouraging wasteful energy use by consumers and providing no incentives for energy conservation via efficiency measures (Jochem, 2000; Sioshansi, 1991; Rosenfeld et al., 1997). Consider, for example, that if all hidden subsidies and externalized environmental costs of road transportation were to be accounted for, the true cost of gasoline in the United States would be US$ 2–7 (by some estimates even US$ 6–16) per gallon higher than is currently paid by consumers (Myers and Kent, 2001). As a result of these market imperfections, over 300 billion dollars worth of energy is wasted in the United States each year (Myers and Kent, 2001). According to a study by the National Academy of Sciences (1991), approximately 50% of CO_2 emissions could be reduced by efficiency measures without additional costs in a perfect market but only 15–20% in an imperfect economy that provides incorrect price signals. Major barriers to efficiency improvement are therefore not lack of innovative technologies but rather powerful special interests which forcefully resist relinquishing long-held subsidies and which are vigorously opposing regulations designed to internalize the costs that are currently being passed on to the environment and to future generations.

But even if the price of energy were to reflect its true cost, it is unlikely that any type of efficiency improvement will significantly reduce global carbon emissions unless the overall size of the economy (GDP or gross world product (GWP)) is held constant. A cursory analysis of Equation (1) indicates that a projected fivefold improvement in energy intensity by 2100 would also decrease net carbon emissions by a factor of five (assuming no change in the current energy mix) if the product of population times per capita affluence were to remain the same, i.e., $P \cdot \mathrm{GDP}/P = \mathrm{GDP} = \text{constant}$. Unfortunately, based on the economic growth predictions in all scenarios presented in Table I, GWP is expected to increase 12–26-fold during the next 100 years, thereby effectively canceling out any potential reductions in carbon emissions via efficiency measures. As a result of the projected aggressive economic expansion, primary energy use is anticipated to increase 1.5–6-fold by 2100 in the four scenarios listed in Table I, indicating that efficiency improvements per se will not result in a decrease of net carbon emissions. This is not surprising, as efficiency improvements generally reduce the cost of energy, thereby increasing the overall consumption – a phenomenon called Jevon's paradox or rebound effect (Huesemann, 2003; Rees and Wackernagel, 1995). This explains why gains in energy efficiency since the Industrial Revolution have always occurred in conjunction with increasing energy usage and economic expansion (Greenhalgh, 1990).

In summary, without policies that limit the total size of the economy, future improvements in energy efficiency will most certainly enable and promote further economic growth rather than reduce net carbon emissions below current levels. If increases in energy efficiency cannot reduce CO_2 emissions, then – according to Equation (1) – only two other technological options remain for addressing the threat of global warming: carbon sequestration (*S*) and a reduction in carbon intensity (*C*/*E*).

3. Sequestering Carbon

Carbon sequestration involves either the capture and secure storage of power plant CO_2 emissions in geologic formations or deep oceans, or the removal of CO_2 from the atmosphere by terrestrial or marine photosynthesis and the subsequent, long-term storage of the carbon-rich biomass (U.S. DOE, 1999). The concept of carbon sequestration is very attractive as it would allow the continuing use of fossil fuels without potential disruptions due to climate change concerns. However, before implementing carbon sequestration schemes on a scale large enough to cause significant reductions in greenhouse gas emissions (i.e., at least 2 Gt of carbon would have to be sequestered per year (Friedmann, 2003)), it is important to first carefully consider the carbon storage capacities, costs, and environmental safety concerns for terrestrial, geologic, and ocean sequestration.

3.1. TERRESTRIAL CARBON SEQUESTRATION

Terrestrial carbon sequestration involves the photosynthetic fixation of atmospheric CO_2 by plants (e.g., trees, food crops, grasses, etc.) and the long-term accumulation and storage of both standing and below-ground biomass. Rates of terrestrial carbon sequestration can be increased by reforestation and afforestation and by changing soil management practices (i.e., reduced or no till agriculture) to promote the formation and retention of soil organic matter (Paustian et al., 1998). The terrestrial biosphere currently stores approximately 2000 Gt of carbon (ca. 600 Gt in plant biomass and 1400 Gt in soil humus) which compares to an estimated 4000 Gt of carbon deposited in fossil fuel reservoirs (Gruebler et al., 1993a; U.S. DOE, 1999). Thus, to store all additional carbon (4000 Gt) that is expected to be released from the burning of the remaining fossil fuel resources in green plants would require a tripling of terrestrial biomass from the current 2000 Gt to 6000 Gt – a proposition which is almost certainly technically impossible.

A more realistic possibility is to reverse the long-term trend of terrestrial carbon loss by reforestation and improved farming practices with the goal of restoring the terrestrial carbon pool to its pre-1750 size. Approximately 200 Gt carbon have been lost during the last 250 years as a result of land use changes, primarily through conversion of forests to farmland (Scholes and Noble, 2001). This is the maximum amount of carbon that can be realistically expected to be sequestered in the terrestrial biosphere via massive restoration efforts (*Note*: This is only 5% of all fossil carbon deposited in reservoirs or ca. 10–20% of predicted cumulative carbon emissions by 2100 – see Table I). Even if all this previously lost carbon could be returned to terrestrial eco-systems during the next 100 years, it would reduce atmospheric CO_2 concentrations by only 40–70 ppm (IPCC, 2001a; Scholes and Noble, 2001), indicating that even under the best conditions, terrestrial carbon sequestration would only be able to make a minor contribution to the mitigation of climate change.

Indeed, it will be a major challenge to even partially "refill" the depleted terrestrial carbon sinks via reforestation and better agricultural soil management practices. Consider, for example, that approximately 1162 million ha of forests have been cleared worldwide in the last 200 years (Gruebler et al., 1993a), an area larger than the United States (i.e., 962 million ha). Thus, a massive reforestation effort would have to be initiated to restore forest biomass to its pre-1800 levels – a proposition which is particularly challenging given that deforestation has not halted but is currently proceeding globally at a rate of 9 million ha per year (Topfer, 2001; Williams, 2003). It is easy to suggest reforestation as a response to global warming but it must be understood that these huge expanses of forests were eliminated to make room for expanding human populations, to supply fuel wood, and to provide new land for agriculture. Consequently, although it would be relatively easy to reforest marginal and degraded lands (i.e., ca. 3% of the United States (Rubin et al., 1992)), it would be a major challenge to implement reforestation on a sufficiently large scale (i.e., 1 billion ha) as it is likely to compete with the need for farmland.

In summary, terrestrial carbon sequestration is a constructive response to global warming as it attempts to reverse the long-term trend of deforestation and soil organic matter loss, thereby having the additional environmental benefit of restoring previously damaged or destroyed ecosystems. However, the maximum size of the terrestrial carbon sink is limited to ca. 200 Gt and even a partial restoration of this amount of carbon via reforestation and changes in agricultural practices will be a challenge given the ever increasing need for food, fiber, and fuel wood by growing human populations. Consequently, terrestrial carbon sequestration can at best be seen as a way to slow the rise of CO_2 emissions (i.e., by ca. 2 Gt per year) for a limited time (50–100 years) until all carbon sinks are filled, thereby "buying" time to develop other sequestration technologies or make the transition to a zero carbon economy.

3.2. GEOLOGICAL CARBON SEQUESTRATION

Geologic carbon sequestration involves the storage of CO_2 in deep underground reservoirs such as depleted oil and gas fields, unmineable coal seams, and saline aquifers (U.S. DOE, 1999; Betts, 2003; Bruant et al., 2002). Prior to sequestration, the CO_2 must first be separated from the flue gases of centralized fossil fuel fired power plants and then transported via pipeline to geologic reservoirs. The total worldwide carbon storage capacity of geologic formations is not precisely known, but estimates range from tens to hundreds Gt carbon for coal seams, hundreds to 10,000 Gt carbon for saline aquifers, and several hundred Gt carbon for depleted oil and gas fields (Bruant et al., 2002; Herzog, 2001). Geological carbon sequestration capacities appear to be more limited in the United States with estimated reservoir sizes of 10–25 Gt carbon for natural gas fields, 10 Gt carbon for coal beds, and 1–130 Gt carbon for deep saline aquifers (U.S. DOE, 1999). According to a detailed analysis by the Department of Energy of known (rather than estimated) US geologic carbon sequestration sites, only 3 Gt of carbon could currently be stored in abandoned oil and gas fields which is equivalent to only 1.5 years of US carbon emissions. Almost nothing is known about saline aquifers (Bergman, 1997).

The primary difficulty with geologic carbon sequestration is the potential leakage of CO_2 from the reservoirs and subsequent adverse effects to human health and the environment (Bergman, 1997; Bruant et al., 2002; Herzog, 2001; Wilson et al., 2003). According to Bruant et al. (2002):

> Even with detailed subsurface characterization, leaks cannot be ruled out in some formations because of the buoyancy of the separate-phase CO_2, the induced pressure gradients from injection, and the variable nature of strata serving as barriers to upward migration. CO_2 leaking from receptor formations may intercept shallow aquifers, surface water bodies, and the land surface.

Thus, given that some leakage is unavoidable because it would be very difficult if not impossible to detect, monitor, and control all potential CO_2 escape routes for hundreds if not thousands of years, geologic carbon storage is not truly permanent. Consider, for example, that a leakage rate of only 1% per year would result in the loss of all "sequestered" carbon within 100 years, indicating that geological carbon sequestration may only provide temporary "relief" from the rising CO_2 concentrations in the atmosphere and thus simply transfers present problems to future generations (Hawkins, 2001). Slow, chronic leakage could result in the dissolution of CO_2 in shallow aquifers, causing the acidification of groundwater and undesirable changes in geochemistry (e.g., mobilization of toxic metals), water quality (e.g., leaching of nutrients), and ecosystem health (e.g., pH impacts on organisms) (Bruant et al., 2002). A sudden catastrophic release of large amounts of CO_2, as a result of either reservoir fracturing by earthquakes or pipeline failures, could result in the immediate death of both people and animals, particularly because CO_2 is odorless, colorless, and tasteless and thus likely to escape detection (Bruant et al., 2002). Consider, for example, that more than 1700 people died of asphyxiation in 1986 as a result of a limnic eruption of CO_2 from Lake Nyos in Cameroon (Clarke, 2001).

But even if carbon sequestration in underground formations were completely safe and the storage capacity virtually unlimited, the geologic sequestration of all CO_2 that is currently emitted from fossil-fuel-fired power plants in the United States would reduce US carbon emissions by up to one-third (Halmann and Steinberg, 1999) as most CO_2 is emitted from widely dispersed sources (e.g., houses, businesses, and automobiles) from which collection of CO_2 is not feasible. Thus, unless hydrogen produced via decarbonization of fossil fuels in centralized power plants replaces the large quantities of fossil fuels that are currently used for transportation and space heating (Hileman, 1997; Hoffert et al., 2002; Rifkin, 2002), the role of geologic carbon sequestration as well as ocean sequestration (see discussion later) will be very limited in mitigating global climate change.

3.3. OCEAN CARBON SEQUESTRATION

Two different types of ocean carbon sequestration schemes have been proposed, (a) the disposal of CO_2 into mid- or deep oceans, and (b) the addition of fertilizers to stimulate the growth of phytoplankton, part of which is expected sink to the ocean floor to become sequestered there.

3.3.1. *CO_2 Disposal*

A number of different CO_2 ocean disposal strategies have been proposed. These include the release of dry ice cubes from a stationary ship, the introduction of liquid CO_2 onto a seafloor depression forming a “deep lake,” the release of CO_2 enriched seawater at 500–1000 m depth, and the injection of liquid CO_2 at 1000–1500 m depth from a stationary outlet or from a pipe towed by a moving ship (U.S. DOE, 1999; Caulfield et al., 1997; Herzog et al., 1996). The rationale for injecting CO_2 into the oceans, which have a combined storage capacity of several thousand Gt carbon (Herzog, 2001; Kasting, 1998), is to accelerate the transfer of CO_2 from the atmosphere to the deep ocean, a process which occurs naturally at an estimated rate of 2 Gt C per year. By increasing the speed of this normally slow process via large-scale CO_2 disposal, it may be possible to avoid the transient high peak of atmospheric CO_2 concentration that is predicted in the next few centuries (Johnston and Santillo, 2003). Given that all atmospheric CO_2 would ultimately be transferred to the oceans anyway (Caldera et al., 2003) (i.e., equilibrium would be achieved in ca. 1000 years (Hanisch, 1998)), it is claimed that reaching the same final equilibrium faster via human intervention should be acceptable.

Aside from the fact that both the natural and accelerated ocean sequestration of CO_2 only transfers more obvious problems from terrestrial ecosystems (i.e., temperature increases) to less-visible marine ecosystems (i.e., CO_2-induced seawater acidification), the main problem with this argument is that the injection of CO_2 and the resulting large pH declines will most likely cause a wide range of localized environmental disruptions that would not occur if marine organisms were given centuries to adapt to the slow changes that take place during natural equilibration. The deep sea environment has been remarkably stable for thousands of years, and deep water organisms have evolved to be specifically adapted to their unique ecosystem (Jannasch and Taylor, 1984; Shirayama, 1997). Consequently, even minor changes in pH or contamination by CO_2 impurities such as NO_x, SO_x, and trace metals (U.S. DOE, 1999) are likely to overwhelm the adaptive capacity of these highly sensitive organisms, resulting in various potentially harmful effects. For example, CO_2-induced seawater acidification can lead not only to the dissolution of exoskeletal components such as calcareous shells of corals and bivalve mollusks, but also to metabolic suppression causing retarded growth and reproduction, reduced activity, loss of consciousness due to disruption of oxygen transport mechanisms (deep sea fish hemoglobins are extremely sensitive to pH), and, if persistent, death (U.S. DOE, 1999; Johnston and Santillo, 2003; Seibel and Walsh, 2001; Tamburri et al., 2000). In addition to detrimental effects on deep sea biota, CO_2 disposal may also negatively affect microbial populations and thus cause changes or disruptions in marine biochemical cycles (Seibel and Walsh, 2001). For example, our own research has shown that marine nitrification, i.e., the microbial conversion of ammonia to nitrate, is progressively inhibited with increasing CO_2-induced seawater acidification (Huesemann et al., 2002). The main concern is that even small changes in the biochemical cycling of essential elements (i.e., carbon, nitrogen, phosphorus, silicon, and sulfur) may have large consequences, many of them secondary and difficult to predict (U.S. DOE, 1999).

The problem of accurately predicting adverse ecosystem impacts is profound and cannot be easily solved as it is directly linked to the inherent limits of current reductionist, mechanistic science. As discussed in more detail elsewhere (Huesemann, 2001, 2002; Longino, 1990; Sarewitz, 1996), current scientific methodologies, with their almost exclusive focus on reductionist mechanisms, were specifically developed during the last few hundred years to study isolated phenomena, with the explicit utilitarian goal of manipulating and exploiting nature for the perceived benefit of mankind. Although science has been extremely successful in discovering isolated cause and effect relationships which, in turn, has often provided the impetus for the development of technologies to exploit nature, current science is inherently unable to elucidate the large and complex networks of cause-effect relationships, and is thus incapable of providing adequate information to protect the environment from human exploitation. We are confronted with the paradox that science generates knowledge for exploiting nature and simultaneously “creates” ignorance of potential secondary- and higher-order consequences, i.e., information critically needed to protect the environment (Ravetz, 1990). Given that there will never be enough research funding to study all potential negative impacts of CO_2 ocean disposal on marine ecosystems, and that overlooking even one important cause and effect relationship could cause serious harm if ignored, it is clear that one should rather be guided by the precautionary principle which advocates that – given the large uncertainties due to the limitations of scientific knowledge – actions should be avoided if they have the potential for serious large-scale and wide-reaching unpredictable consequences.

It is exactly this concern regarding unexpected disruptive environmental consequences which will cause the public to oppose CO_2 ocean disposal. In fact, environmentalists are even objecting to injecting small amounts (i.e., a few tons) of CO_2 into the ocean to test the basic feasibility of the concept. As a result of intense pressure by environmental groups, two proposed small-scale CO_2 disposal experiments off the coasts of Hawaii and Norway were cancelled in 2002 (Burke, 2002). Given the intense public resistance to even the idea of injecting CO_2 into oceans (Hileman, 1997) as well as potential international legal hurdles that are likely to be encountered for amending the 1972 London Dumping Convention (Hanisch, 1998), the future of CO_2 ocean disposal does not look promising.

3.3.2. *Ocean Fertilization*

Ocean fertilization involves the addition of limiting micronutrients such as iron to stimulate the growth of phytoplankton (Chrisholm et al., 2001; Jones, 2001; U.S. DOE, 1999). While most of the additional photosynthetically fixed biomass carbon will be recycled in the photic zone, a small fraction will sink to the ocean floor where it will become incorporated into deep-sea sediments, thereby escaping reentry into the global carbon cycle for a limited period. In short, ocean fertilization accelerates the action of the "biological pump" which removes CO_2 from the atmosphere and transports some of it for storage in the deep ocean.

Ocean fertilization would have to be carried out on a very large scale to have any significant impact on climate change. A recent estimate by Buesseler and Boyd (2003) indicates that sequestration of only 30% of all carbon that is currently emitted worldwide would require the artificial fertilization of 1 billion km^2 of ocean surface waters – an area more than an order of magnitude larger than that covered by the entire Southern Ocean which is considered a best-case scenario for iron fertilization because of the large quantities of nutrient-rich waters there which are low in biomass. Thus, large-scale ocean fertilization would be a tremendous geoengineering exercise involving the manipulation of immense expanses of ocean surface waters.

As in the case of CO_2 injection, the main concern is whether large-scale ocean fertilization will result in unexpected detrimental consequences to marine ecosystems and biogeochemical cycles. For example, large-scale eutrophication could result in the depletion of oxygen, leading to deep-ocean anoxia which, in turn, would shift the microbial community structure towards organisms that produce methane and nitrous oxide, i.e., greenhouse gases with much higher warming potentials than CO_2 (Chrisholm et al., 2001; U.S. DOE, 1999; Watts, 1997). In addition, because of the inherent limitations of reductionist science, it will be difficult if not impossible to predict all secondary- and higher-order effects of ocean fertilization on the ocean food web structure and dynamics, including changes in the biogeochemical cycling of important elements such as carbon, nitrogen, phosphorus, silicon, and sulfur (U.S. DOE, 1999). Because of the high degree of scientific uncertainty and the potential for harmful unpredictable consequences, the American Society of Limnology and Oceanography issued a resolution in 1991 discouraging iron fertilization as a policy option for climate change mitigation, and more recently, leading researchers in the field have strongly opposed it as well (Chrisholm et al., 2001).

But even in the unlikely event that ocean fertilization could be shown to have no adverse effects, it would not be able to sufficiently reduce atmospheric CO_2 concentrations to avert global warming. Modeling results by Peng and Broecker (1991) indicate that a 100% successful ocean fertilization carried out for a duration of 100 years would only reduce atmospheric CO_2 concentrations by ca. 10%. Similarly, if all unused nitrogen and phosphorus in Southern Ocean surface waters were converted to organic carbon over the next 100 years, only 15% of anthropogenic CO_2 would be transferred to the deep ocean (Chrisholm et al., 2001). This is a very optimistic upper estimate, as deep ocean CO_2 reservoirs are eventually re-exposed to the atmosphere through global carbon circulation, indicating that ocean fertilization does not provide a permanent solution to climate change. It therefore appears that the limited benefit of temporarily locking up a small fraction of fossil CO_2 in deep ocean sediments via iron fertilization does not justify the potentially large risks of disrupting marine ecosystems and global biogeochemical cycles.

Based on the earlier analysis of the different carbon sequestration options, it can be concluded that terrestrial carbon sequestration is safe and constructive but has very limited storage potential; whereas both geological and ocean carbon sequestration are likely to have significant adverse environmental consequences but substantially higher carbon storage capacities. However, given that (a) science is unable to correctly predict all possible negative impacts, (b) the public will be strongly opposed to ocean and possibly even geologic carbon sequestration, and (c) both geologic and ocean sequestration for the most part do not permanently remove CO_2, either because of unavoidable leakage or ocean circulation, it appears that carbon sequestration strategies (other than terrestrial) are unlikely to have a significant impact in terms of averting climate change and, at best, only buy time to develop carbon-free energy sources.

4. Reducing Carbon Intensity

As indicated in Equation (1), another way to decrease the threat of global warming is to reduce the carbon intensity (C/E) of the energy sources which are required for the performance of economic activities. In the short-term, the easiest way to reduce carbon intensity is to switch from carbon-rich fossil fuels such as coal to hydrogen-rich ones such as natural gas (Nakicenovic, 1996; Gruebler et al., 1993b). However, as the supply of natural gas is limited and significant amounts of CO_2 would still be emitted into the atmosphere, in the long run CO_2 emission-free energy will have to be generated by one of three principal means, namely by (a) decarbonizing fossil fuels in order to generate the carbon-free energy carrier hydrogen and CO_2, the latter of which must be sequestered, (b) changing to renewable solar energy sources such as biomass, wind, photovoltaics, solar thermal, and hydroelectric, or (c) reviving nuclear energy. Presently, the fossil fuel option is favored, but its success depends not only on a relatively fast transition to a hydrogen-based energy infrastructure[2] (Cherry, 2004; Rifkin, 2002; Romm, 2004) but also on safe and effective permanent sequestration of the separated CO_2 fraction which – as was shown in the preceding section – will become a major technical and public policy challenge. The renewables option has for long been promoted by environmentalists and various "soft energy path" advocates (Boyle, 1996; Brower, 1992; Hayes, 1977; Lovins, 1977), whereas the nuclear option appears to be supported by a small minority of techno-optimists despite the numerous potentially insurmountable problems associated with it (Reed, 2000; Sailor et al., 2000).

4.1. RENEWABLE ENERGY SOURCES

Renewable energy sources include direct solar heating, solar thermal, photovoltaics, wind power, hydroelectric, and biomass energy. Given that long-term technical potentials for renewable energy (i.e., >4200 EJ per year) exceed current worldwide energy consumption (i.e., 351 EJ per year, see also Table I) by at least one order of magnitude, there is no doubt that renewable solar energy should in principle be able to supply present and even greater future energy demands (IPCC, 2001c). The primary reason why renewable energy sources have not been more widely used is their high cost relative to fossil fuels. However, renewable energy technologies could easily become commercially competitive in the near future with more aggressive investment in research and development and if they were to be subsidized as heavily as are fossil fuels (*Note*: The subsidy ratio for renewables versus non-renewables is on average 1:10, and it can be as high as 1:35 in some countries such as Germany (Myers and Kent, 2001)). Thus, the barriers to a rapid transition from fossil fuels to renewables are more economical and political than technical.

It has been commonly assumed that renewable energy generation is more environmentally friendly than the use of nonrenewable energy sources such as fossil fuels or nuclear power (Boyle, 1996; Brower, 1992; Hayes, 1977; Lovins, 1977). Although this assumption may be correct, it must be realized that the capture and conversion of solar energy will have significant negative environmental impacts, especially if solar renewables are employed on such a large scale as to supply the growing demand (see Table I) for CO_2 emission free power (Huesemann, 2001, 2003; Trainer, 1995a).

Before discussing some of the potential negative impacts of various solar energy technologies, it is useful to review the implications of the second law of thermodynamics in order to show that environmental impacts of renewable energy generation are inherently unavoidable. This is because the flux of solar energy (or neg-entropy) onto earth is used to create highly ordered (i.e., low entropy) so-called "dissipative structures" in the environment (Atkins, 1984; Ayres, 1998; Nicolis and Prigogine, 1977). Evidence of such structures can be seen in the complexity of organisms, ecosystems, biodiversity, and carbon and nitrogen cycles, all of which are maintained by the constant in-flow of solar energy (Ayres and Martinas, 1995).

If the flow of solar energy were to stop, as it ultimately will in a few billion years, all these complex structures would decay and reach a final equilibrium state where entropy is maximized. Similarly, if humans divert a fraction of solar energy away from the environment to create ordered structures for their own purposes (i.e., houses, appliances, transportation infrastructure, communication systems, etc.), less energy is available to maintain highly ordered dissipative structures in nature. The disturbance of these structures translates into the various environmental impacts that are associated with renewable energy generation.

Thus, the second law of thermodynamics dictates that it is impossible to avoid environmental impacts (disorder) when diverting solar energy for human purposes. This prediction is not unexpected considering the numerous roles solar-based energy flows play in the environment (Clarke, 1994; Haefele, 1981; Holdren et al., 1980). For example, direct solar energy radiation is responsible for the heating of land masses and oceans, the evaporation of water, and therefore the functioning of the entire climatic system. Wind transports heat, water, dust, pollen, and seeds. Rivers are responsible for oxygenation, nutrient and organism transport, erosion and sedimentation. The capture of solar energy via photosynthesis results in biomass that provides the primary energy source for all living matter and therefore plays a vital role in the maintenance of ecosystems (Clarke, 1994).

According to John Holdren, the potential environmental problems with solar energy generation can be summarized as follows:

> Many of the potentially harnessable natural energy flows and stocks themselves play crucial roles in shaping environmental conditions: sunlight, wind, ocean heat, and the hydrologic cycle are the central ingredients of climate; and biomass is not merely a potential fuel for civilization but the actual fuel of the entire biosphere. Clearly, large enough interventions in these natural energy flows and stocks can have immediate and adverse effects on environmental services essential to human well-being (Holdren et al., 1980, p. 248).

In conclusion, the potential environmental impacts of large-scale biomass energy production, solar thermal plants, photovoltaic electricity generation, as well as wind energy capture and hydroelectric power, although presently not as obvious as those caused by fossil fuel use, may be significant and therefore must be carefully considered.

4.1.1. *Biomass*

Biomass currently provides about 3.6 quads (3.8 EJ) of energy in the United States and about 55 EJ worldwide (Pimentel et al., 1994b; IPCC, 2001c). If biomass were to supply all primary energy currently used (i.e., 351 EJ in 1990, see also Table I), biomass energy production would have to increase ca. sevenfold, and up to 40-fold by 2100 if growth in primary energy use continues as predicted by the IPCC (see Table I). Before discussing the feasibility of increasing biomass energy production in more detail, it must be kept in mind that humans already appropriate 30–40% of the terrestrial primary productivity (i.e., photosynthetically fixed carbon) worldwide (Rojstaczer et al., 2001; Vitousek et al., 1986), indicating that two-fifth of the land's productive capacity is tightly controlled and managed for supplying food, fiber, and energy. Thus, it is unlikely that human appropriation of biomass for energy generation can be increased substantially without causing the collapse of complex ecosystems as countless species would be deprived of their photosynthetically fixed carbon energy food sources, thereby threatening or causing their extinction (Ehrlich and Ehrlich, 1981; Vitousek et al., 1986; Wright, 1990).[3]

The fact that biomass will not be able to supply a substantial fraction of the energy demand is particularly evident in the United States. Consider, for example, that the total amount of energy that is captured by US vegetation each year is ca. 58 quads (61.5 EJ), about half of which (28 quads or 29.7 EJ) is already harvested as agricultural crops and forest products and therefore not available for energy production (Pimentel et al., 1994a). As most of the remaining non-harvested biomass is required to maintain ecosystem functions and biodiversity, very little will be available for additional energy generation. Given that the current US energy use is around 100 quads per year (U.S. DOE, 2003a), it follows that biomass could at best supply only a relatively small and insignificant fraction of the total US energy demand.

The limited potential of biomass energy becomes even more obvious if land requirements are considered. To supply the current worldwide energy demand of 351 EJ per year (ca. 11 TW, see Table I) solely with biomass would require more than 10% of the Earth's land surface, which is comparable to the area used for all of world agriculture, i.e., ca. 1500 million ha (Hoffert et al., 2002; Nakicenovic et al., 1998b). If ethanol from corn were to substitute for 100% of the gasoline consumption in the US, all of the available US cropland (i.e., both active and inactive, totaling about 190 million ha) would have to be devoted to ethanol production, leaving no land for food production (Kheshgi et al., 2000). Clearly, there is simply not enough land for generating sufficient quantities of biomass energy to supply even the current worldwide energy demand, let alone the vastly increased energy needs that are predicted for the next 100 years (see Table I).

In addition, any significant increase in biomass energy production will cause land use conflicts with agriculture, particularly given the increased demand for food that will be driven by future population growth (Pimentel et al., 1984a). In any conflict between food and energy, it is unlikely that energy will win, and if it would, should be cause for serious ethical concern.

The World Energy Council estimated that an additional 1700 million ha of farmland will be required by 2100 and that 690–1350 million ha of additional land would also be needed for biomass to support a "high growth scenario" (Nakicenovic et al., 1998b). In order to achieve high biomass productivities, it will be necessary to use large-scale, high-tech agricultural methods such as intensive irrigation as well as the application of synthetic fossil-fuel-derived fertilizers and toxic chemicals such as pesticides and herbicides. According to Giampietro et al. (1997), fresh water demand for the production of biomass fuels would exceed the current fresh water supply by a factor of 3–104 in the 148 countries that were included in their study, thus clearly indicating that in addition to land, water may also become a limiting factor. As in modern agriculture, the large-scale application of fertilizers and toxic pesticides and herbicides is likely to create various negative impacts such as groundwater and surface water pollution, fish and bird deaths, species extinction, and increased health threats to biomass plantation workers (Pimentel et al., 1993).

Finally, it must also be recognized that growing biomass for fuel production directly conflicts with terrestrial carbon sequestration. This is because the establishment of large-scale biomass plantations would require the clearing of hundreds of million hectares of forests to create new agricultural land for growing short-rotation biofuel crops. In conclusion, biomass would only be able to supply a rather small fraction of the total energy demand, and any significant expansion of biomass energy would be restrained by the availability of land and water, potential conflicts with food production and terrestrial carbon sequestration, and environmental concerns such as chemical pollution, habitat loss, and species extinction. Consequently, other solar renewable energy sources will be needed to meet rising energy demands.

4.1.2. *Other Renewable Energy Sources*

In addition to biomass, other renewable energy sources such as passive solar, solar thermal, hydroelectric, photovoltaics, and wind power may also provide carbon-free energy in the future. However, all of these alternative energy technologies will have significant environmental impacts, particularly if deployed on a large scale.

Approximately one-fourth (i.e., 18.4 quads or 19.5 EJ) of all fossil energy consumed per year in the United States is used for space heating and cooling of buildings and for generating hot water (Pimentel et al., 1994b). As only 0.3 quads of fossil energy is currently saved by using passive solar technologies, tremendous potential exists for capturing more solar energy by redesigning buildings, particularly when combined with improved insulation (Pimentel et al., 1994b). Environmental impacts are likely to be minimal and would be generally limited to the removal of shade trees and visual glare from solar panels.

The direct capture of sunlight by solar thermal receivers consisting of computer-controlled sun-tracking parabolic mirrors that focus sunbeams to generate steam for electricity generation is another promising method for to producing renewable energy, particularly in desert regions. As solar thermal energy systems are capable of converting 22% of incoming sunlight into energy, compared to the approximate 0.1% efficiency of green plants which convert light to biomass via photosynthesis, much less land is required (Pimentel et al., 1994a). For example, only about 1100 ha are needed to produce 1 billion KWh per year (0.0036 EJ per year) (Pimentel et al., 1994b). Thus, if the entire annual US energy demand of ca. 100 quads or 106 EJ (U.S. DOE, 2003a) were to be supplied by direct solar thermal energy, 32 million ha or an area the size of a 570 km × 570 km (354 miles × 354 miles) square would be required. Potential environmental effects would be relatively minor for small solar thermal receivers, which may incinerate birds and insects that accidentally fly into the high-temperature portion of the beam (Pimentel et al., 1984b), but impacts may become significant for very large installations, which may destroy fragile desert ecosystems and cause changes in the microclimate (Pimentel et al., 1994b).

In the United States, hydroelectric dams provide annually about 3 quads (3.2 EJ or 870 billion KWh per year) or equivalently 3% of the total US energy demand (U.S. DOE, 2003a). Considering that the best candidate sites have already been exploited, and that many negative environmental impacts are associated with hydropower generation, it is unlikely that the hydroelectricity supply can be expanded significantly, i.e., probably up to 50–100 billion KWh per year in the United States (Pimentel et al., 1994b, 1984b). In fact, because of severe environmental problems such as obstructing salmon migration, it is even possible that some hydroelectric dams will eventually be dismantled, thereby reducing the contribution of hydropower to the US electricity supply.

Photovoltatic (PV) cells could in theory provide for all of the energy demand in the United States, particularly if the generated electricity were to be converted into a more versatile energy carrier such as hydrogen, thereby avoiding problems of intermittency and storage. Assuming a 10% solar to electricity conversion efficiency, an area the size of a 161 km × 161 km (i.e., 100 miles × 100 miles) square would have to be covered in a desert region such as Nevada to produce all of the energy currently consumed in the United States (Turner, 1999). To cover such an area would be detrimental to the affected fragile desert ecosystems and may also cause changes in the microclimate. These environmental impacts might be reduced by collecting solar energy in widely dispersed small units rather than using PV installations covering very large land areas. In addition, the manufacture of extremely large numbers of photovoltaic cells is likely to contribute to pollution problems (Holdren et al., 1980).

Finally, large windmills – if deployed by the millions – could also provide a fraction of carbon-free power. According to a US wind energy potential study by Elliott et al. (1992), at least 80 million ha (i.e., more than 40% of all available US farmland!) would have to be covered with windmills (50 m hub height, 250–500 m apart) to generate about 100 quads (106 EJ) of electricity which is equivalent to 100% of the current annual US energy demand (U.S. DOE, 2003a). It is highly questionable whether the public would tolerate huge wind farms that cover large land areas given concerns about blade noise and aesthetics. Consider, for example, that in Germany where more than three times as much wind energy is currently generated as in the United States (i.e., 14600 MW with ca. 15000 large windmills), public resistance against wind farms has developed to an intensity comparable to that against nuclear power plants, making the further expansion of wind energy capture highly unlikely (Dohmen and Hornig, 2004). Thus, at best only a rather small fraction (i.e., $\leq 5\%$) of carbon-free energy is likely to be generated in the future by large windmills that are selectively placed in the most windy locations.

In summary, with the possible exception of hydropower and biomass, renewable energy generation such as solar thermal, photovoltaics, windpower, and especially passive thermal can in principle be significantly expanded to produce carbon-free energy. However, before assuming – as many environmentalists do – that renewable energy is the best solution to global warming, it is necessary to carefully study the environmental impacts and the public attitudes towards large-scale solar energy installations, many of which may cover hundreds of square kilometers. As the history of technology has repeatedly shown, new technologies are often enthusiastically and optimistically adopted only later to be found to have serious shortcomings. Such naïve techno-optimism was responsible for the development of nuclear energy which was promised to be “too cheap to meter” but now is expensive and is vehemently opposed by the public because of safety and environmental concerns.

4.2. NUCLEAR ENERGY

Nuclear power plants currently (2000) provide about 6% (U.S. DOE, 2003a) of energy worldwide (8% in United States), all of it in the form of electricity. If nuclear reactors were to supply all of the world’s energy needs, all proven and recoverable uranium reserves would last only 6–30 years, indicating that nuclear power cannot be a long-term solution to global climate change (Hoffert et al., 2002). It may be possible to overcome uranium shortages with breeder reactors that generate fissionable plutonium (^{239}Pu) and/or uranium (^{233}U), but commercial breeding is currently illegal in the United States because of concerns over nuclear waste disposal and weapons proliferation (Hoffert et al., 2002). Given the recently escalated fears of terrorist attacks, it is unlikely that breeder reactors will be permitted in the near future, as they would substantially increase the availability of nuclear materials to terrorist organizations (Werbos, 1992).

In addition to problems of supplying sufficient amounts of fissionable materials in a safe manner, it would be extremely difficult to reverse the long-standing negative attitude of the public towards nuclear power. Because of public concerns over a variety of issues such as nuclear reactor safety, long-term storage of radioactive wastes, environmental problems involved in uranium mining and power plant operation (e.g., the release of radioactivity and waste heat to aquatic ecosystems), no new nuclear reactors have been built in the United States since 1978, and it appears unlikely that public attitudes will change toward nuclear power in the near future

(Goldemberg, 2000; Pimentel et al., 1994a; Sailor et al., 2000). In addition, it would be economically unwise to invest more capital into expensive nuclear power as it would only aggravate the problem of climate change. According to David Reed at the Rocky Mountain Institute, this is because "capital is finite: sinking it into an expensive solution means it is not available for cheaper ones. In the United States, each dollar invested in electric efficiency displaces nearly seven times as much carbon as a dollar invested in nuclear power – without nasty side effects (Reed, 2000)." In conclusion, nuclear power is unlikely to be a viable solution to the problem of global warming.

Based on the earlier analysis of various climate change mitigation options, it appears that no single technological approach, such as efficiency improvements, terrestrial, geologic, and ocean carbon sequestration, or renewable and nuclear energy[4] will by itself be able to bring about the drastic reductions in per capita carbon emissions that are required to stabilize atmospheric CO_2 concentrations at around 350 ppm. This is because each individual climate change mitigation technology has serious limitations, particularly if deployed on a large scale, ranging from limited carbon storage capacity and unpredictable environmental consequences to safety concerns, high costs, and public acceptance issues.

Given that a single technological development (i.e., the burning of fossil fuels) is the primary cause of global warming but that no single technology alone can address this environmental threat is, by itself, a sign of the seriousness of the problem we face. In response to this challenge, it has been proposed that a portfolio of different climate change mitigation technologies be used. For example, Pacala and Socolow (2004) have suggested that carbon emissions be stabilized at current levels (i.e., ca. 7 Gt C per year) by deploying seven different proven technologies, each of which would eliminate 25 Gt C over the next 50 years. However, the use of many different mitigation technologies would spread their associated risks spatially and over time but would not eliminate them. In fact, the risks may appear smaller than they really are because many of them would simply be transferred to future generations, as would be the case for ocean and geologic carbon sequestration and nuclear energy generation.

The recognition that drastic reductions in carbon emissions would involve significant technological and economic challenges, and would also entail many unpredictable risks may have led to the relaxation of the stabilization target for atmospheric CO_2 concentrations to 550 ppm (instead of 350 ppm) by the IPCC in their Summary for Policy Makers report (IPCC, 2001a). Although this will reduce the risks associated with the large-scale implementation of various climate change mitigation technologies, it will increase the risk of global warming, as stabilization of atmospheric CO_2 at 550 ppm will result in temperature increases of at least 2 °C (3.6 °F) by 2100, which will likely result in severe environmental consequences discussed earlier. The problem of deciding which of these risks are preferable is a very difficult, given the inherent limitations of reductionist science. However, many of these issues could be significantly reduced in complexity or possibly completely circumvented if the two key non-technological factors in equation 1, namely population (P) and per-capita consumption or “affluence” (GDP/P), were to be controlled in a way as to stabilize the climate.

5. Limiting Population Growth

The problem of human overpopulation has been succinctly summarized by Harvard sociobiologist E.O. Wilson:

> The pattern of human population growth in the 20th century was more bacterial than primate. When *Homo sapiens* passed the six billion mark we had already exceeded by perhaps as much as 100 times the biomass of any large animal species that ever existed on land. We and rest of life cannot afford another 100 years like that (Wilson, 2002).

Despite the fact that overpopulation is a serious problem and a key causative factor of the growth of CO_2 emissions as indicated in Equation (1), it is rarely considered when searching for effective solutions to global warming. Population specialist Lindsey Grant identified this important omission when he stated:

> The IPCC poses an insuperable task for itself by the way the problem has been defined. Like almost every group addressing almost every problem in the modern world, these scientists fell, perhaps unconsciously, into a fatal error: They treated population growth as an independent variable to which they must adjust, rather than a factor that must be controlled if a real solution to their problem is to be found. . . . Why did it not occur to them to say the obvious? The entire problem would be reduced to the extent that population growth could be stopped or turned around (Grant, 1996, p. 72).

The critical question is, to what extent can carbon emissions be decreased in the future by slowing or even reversing population growth?

The historical population growth rate has been on average about 1% per year during the last two centuries (Nakicenovic et al., 1998a) but the world’s global population is currently increasing at a rate of 1.6% per year (Nakicenovic, 1996). This growth in human numbers has been to a large degree responsible for the growth in energy use. For example, the growth of the world population from 1850 to 1990 was responsible for 52% of the concomitant 20-fold increase in energy consumption, whereas in the United States during the same period, population growth accounted for 66% of the 36-fold increase in energy use (and even 93% during 1970–1990) (Holdren, 1991). Given these historical trends, a rapid stabilization of the human population would have a significant impact on the reduction of future CO_2 emissions (Gaffin and O’Neill, 1997).

Several studies have shown that the projected population growth between 1985 and 2100 accounts for more than 33% of the future growth in CO_2 emissions globally and close to 50% in the developing nations (Bongaarts, 1992; The Population Council, 1994). If global fertility could be reduced by only 0.5 births per woman to achieve the United Nation's low variant population projection of 5.6 billion (Gaffin, 1998), the projected population would decrease by 18% in 2050 and by 46% in 2100. This would translate into similar reductions in energy demand and greenhouse gas emissions (Gaffin and O'Neill, 1998).

Given that population growth significantly aggravates global warming and therefore should be first halted and then reversed, the question becomes whether fertility can be reduced globally by 0.5 births per woman in a non-coercive way. It is generally accepted that the following three pre-conditions are necessary to bring about lasting decline in fertility (O'Neill et al., 2001; Weeks, 1992):

1. Women must become sufficiently educated to bring fertility into the realm of conscious choice, as universal basic education is recognized as the most successful antidote to traditional attitudes that prevent women from exercising full control over their reproductive choices. Education works directly to lower a woman's fertility by delaying the age of marriage and indirectly by introducing alternatives to a life with many children (Weeks, 1992). Recent studies have shown that improvements in female education alone could account for 40–67% of fertility decline in South American countries (Weeks, 1992) and that just 1 year of additional female schooling reduces fertility by 5–10% (Birdsall, 1994).
2. There must be a clear perception that reduced fertility is economically and socially advantageous. Traditionally, couples had many children because the benefits (i.e., free child labor, support in old age) outweighed their costs (i.e., childbearing and child care, education) (O'Neill et al., 2001). This cost-benefit ratio can be consciously changed to promote smaller families by implementing policies that provide a set of clear incentives (i.e., awards for small families) and disincentives (i.e., punishments for large families). Examples of incentives include payments to couples for delaying pregnancies and for undergoing surgical contraception, giving women the opportunity to enter the paid labor force, or providing priority for housing and educational placement for first and second children but not for higher-order births. Disincentives may consist of taxation for any children that are borne after the second one, and each successive child might result in higher user fees for maternity care, educational services, and other public resources (Weeks, 1992). Finally, social pressures may be applied to people with large families.
3. Couples must have access to family planning services and knowledge of birth control methods in order to limit their family to the desired size (Weeks, 1992). There is a desperate need for family planning, as there are currently at least 100 million women in the Third World who do not want additional children.

Because of insufficient access to contraceptives, about one in every five births is unwanted and 25 million abortions are carried out annually (Bongaarts et al., 1997).

As industrialization and economic development simultaneously created these three pre-conditions for fertility decline in the nations of Europe and North America and thus considerably slowed or even reversed the population growth, it is generally believed that more aggressive economic growth and development is needed in the Third World to bring about a large reduction in birth rates. However, according to population specialist John Weeks, economic development would not only take too long to cause the required rapid decline in fertility, but the three pre-conditions can often be created without resorting to western-style economic growth in Third World countries:

> In developed nations the path to lower fertility has been alongside the road to economic development, and the classic statement of the demographic transition spotlights development as the major stimulus to fertility limitation. From that concept were born the maxims that 'development is the best contraceptive' and 'take care of the people and population will take care of itself'. The problem with development as a policy initiative is that it is a much slower process than imitation. But we do not need to imitate our past. We simply must extract the appropriate lessons. One of the crucial elements of industrialization was that it reversed the flow of income between children and parents: Children became economic liabilities rather than assets. Furthermore, it was built on the back of a better-educated labor force that increasingly moved toward maximizing human capital by bringing women into the paid labor force. The lesson, then, is that economic development appears always to be associated with fertility declines because the process of development incorporates a complex set of direct and indirect incentives to limit family size along with direct and indirect disincentives to have large families. The task of the modern policy planner is to sort through those factors that may be implemented independently of the process of development and that, through diffusion rather than innovation, may lead to lower fertility (Weeks, 1992, p. 184).

Both Singapore and Iran provide good examples of extremely rapid fertility declines that were brought about by specific population policies rather than by intensive western-style economic development: In Singapore, the average number of children per woman decreased from 4.5 in 1966 to only 1.4 in 1988 (Weeks, 1992). Iran has now reached European birth rates after intensive state-supported family planning campaigns initiated in the late 1980s, resulting in the birth of 37 million fewer people than were predicted by 2006 on the basis of high pre-1980s fertility levels (Muir, 2002). Thus, western-style economic development (and GDP growth) is not necessary to slow population growth in the Third Word, a fact which is crucial as atmospheric CO_2 concentrations cannot be realistically stabilized at present levels if GWP is allowed to increase 12–26-fold by 2100, as predicted (see Table I).

Finally, compared to often proposed technological solutions such as carbon sequestration and the development of carbon-free energy sources, controlling population growth is one of the cheapest methods to avoid future CO_2 emissions. According to an analysis by Birdsall (1994), the costs of reducing births through family planning and female education are US$ 4–11 and US$ 3–9 per ton of carbon avoided, respectively, which is generally lower than the US Department of Energy's ambitious goal of US$ 10 per ton of carbon sequestered or avoided (U.S. DOE, 2003b) (*Note*: The cost of carbon sequestration using the various proposed innovative technologies, with the exception of reforestation, are currently in the range of US$ 100–300 per ton of carbon (U.S. DOE, 2003b) and thus do not even closely approach this target). Considering that the control of population growth has many other environmental, social, and even political benefits, high priority should be given to this no-regrets policy for avoiding the growth of future CO_2 emissions.

6. Limiting Economic Growth

Based on the earlier analysis, it appears that many technologically advanced approaches to slowing global warming such as geological and ocean carbon sequestration or the large-scale generation of solar and nuclear energy may have numerous negative consequences such as known deleterious as well as unknowable and unpredictable environmental effects, and therefore are likely to be opposed by the public. Other than controlling fertility, only a few technological no-regrets options remain: Terrestrial carbon sequestration, passive solar energy capture for buildings, and small-scale generation of solar energy using photovoltaics, windpower, or solar thermal, and, most importantly, drastic improvements in energy efficiency. Indeed, total carbon emissions could probably be cut by 90% or more within the next 100 years if efficiency could be increased fivefold, all forests and soils restored to their original (pre-1750) carbon storage levels, and solar energy generation cautiously expanded in a way that circumvents the environmental impacts associated with large-scale installations. But this extreme reduction in carbon emissions, which is required to stabilize atmospheric CO_2 concentrations at around 350 ppm in order to avoid most predicted threats of global warming, is only possible if the size of the world economy (GWP) is kept constant (see Equation (1)). As was mentioned earlier, efficiency improvements, however dramatic, are useless in the long run if economic growth continues unrestrained (see Table I for the predicted 12–26-fold increase in GWP by 2100, and 4–19-fold increase in per capita affluence).

There would, in principle, be no problem with continued economic expansion if either economic growth could be detached from energy use (i.e., industrial and economic activities could ultimately be carried out without energy) or energy could be generated without causing negative environmental impacts. Unfortunately, it is technically impossible to satisfy either condition.

Regarding the decoupling of economic activities from energy use: Although historical trends in decreasing energy intensities (i.e., primary energy/GDP) are often viewed as evidence that the link between energy use and the economy is becoming weaker with time, it is obvious that they cannot be decoupled completely, as energy will always be required to carry out economically useful work. In fact, the industrial revolution and the enormous economic expansion was possible only because large amounts of cheap energy in the form of fossil fuels (i.e., coal, oil, and natural gas) became available. Economic wealth has been and is constantly being created with the help of innovative technologies that convert available energy into useful products and services. Without input of energy, no technological device – however ingeniously designed – will be able to function. The profound importance of energy in wealth creation becomes even more apparent if one converts per capita energy use into the equivalent of human servants or "energy slaves," who, before industrialization, were the only source of "energy service" in the form of labor. The per capita energy use in the United States is about 270 KWh per day which corresponds to 90 "energy slaves" per person delivering about 3 KWh of labor per day (Hall et al., 2001). Cheap available energy will obviously be as necessary for continued wealth generation and economic growth as were servants and slaves for creating riches for landowners and nobility throughout history.

Regarding the generation of energy without concomitant negative environmental impacts: The second law of thermodynamics dictates that any type of energy generation – whether renewable or non-renewable – has negative environmental impacts. In the case of non-renewable energy sources such as coal, oil, natural gas, and uranium, the generation of energy involves the conversion of these low-entropy materials into high-entropy wastes such as dispersed CO_2, SO_x, NO_x, and radiation (Daly, 1980, 1996; Ruth, 1993). As the use of non-renewable energy sources results in the increase of entropy in the geosphere and entropy increase is believed to be a causative factor in environmental disruptions (Glasby, 1998; Huesemann, 2001; Kuemmel, 1989; Ruth, 1993), it is impossible to avoid environmental problems by relying on fossil or nuclear energy. Similarly, when solar energy is diverted for human purposes, less is available to maintain the complex (low-entropy) structures and processes found in nature, thus resulting in various negative environmental impacts. In short, any type of energy generation will have adverse environmental consequences.

Even if large amounts of energy could be generated in a entirely environmentally benign way, the problem remains as to how the use of this energy will affect the environment. It should be remembered that most, if not all, major environmental problems encountered today are the result of industrialization and economic growth that have been driven by the availability of cheap fossil energy. Thus, it is probably fortunate that it is impossible to generate large amounts of environmentally friendly energy, as more available energy would most likely translate into additional environmental destruction. This point was forcefully made by Stanford biologist Paul Ehrlich who said that "giving society cheap abundant energy at this point would be equivalent to giving an idiot child a machine gun (cited in Simon, 1996, p. 182)." According to William Rees, considerable restraint would be required to use energy wisely:

> The sun beams 175000 terawatts to our planet, compared to just 10 terawatts of commercial energy, mainly fossil fuels, used by the human economy. However, imagine the impact of an unlimited energy supply, if not used wisely or with restraint. We have run down much of the planet with just 10 terawatts! Unlimited cheap energy could simply expand human activities further, depleting other natural capital stocks until we run into some new – and probably more severe – limiting factor. It may not be energy resources, but the waste assimilation capacity of our planet, that becomes the most limiting (Rees and Wackernagel, 1995, p. 27).

Given that all industrial and ecological activities require energy and that large amounts of energy cannot be generated or used without negative environmental impacts, it follows that western-style industrial and economic growth is guaranteed to cause some type of damage to the environment.[5] The question then becomes: How much additional economic growth is achievable without causing large and irreversible environmental impacts?

Although the exact answer to this question is not known, it is obvious that even current human activities are having major negative impacts on the environment and that a predicted 12–26-fold increase in GWP (see Table I) would most certainly be disastrous. Consider, for example, that the ecological footprint – the average amount of productive land and shallow sea appropriated by each person for food, water, housing, energy, transportation, commerce, and waste absorption – is around 1 ha (2.5 acres) in developing nations, but about 9.6 ha (24 acres) in the United States (Wilson, 2002). If every person in the world enjoyed the same level of material consumption as in the United States, three to four additional planets would be required, and even more (up to 12) if future population and economic growth is taken into account (Rees and Wackernagel, 1995; Wilson, 2002). According to Rees and Wackernagel (1995), the originators of the ecological footprint analysis, "there are real biophysical constraints on material growth after all. Not even the present world population ... let alone the 10 billion expected by 2040 can hope to achieve North America's material standard of living without destroying the ecosphere and precipitating their own collapse" (pp. 89 and 90). Similarly, E.O. Wilson warns that

> the constraints of the biosphere are fixed. The bottleneck through which we are passing is real. It should be obvious to anyone not in euphoric delirium that whatever humanity does or does not do, Earth's capacity to support our species is approaching the limit. We already appropriate by some means or other 40 percent

> of the planet's organic matter produced by green plants. If everyone agreed to become vegetarian, leaving little or nothing for livestock, the present 1.4 billion hectares of arable land (3.5 million acres) would support about 10 billion people. If humans utilized as food all of the energy captured by plant photosynthesis on land and sea, some 40 trillion watts, the planet could support about 16 billion people. But long before that ultimate limit was approached, the planet would surely have become a hellish place to exist (Wilson, 2002, p. 88).

In summary, it is highly questionable that 12–26-fold increases in GWP (as predicted by the IPCC and shown in Table I) are even remotely achievable because of biophysical constraints and the inability of technology to sufficiently uncouple energy and materials use from the economy (Cleveland and Ruth, 1999; Huesemann, 2003).

One option, of course, is to continue along the current path of technological development and economic growth, hoping that scientific and technological innovations can solve all the problems created by energy generation and economic expansion as fast as they arise. This approach is characteristic of so-called "complex societies" that invest in the development of complex solutions to self-created problems (Tainter, 1988, 1995). As more and more time and money is devoted to scientific research, technological innovation, education and training, information processing, government regulations, and other command and control strategies to address problems such as global warming, the proposed solutions will become more complex and expensive, particularly given the law of diminishing returns characteristic of R&D activities. This high level of complexity can only be maintained by the continued, and ideally increasing, availability of cheap energy. In ancient complex societies such as the Roman Empire, the solution to declining marginal returns was to capture new energy subsidies by territorial expansion, which provided access to cheap agricultural products, livestock, and human labor (Tainter, 1988). In present times, the complexity of industrialized societies is maintained by the cheap availability of fossil fuels.

The core problem is that a continued supply of cheap energy is needed to solve the problem of global warming which, in turn, was created in the first place by the use of cheap energy, i.e., fossil fuels. Unfortunately, it is not clear at this point how the necessary large amounts of carbon-free energy can be generated in an inexpensive way. The price of fossil fuels will certainly increase in the future, either because of increasing scarcity, particularly after peak production has been reached (Campbell and Laherrere, 1998; Romm and Curtis, 1996), or because of increasing costs associated with decarbonization and carbon sequestration. In addition, renewable energy is still significantly more expensive than fossil energy, and it will require intensive R&D to make solar energy even competitive with fossil fuels, let alone cheaper.

If we choose to continue along the path of increasing complexity and economic growth, it is therefore imperative that new sources of cheap energy are found soon – otherwise our highly industrialized societies could be threatened by irreversible collapse.[6] This, according to Joseph Tainter who has extensively studied the collapse of complex societies throughout history, would be catastrophic to civilization as we know it:

> Complex societies historically are vulnerable to collapse, and this fact alone is disturbing to many. Although collapse is an economic adjustment, it can nevertheless be devastating where much of the population does not have the opportunity or the ability to produce primary food resources. Many contemporary societies, particularly those that are highly industrialized, obviously fall into this class. Collapse for such societies would almost certainly entail vast disruptions and overwhelming loss of life, not to mention a significantly lower standard of living for the survivors (Tainter, 1988, p. 209).

If investments in more complexity will not solve the problem of global warming and may even cause societal collapse because large amounts of cheap energy may not become available fast enough, what, then, are the alternatives? An obvious option would be to look for solutions that are less complex (and therefore less energy intensive) and which would not require immense investments in science and technology. Examples include reforestation, agricultural soil management, passive solar energy capture for buildings, simple efficiency improvements such as better insulation, and small-scale renewable energy generation (e.g., windmills). However, these simple steps would be effective only if there were a strong commitment to population control and a reversal of economic expansion, i.e., to a transition to a steady-state economy where the total throughput of matter-energy is stabilized at sustainable levels (Daly, 1980; 1996).

7. Conclusions

Based on the earlier analysis, there are basically three different options for addressing the threat of global warming. The first is to continue “business as usual,” i.e., maintain a strong commitment to unlimited economic growth that will be fueled – as it has been in the past – primarily by non-renewable fossil energy. This path would lead to a tripling of atmospheric CO_2 concentrations to ca. 1000 ppm by 2100 (see Table I), which, in turn, would not only result in very large global temperature increases (>4 °C; >7 °F) but also catastrophic weather events, substantial sea level rise, and possibly even abrupt climate change (NRC, 2002). Given the seriousness of these potential threats, it would be highly imprudent to continue “business as usual.”

A second option is to continue along the present path of economic expansion but simultaneously reduce carbon emissions sufficiently to stabilize atmospheric CO_2 concentrations at around current levels (i.e., ca. 350 ppm), thereby minimizing potential risks associated with global warming to the greatest possible extent. In order to meet this stringent 350 ppm target, per capita carbon emissions in industrialized countries would have to be reduced at least 20-fold during the next 50–100 years, an ambitious goal that clearly poses many significant scientific, technological, economic, and political challenges. Although large improvements ($\geq$5-fold) in energy efficiency are in principle possible, these will per se not result in a reduction in carbon emissions if, as predicted by the IPCC, the size of the global economy expands 12–26-fold by 2100 (Table I). Terrestrial carbon sequestration via reforestation and improved agricultural soil management has many environmental advantages but only limited CO_2 mitigation potential, because the global terrestrial carbon sink (ca. 200 Gt C) is small relative to the size of fossil fuel deposits ($\geq$4000 Gt C). By contrast, very large amounts of CO_2 can potentially be removed from the atmosphere via sequestration in geologic formations and oceans, but this carbon storage is not permanent and is likely to create many unpredictable environmental consequences. Renewable energy can, in theory, provide large amounts of carbon-free power. However, biomass and hydroelectric energy can only be marginally expanded, and large-scale solar energy installations are likely to have significant negative environmental impacts. Expansion of nuclear energy is highly unlikely due to concerns over reactor safety, radioactive waste management, weapons proliferation, and cost.

If economic growth and the associated energy demand continue to increase as predicted, a portfolio of different climate change mitigation approaches will have to be selected because no single technology by itself can address the challenge of reducing per capita carbon emissions to the required 0.1 tons C per year. By deploying a wide range of different technologies, the risks will be spread spatially and over time. As a result, they may appear smaller than they really are because many risks would be transferred to future generations, as would most obviously be the case for ocean and geologic carbon sequestration, and nuclear energy generation.

The challenge of developing new and technologically complex climate change mitigation technologies, and their associated risks could be avoided to some extent by simply relaxing the atmospheric CO_2 concentration target to 550 ppm (IPCC, 2001a). This would, however, only result in a shift from one set of risks to another, i.e., from those associated with the implementation of climate change mitigation technologies to those associated with global warming. The dilemma of choosing between these two negatives could be resolved to a large extent by halting immediately both economic growth and population expansion.

Thus, the third option entails a transition to a steady-state economy where the total throughput of matter energy is stabilized at sustainable levels (Daly, 1980, 1996). This would not merely address the root cause (i.e., economic expansion) of most environmental problems including global warming but also would allow for the implementation of only relatively simple and low-risk climate change mitigation approaches such as reforestation, agricultural soil management, passive solar energy capture for buildings, simple efficiency improvements, and small-scale renewable energy generation.

The idea of abandoning our belief in unlimited economic growth will appear disagreeable to many, particularly because economic growth is generally seen as a solution to countless problems ranging from poverty to environmental pollution. But it should be recognized that throughout most of human history, periods of economic expansion have always been transient (Hubbert, 1992) and, according to Daly, "in the long run, stability is the norm and growth the aberration" (Daly, 1994, p. 104). It is unfortunate that even "sustainable development" is commonly thought to mean more economic growth with better environmental protection (Huesemann, 2003) despite the fact that it was originally defined in the Brundtland Report "to ensure that humanity meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 9). It is not necessary to resort to more global economic growth to satisfy the basic needs of humanity which consist primarily of food, shelter, and healthy living conditions. Rather, basic needs for all could be met by the redistribution of wealth which would involve some modest economic development of Third World nations but a significant reduction in material consumption in the "overdeveloped" industrialized countries.

The proposal of reducing frivolous consumption in industrialized nations may be unpopular, but it should be recognized that our unwavering commitment to economic growth and materialism has been an utter failure in at least two ways: First, it has precipitated a variety of environmental problems, including global warming. Second, it has failed to fulfill its major promise of increasing people's happiness and well-being. Regarding the latter point, there is clear evidence that, as soon as basic material needs have been satisfied, further increases in the material standard of living do not result in greater happiness (Kasser, 2002; Lane, 2001). For example, although the average income after taxes more than doubled in the United States from 1960 to 1990, the fraction of people who consider themselves "very happy" remained virtually constant at around 35% (Myers and Diener, 1996).[7] This is not unexpected, as relative rather than absolute income determines social status and therefore feelings of superiority, accomplishment, and pleasure for many people (Durning, 1992). As long as per capita income increases "across the board" due to economic growth, social status and overall happiness remain unaffected.

It appears then that economic growth, beyond that required to meet basic needs, is not only damaging to the environment but also useless in increasing human happiness. For the sake of human well-being, the environment, and the future of the planet in general, it would be highly beneficial if we were to begin satisfying our needs for fulfillment in non-materialistic ways, as has been done throughout most of human history: By enjoying close relationships among family and friends, as well as becoming involved in the myriad of social, artistic, religious, and spiritual activities that define people's identity and culture (Durning, 1992; Trainer, 1995b).

In the final analysis, the threat of global warming is therefore not a purely technical or scientific problem, but it also poses a serious challenge to our core values that equate material satisfaction and economic growth with happiness and well-being. It is unlikely that global warming can be successfully averted unless we seriously reconsider our commitment to unlimited economic growth and consumption, and instead find fulfillment in less materialistic ways. Why should we continue along a path that not only aggravates global warming, but also does not improve our sense of well-being? It is time to reexamine our priorities.

8. Disclaimer

The views expressed in this article are solely those of the author and do not necessarily reflect the official position of Battelle Memorial Institute, Pacific Northwest National Laboratory, or the U.S. Department of Energy.

Notes

1. This equation is related to the more commonly used I = PAT equation, see Ehrlich and Holdren (1971) and Graedel and Allenby (1995).
2. The transition to a hydrogen economy is by itself a formidable technical challenge, a discussion of which is beyond the scope of this paper.
3. In this context, it is also interesting to note that all fossil fuels that were burned worldwide in 1997 were originally created from organic matter, containing approximately 44×10^{18} g carbon, which is more than 400 times the net primary productivity of the planet's current biota (Dukes, 2003).
4. In addition, the transition to carbon-free energy will be an economic and technological challenge. According to a recent analysis by Caldera et al. (2003), approximately 900 MW (±500 MW) of carbon emission free power generating capacity would have to be installed each day over the next 50 years to achieve climate stabilization at a 2 °C warming. This is equivalent to a large power plant becoming functional somewhere in the world every day.
5. This conclusion is also confirmed by the second law of thermodynamics (see Huesemann, 2003; Georgescu-Roegen, 1980).
6. This prediction of collapse is also in agreement with the second law of thermodynamics, which states that energy is required to create and maintain complex structures (Nicolis and Prigogine, 1977).
7. Even worse, while the per capita GNP rose by 49% in the United States from 1976 to 1998, the per capita "genuine progress," as defined by the economy's output with environmental costs subtracted and added weight given to education, health, etc., declined by 30% (Myers, 2000).

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