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Achieving CO_2 Stabilization: An Assessment of Some Claims Made by Working Group III of the Intergovernmental Panel on Climate Change

Chris Green[1,2]
H.D. Lightfoot[2]

ABSTRACT

The Intergovernmental Panel on Climate Change (IPCC) issued its Third Assessment Report in July 2001. When President Bush announced the U.S. would not ratify the Kyoto Protocol, he also asked the U.S. National Academy of Science (NAS) to assess the IPCC's climate science analysis and conclusions – the domain of the IPCC's Working Group I. The NAS supported the IPCC's climate science, laying to rest most doubts about predictions that the build-up of greenhouse gases in the atmosphere is likely to generate changes in the world's climate in the 21st century. However, no assessment was made of the report of the IPCC's Working Group III, charged with assessing the scope for and impact of policies to mitigate greenhouse gases. While the report of WG III contains a large amount of useful information, it makes some claims that require scrutiny. This paper focuses on the validity of the claim made by WG III that "Known technological options could achieve a broad range of atmospheric CO_2 stabilization levels, such as 550 ppmv, 450 ppmv or below" without requiring "drastic technological breakthroughs." This claim is made despite the fact that it will take a 17 to 20 fold increase in carbon-free power to achieve stabilization at 550 ppmv by 2100. This paper shows that the claim appears to rest on (1) IPCC reference emission scenarios that build in 110 year average annual rates of energy intensity decline that exceed historical experience and estimates of what is technologically attainable on a century-long basis; (2) IPCC reference scenarios that build in rates of carbon intensity decline that are three to five times the global average annual rate of decline experienced in the past few decades; (3) renewable energy potentials that are eight times larger than the energy actually attainable from solar, wind, and biomass sources; and (4) estimates of the economic cost of stabilization that appear to take no account of the possibility that there may be upper limits to the long-term rate of decline in energy intensity and to the amount of carbon-free energy that renewable energies can be expected to deliver. The paper's assessment of the IPCC's emission scenarios, renewable energy estimates, and stabilization cost estimates, suggest that WG III's claims regarding the capacity of "known technological options" to stabilize climate, and its estimates of the cost of achieving atmospheric CO_2 stabilization, are not valid.

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[1] Green is Professor of Economics, McGill University.
[2] Lightfoot and Green are members of McGill University's Centre for Climate and Global Change Research.

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INTRODUCTION

Future historians may well regard the year 2001 as a watershed for climate policy. The year began with the 1997 Kyoto Protocol still unratified, and the developed nations divided over issues necessary to its implementation. The U.S. was about to inaugurate a new President, no more committed to the Kyoto Protocol than the U.S. Senate which, in 1997, had voted 95-0 to refuse to ratify any agreement which did not include commitments by less developed countries to reduce their GHG emissions. At the scientific level, the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) was released in mid-2001. In advance, early in 2001, the IPCC made available at its web site the Summary for Policy Makers (SPM) and, a little later, the Technical Summary (TS) of each of its three Working Groups.

In March 2001, President Bush announced that the U.S. would not ratify the Kyoto Protocol. In rejecting the Kyoto pact, Bush declared it “fatally flawed” – and that it would substantially damage the economy if the U.S. attempted to meet its Kyoto commitment. The President indicated that at some future point the U.S. would set forth its own approach to curbing greenhouse gas (GHG) emissions. Despite U.S. rejection, 178 nations meeting at Bonn, Germany in July 2001, ironed out their differences and compromised on language for the Kyoto Protocol. They pledged to ratify the Kyoto Protocol, with or without the U.S., in 2002, the 10th anniversary of the international congress at Rio de Janeiro (1992) which inaugurated a global climate policy. At Marrakech, in October 2001, these nations

[2] Green is Professor of Economics, McGill University.
[2] Lightfoot and Green are members of McGill University’s Centre for Climate and Global Change Research.

compromised on compliance rules and other details not completed at Bonn. In the meantime, the U.S. Congress has begun to consider a number of legislative initiatives that would curb GHG emissions and promote technologies capable of achieving these reductions.

This paper concerns climate policy. We are particularly interested in the climate policy implications of the Third Assessment Report (TAR) of the IPCC. The TAR is divided into three parts, each the product of a Working Group (WG). Climate science is the domain of WG I; impacts of and adaptation to climate change is the domain of WG II; WG III, made up mainly of economists and technologists, is responsible for assessing the scope for and impact of policies to mitigate greenhouse gases. Our paper focuses on the report of WG III (Metz, et al, 2001) and the accompanying Special Report on Emission Scenarios (IPCC, 2000).

We take it as firmly established that the build-up of GHGs in the atmosphere in the 21st century will raise the global average temperature and change our climate in other ways, and that GHGs almost surely account for at least some of the 0.7^{o}C in the past century. Still uncertain is how much change there will be, estimates ranging from 1^{o}C to more than 4^{O}C, how fast change will occur, and what the regional/local manifestations of these changes will be. These and other uncertain elements in climate change will play an important role in determining the magnitude of the impact of climate change (global warming) on human society and the environment.

When he rejected the Kyoto Protocol, President Bush initially injected some doubts about the IPCC's climate science analysis and conclusions, the domain of Working Group I (WG I). The Bush administration asked the U.S. National Academy of Sciences (NAS) to provide "assistance in identifying the sources of climate change where there are the greatest certainties and uncertainties". The NAS blue ribbon panel of climate scientists was also asked for their "views on whether there are any substantive differences between the IPCC reports and the IPCC summaries".

In its answers to the fourteen questions posed by the Bush administration, the NAS committee supported the report of WG I on climate science, although it made clear that important uncertainties remain. On the IPCC's report and its summaries, the NAS committee has this to say:

> "The committee finds that the full IPCC Working Group (WG I) report is an admirable summary of the research activities in climate science, and the full report is adequately summarized in the Technical Summary. ... The Summary for Policy Makers reflects less emphasis on communicating the basis for uncertainty and a stronger emphasis on areas of major concern associated with human-induced change" (NAS, 2001: 5)

As a matter of fact, the NAS Committee report, written for policy makers, is itself an excellent summary of <u>what is known</u> scientifically about climate change, and clearly explains where the uncertainties reside. It would be difficult to conclude other than that climate science provides a coherent and convincing case for the prediction that the global climate will warm due to the build-up of greenhouse gases (GHGs) in the atmosphere – and that it has already begun to do so.

<u>MITIGATION AND STABILIZATION</u>

Accepting the predictions of climate science provides a strong basis for having a climate policy. But precisely what policy depends on a number of factors, including available energy technologies and the economic impact of curbing GHG emissions. The scope for curbing GHG emissions at a cost that does not exceed the damage created by climate change depends heavily on: (1) the attainable rate of improvement in energy efficiency (the chief determinant of the rate of decline in energy intensity); (2) the capability of replacing fossil fuels with carbon-free energy sources (nuclear, hydro and the renewables, solar, wind, biomass, and geothermal); and (3) the feasibility of sequestering the carbon dioxide produced when fossil fuels are burned. Thus, at the core of any policy to abate or "mitigate" GHG emissions are achievable rates of decline in energy intensity and the decarbonization of the energy supply. These issues are treated extensively in the TAR of the IPCC's WG III, which is aptly entitled "Mitigation". That report, relies, in part, on the Special Report on Emissions Scenarios (SRES). The latter report is of particular interest because the SRES scenarios provide a background or benchmarks against which policies to mitigate GHG emissions are applied. Thus, any assessment of mitigation policies also requires an assessment of what is embedded in the benchmark emission scenarios. We start with these.

a) <u>The Special Report on Emission Scenarios</u>

Early in the 1990's, the IPCC developed a number of carbon dioxide emission baselines, with IS92a coming to stand as the virtually universal "business as usual" (BAU) scenario against which emissions policies could be measured. In 1998, the IPCC commissioned a new set of scenarios (the SRES) by a subgroup of climate, economic, and energy specialists attached to WG III. The SRES encompasses four story lines around which are built 40 emission scenarios. For each story line, there is a central or "marker" scenario. Instead of any one scenario dominating as had IS92a, each of the four basic story lines about how the world will develop in the 21st century has been accorded a more-or-less equal degree of credibility by WG III. Subsequently, the A1 story line was broken into three scenarios, so that there are now six basic SRES scenarios. Each of the six represents a family of more detailed scenarios, and each of these reflects different assumptions about the main economic and technological factors that determine carbon emissions. (IPCC, 2000).

Two of the factors influencing carbon emissions are future improvements in energy efficiency and the availability of carbon-free energy. Hoffert <u>et al</u> (1998) demonstrated that, given the rate of growth of gross domestic product (GDP), the amount of carbon-free power (or energy) required to stabilize the atmospheric CO_2 concentration is inversely related to the rate of decline in energy-intensity – a decline that is chiefly due to improvements in energy efficiency. A useful way to characterize carbon emission scenarios is, therefore, in terms of their (implicit) rates of energy intensity decline and the increase in carbon-free energy, keeping in mind that scenarios may also differ due to different assumptions made about the rates of population and economic growth (GDP).

We have examined the six basic SRES scenarios for what they imply for: (a) average annual rates of improvement in energy efficiency – i.e., declines in energy per unit output – over the 110 year period, 1990-2100; and (b) amounts of carbon-free energy – measured in exajoules of energy per year (EJ/yr) and terawatts (TWs) of power available to meet energy consumption needs in 2100. (1 EJ = 10^{18}J; 1 TW = 10^{12}W; 1 TW = 31.5 EJ/yr.) These and other characteristics of the six SRES scenarios are presented in Table 1. Note that the A1 series (A1B, A1T, and A1F1) all assume much faster rates of growth of GDP than do the other three scenarios, A2, B1 and B2.

It is of interest that four of the six scenarios imply average annual rates of decline in energy per unit output substantially above the global one percent average annual rate of decline experienced in the past thirty years. It is also evident that all six scenarios imply amounts of carbon-free energy that very substantially exceed the 57 EJs (1.8 TWs) of carbon-free power available in 1999. In other words, the implicit assumption of those who developed the SRES scenarios is that even without policies to mitigate emissions, the world will be able to maintain or, in most cases, substantially exceed its current rates of improvement in energy efficiency – and do so for 110 years. Further, each scenario assumes that over the course of the 21st century the amount of carbon-free energy available to meet energy consumption needs will increase, in four cases by substantially more than an order of magnitude.

Despite the generally optimistic view of how energy efficiency and carbon-free energy will evolve, CO_2 emissions continue to grow in five of the six scenarios, with only B1 holding out the possibility of stabilization of carbon concentration at 550 ppmv or less by 2100. (AIT stabilizes at 550 ppmv after 2100.). This is clear from col. 6 in Table 1. The exceptional case of B1 is based on the remarkable assumption that for a 110 year period (1990-2100), the world can reduce energy per unit output at an annual average rate in excess of 2.1 percent. One may entertain doubts about such a scenario. No evidence is provided that an average annual rate of decline in excess of 2.0 percent, or even a 1.5 percent rate, for very long periods is consistent with anything we know about absolute levels of energy efficiency. Indeed, in separate research that we have undertaken (Lightfoot and Green 2001b), and summarized in Appendix A, we find that even with very substantial shifts in economic activity from high to low energy intensive industries and sectors, it will be difficult to exceed an annual rate of decline in energy per unit output of 1.0 percent as an average for 110 years. Our findings suggest that upper limits on energy efficiency would keep the long-term average annual rate of decline in energy-intensity to under 1%. Adding in the impact of shifts from more to less energy intensive activities raises the long-term rate of energy intensity decline to between 1.0 and 1.1%. The assumption of a 1% average annual rate of decline in energy-intensity, E/Y, where E is energy in exajoules and Y is real, or inflation adjusted, GDP, is therefore a reasonable one.

Table 1 also provides estimates of how much carbon-free energy would be needed to stabilize the atmospheric CO_2 concentration at 550 ppmv for each scenario, taking as given all the other assumptions, including those relating to the rate of decline in energy per unit output.

The required amounts of carbon-free energy (power) are indicated in column 7. In all but the exceptional case, B1, huge amounts of carbon-free energy (power) will be needed to stabilize atmospheric CO_2 concentration. Table 1, col. 8, also tells us what average annual rate of decline in carbon per unit energy (i.e. the rate of decarbonization) is implied by the growth of carbon-free energy (power) needed to achieve stabilization in each of the scenarios. For all but B1, these rates are three to five times the 0.3 global average annual rate of decline experienced in the past few decades.

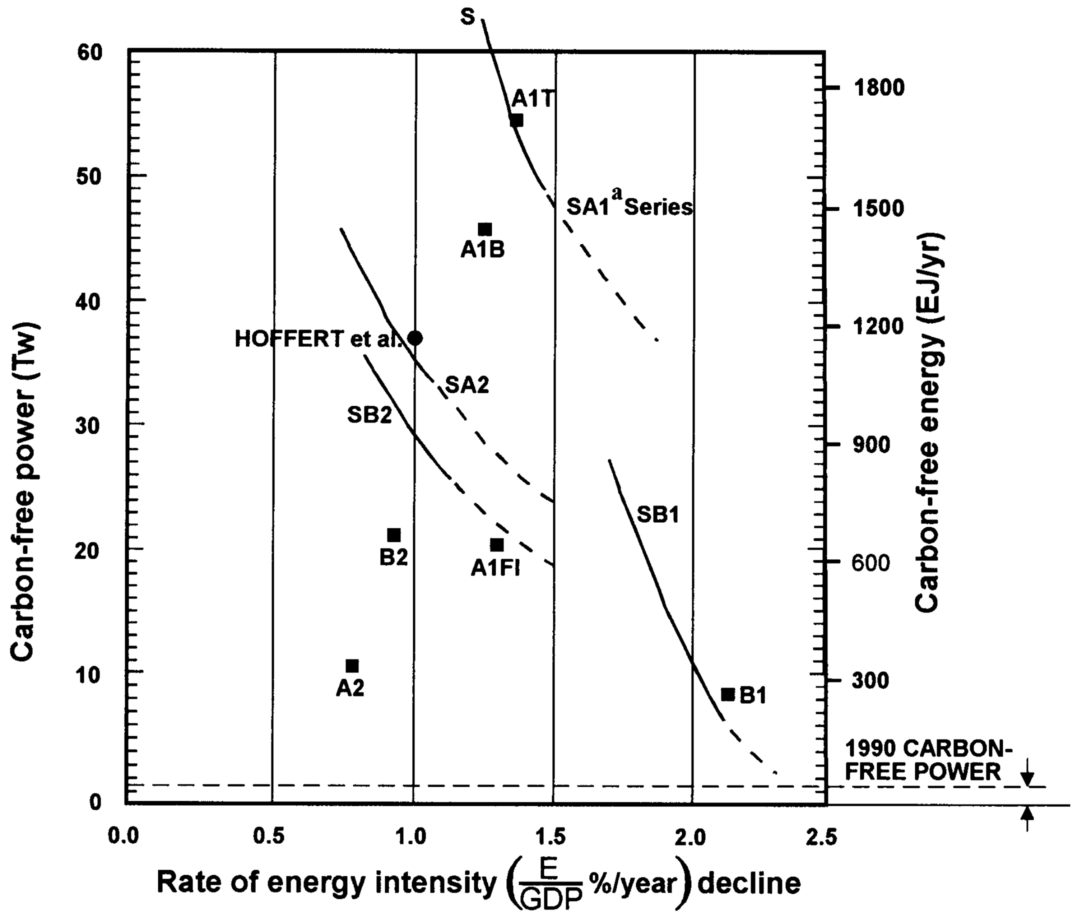
Figure 1 pulls together the key elements of Table 1 to provide the reader with a "birds-eye" view of what the SRES scenarios imply in terms of carbon-free power (energy) and rates of decline in energy intensity. It also indicates what more it would take in terms of additional carbon-free energy and/or higher rates of energy intensity decline to stabilize CO_2 concentration at 550 ppmv by the last half of the 21st century. In the absence of absolutely extraordinary rates of decline in energy intensity, ones that simply are not credible over the course of a century, it is clear that it will take a huge amount of carbon-free energy to achieve stabilization. (See the curves indicating the tradeoff between carbon-free energy and higher or lower rates of decline in energy intensity for each scenario.)

b) <u>Third Assessment Report of WG III</u>

When President Bush asked the NAS to comment on the climate science findings and conclusions of IPCC WG I, he did not include an assessment of the findings of WG III, the working group responsible for an analysis of the prospects for and impacts of mitigation of greenhouse gas emissions. However, at least one important statement in the Summary for Policy Makers (SPM) of WG III may not bear up to the same scrutiny that the NAS applied to the findings on climate science by WG I. In its SPM, WG III states that:

(INSERT TABLE 1 HERE)

FIGURE 1[(1)]



a = roughly applies to A1T, A1B, and A1FI
S = stabilization
(1) Adapted from Hoffert et al., 1998

"... known technological options could achieve a broad range of atmospheric CO_2 stabilization levels, such as 550 ppmv, 450 ppmv or below over the next 100 years or more". (Metz, et al, 2001: 8)

By "known technological options" WG III is referring to:

"technologies that exist in operation or pilot plant stage today. It does not include any new technologies that will require drastic technological breakthroughs..."
(Metz, et al, 2001: 8))

Taken at face value, these statements appear to imply that the current goals of climate change policy are not only achievable (as one hopes they will be in time), but are achievable with the tools at hand. If the statements are true, the pursuit of Kyoto type emission control targets should not only control GHG emissions, but will eventually achieve the goal of stabilizing the atmospheric concentration of GHGs at tolerable levels, and do so with existing technologies. This, in fact, is the view conveyed in the presentations by representatives of WG III to the delegates at the Bonn meeting in July 2001 (IPCC website).

The picture painted by WG III is a rosy one. But are the technology claims valid? Can they be supported by the evidence? To put the claims in perspectives, in 1999, there were only 57 EJ (1.8 TW) of carbon-free energy (power), almost all of it produced by hydroelectric turbines or nuclear energy plants. The expansion of hydro electric energy is limited by available sites, while the expansion of nuclear energy may be limited politically or by uranium supplies (Hoffert, et al, 2001). The renewables, solar, wind and (new) biomass, accounted for less than 5 percent of carbon-free energy (or less than 1 percent of total energy) in 1999. Assuming a population growth rate that falls from the current 1.3% a year to zero by 2100, a continuance of the long-term growth rate in GDP per capita of 1.6 percent, and a long-term rate of decline in energy intensity of 1.1% per year (see Lightfoot and Green, 2001b), it will take an estimated 1100 EJ/yr+ (35 TW+) of carbon-free power to stabilize the atmosphere CO_2 concentration at twice the pre-industrial level by 2100. In other words, a 20-fold or more increase in carbon-free energy (power) will be needed.

In contrast to WG III, Hoffert et al (1998: 884) stated that to stabilize the atmospheric concentration of CO_2 at 550 ppmv, or twice its pre-industrial level, involves "researching, developing, and commercializing carbon-free primary power technologies capable of 10-30 TW by the mid twenty-first century", and could require an effort "pursued with the urgency of the Manhattan Project or the Apollo space program". More recently, Hoffert et al (2001) investigate carbon reducing energy technologies and find that we have a very long way to go before we are able to mount technologies, including energy delivery systems, capable of producing and delivering the amount of carbon-free power required for stabilization of atmospheric CO_2. There appears, therefore, to be a conflict between the predictions of the Hoffert et al papers on the one hand and the claims made by WG III that available technologies now exist, and that new technologies and drastic technological breakthrough are not needed for atmospheric CO_2 stabilization.

We think that the statements by WG III on carbon-free technologies and on stabilization warrant careful scrutiny. In particular, we are concerned that:

1. WG III, in its analysis of the scope for and impacts of mitigation is building on benchmark scenarios that already include very large amounts of carbon-free energy – amounts that are larger than can be expected in a climate-policy-free environment or from existing technologies. These scenarios, contained in the Special Report on Emission Scenarios (SRES), act as benchmarks for WG III's "post-SRES mitigation" analyses. To the large

amounts of carbon-free energy implied by the scenarios must be added that attributable to post-SRES mitigation policies. Otherwise, there is a risk that the potential contribution from technological change will be double counted – once as part of the benchmark scenarios and again as part of the mitigation exercise. WG III is clearly aware that double counting must be avoided (Metz, et al. 2001: Ch. 2). But its chapter (3) on technological potentials for mitigation does not provide an analysis showing that existing technologies will allow the world to achieve, much less substantially exceed, on a century-long basis, the rates of energy intensity decline and decarbonization embedded in most of the SRES scenarios presented in Table 1.

2. WG III is building on benchmark scenarios that have higher average annual rates of reduction in energy per unit output (or improvements in energy efficiency) than current experience and higher than can be sustained for the whole of the 21st century (Lightfoot and Green, 2001b). To these rates must be added any further increase in the rate of reduction in energy-intensity induced by the post-SRES mitigation policies. We do not think, therefore, that the further contributions to energy intensity decline that supposedly would be induced by the post-SRES mitigation scenarios, and which are necessary to achieve stabilization, are plausible, at least with existing technologies. (See Appendix A)

STABILIZATION AND THE KAYA EQUATION

One way to comprehend what is involved in first stabilizing carbon dioxide emissions and then stabilizing the atmospheric CO_2 concentration is to employ the Kaya identity (Kaya, 1989). The Kaya identity relates carbon dioxide emissions to the rates of change in population; output per capita; energy intensity; and "decarbonization" (replacement of carbon-emitting energy sources with carbon-free ones). As Appendix B shows, to stabilize emissions requires that these four rates of growth be offsetting (i.e. that the percentage rate of change in carbon emissions, $\% \in C$, is zero). Thus, simply to stabilize emissions will be no small feat – it will require major reductions in population growth or output per capita and/or large increases in the long-term rates of decline in energy intensity and carbon intensity (decarbonization). Much more will be needed to stabilize the atmospheric CO_2 concentration.

A useful rule of thumb is that if carbon emissions could be immediately stabilized at something near the current level of 6 to 7 GtC, per annum, implying $\% \Delta \dot{C} = 0$ then the concentration of CO_2 in the atmosphere eventually can be stabilized at approximately 550 ppmv – or twice the pre-industrial level. If global carbon emissions continue to grow, as they almost certainly will, Kyoto or no Kyoto, then large cuts in global carbon emissions ($\dot{C}$) will be required for stabilization.

In the TAR, WG III argues that the technology is at hand to first achieve stabilization of global carbon emissions and then stabilization of atmospheric CO_2 concentration at 550 ppmv or even 450 ppmv (Metz, et al, 2001: SPM and chs. 2,3). If this were so, the problem is not so much one of technology as of overcoming the many political, economic, social, and behavioural barriers to implementing mitigation options. But if feasible rates of improvements in energy efficiency and increases in carbon-free energy are not up to the task, then simply overcoming the barriers implies accepting substantial reductions in economic activity across the world.

An important question is: how did WG III arrive at the view that the means to achieve stabilization are at hand? We know that the SRES benchmark scenarios themselves imply optimistic rates of improvement in energy efficiency and decarbonization. It then appears that WG III is assuming, in its post-SRES mitigation scenarios, that there is additional slack, flexibility, and existing but not yet adopted technologies, to allow substantial further reductions in energy intensity and carbon emissions through the use of less carbon emitting fuels. Or, in terms of the Kaya equation, the rates of energy intensity and carbon intensity (of energy) decline are sufficiently elastic to allow the stabilization of atmospheric CO_2, without unduly reducing the long-term rate of growth of world output.

It can be argued that WG III is resting its case on very strong – and unsubstantiated – assumptions and claims. For one, there is an implication that substantially more rapid rates of improvements in energy efficiency can be sustained in the 21st century (Metz, et al, 2001: Ch. 3). However, WG III does not demonstrate that higher average annual rates of energy intensity decline are sustainable for a century or more. For another, there is the claim that the means are at hand to tap very large amounts of carbon-free energy, amounts sufficient to displace fossil fuels. This claim appears to rest, however, on misleading calculations of what is attainable from renewable energies. It is these calculations to which we now turn. Then we investigate the impact on GDP of stabilizing atmospheric CO_2 when there are constraints on the long-term average annual rates of decline in energy and carbon intensities.

DECARBONIZATION OF THE ENERGY SUPPLY

Decarbonization of the fuel supply means replacing fossil fuels with carbon-free energy as additional energy is needed. What are those carbon-free energy technologies which WG III has in mind? WG III places heavy emphasis on the role of renewables, especially solar and wind, and to a lesser extent biomass as sources of carbon-free energy (Metz, et al. 2001, ch. 3). But the renewables are dilute and highly land-intensive, and in the case of wind and solar, are intermittent. (Lightfoot and Green, 2001a; Eliasson, 1998). For example, one EJ/yr of electricity from solar voltaic cells requires an area of over 2,000 km^2 or more in a region of high insolation, while one EJ/yr of electricity from wind energy requires 20,000 km^2 in a windy area (Lightfoot-Green 2001a). For a TW of power the respective areas covered would be 70,000 km^2 and 600,000 km^2, respectively. In regions with less insolation or wind, the land required for solar or wind energy would be much larger. Biomass energy is even more land-intensive than solar and wind energy, requiring an average of upwards of 30,000 km^2 of cropland per EJ/yr for solid biomass and upwards of 60,000 Km^2 for liquid fuels derived from biomass.

WG III purports to show (Metz, et al, 2001, Ch. 3) that the required magnitudes of solar, wind, and biomass energy are potentially available. Unfortunately, their estimates of 396 EJ/yr for biomass, 1575 EJ/yr solar, and 636 EJ/yr wind energy potential (Metz, et al, 2001: Tables 3.31, 3.32 and 3.33; 244-248), or 2600 EJ/yr in all, are at best only estimated potentials. The estimates of potential energy from renewables do not include the necessary adjustments that would differentiate between what is a theoretical potential and what might actually be attainable or available. It turns out, that the difference between theoretical potentials and what would actually ever be attainable is very large. We take up each of the three renewables, biomass, wind, and solar, in order, distinguishing in each case between WG III estimated potentials and our calculation of what might be attainable.

The estimated potential for biomass of 396 EJ/yr is based on the assumption that 100 percent of all land with crop production potential that is not needed for food production is used to produce biomass energy (Metz, et al. 2001: 244). But basing biomass potential on 100% of potentially cropable land that is not used for food production is highly unrealistic, failing to consider, among other things, where the land is or its quality. It is thus not a useful guide to what is actually attainable. For example, potential land available does not take into consideration the necessity of matching fuel crops with local growing conditions and the type of land available (to avoid disasters such as the great groundnut scheme). It does not take into consideration that the conversion of solid biomass into liquid uses for worldwide transport and use is very energy consuming, reducing the net energy actually available to half of the potential based on solids. Further, currently, half of the theoretically available land for biomass production is in Africa, a continent that may have the greatest need for expansion of local food production. When each of these modifying factors is taken into consideration, we estimate that the maximum amount of biomass energy that might actually become available is no more than one third of the 396 EJ/yr "potential", or, at best, 132 EJ/yr.

The estimate of 636 EJ/yr of wind energy potential is based on situating wind turbines on all of the 30 million km^2 of land in the world with an average wind speed higher than 5.1 m/s. However, WG III itself admits, that for "practical reasons just 4% of that land area could be used" (or 1.2 million km^2).for wind energy production (Metz, et al. 2001: 246). If only 4% of windy land is used for wind energy production, the 636 EJ/yr potential is reduced to a 25 EJ/yr actual. Interestingly, the 25 EJ/yr is less than the 60 EJ/yr we estimate is attainable from 4% of 30 million km^2 of windy land, or 1.2 million km^2. Our estimate is based on calculations indicating that the average amount of wind/land required per EJ/yr is 20,000 km^2 (Lightfoot and Green, 1992, 2001a).

The estimate of a solar energy potential of 1575 EJ/yr reported by WG III is based on the amount of "unused" land that would be available for solar arrays. The IPCC assumes that a minimum (we would regard it as a maximum) of 1% of the world's "unused land" totalling 39 million km^2, can be covered with solar arrays for energy production. However, this calculated potential neither adjusts for photovoltaic cell energy conversion efficiency, which is currently 15 percent (and might rise to a maximum of 30%), nor for spacing between solar arrays. For solar arrays in a horizontal collector panel, the usual assumption is that the plant to covered area is in the ratio of 2:1, mainly for reasons of maintenance (Lightfoot and Green, 1992: Eliasson, 1998). For arrays with a two-axis collector panel, which approximately doubles the solar energy captured, the plant to covered ratio rises to 5:1, primarily to avoid one panel shading another.

With current photovoltaic cell efficiency of 15% and assuming spacing which is double the area covered by solar arrays, the solar energy that would actually be available is 140 EJ/yr -- more than an order of magnitude smaller than the reported potential. Alternatively, if we take the annual average irradience reported by WG III (p. 248) of 0.2 kW/m2 (i.e. 200 W/m^2) -- a figure we think is on the high side -- the available solar energy at 15 percent conversion efficiency ranges from 186 EJ/yr down to 149 EJ/yr, depending on whether the solar arrays are horizontal or two axis tracking collector panels.

When the necessary adjustments to the biomass, wind and solar energy potentials reported by WG III are made, we calculate that these renewable sources of energy might supply between 310 and 380 EJ/yr of carbon-free energy. Even after adding in the maximum capabilities of hydro (50 EJ/yr) and tripling energy from nuclear fission (75 EJ/yr), the total carbon-free energy is considerably lower than the carbon-free energy in 4 of the SRES emission benchmark scenarios (see Table 1). Our estimates of the amount of energy that might be available from biomass, wind, and solar are, collectively, a factor of eight or more lower than the potentials reported by WG III.

In terms of TW of carbon-free power, our estimates of what the renewables can collectively contribute, is at most 11 to 13 TW of power. Since stabilization will require 30+ TW of power by 2100, it is doubtful that the renewables can contribute more than a fraction (perhaps a third) of the carbon-free energy required to stabilize atmospheric CO_2. Even if the conversion efficiency of solar energy is raised to its 30% maximum, biomass, solar and wind energies would contribute less than half of the carbon-free energy required for stabilization. Moreover, even these estimates assume that the very large amounts of land required will actually be available. The land availability assumption is not trivial, given the many competing uses for land, an increasingly scarce resource.

There are a number of the “nuts and bolts” problems in employing vast arrays of solar plates or wind turbines that requires careful attention and which may further limit the role of renewable energies. The calculated amounts of solar and wind energy not only assume that the required amounts of land are actually available, but that the time, cost, and energy needed to keep solar plates free of dust and sand and to keep an accumulation of dead insects on wind turbine blades from reducing wind turbine power, are not prohibitive. Further, because the electricity produced by solar arrays or wind turbines is intermittent, much of it could not be supplied directly to the energy generating and transmitting systems, but would have to be stored. As WG III points out, “in large integrated systems it has been estimated that wind could provide up to 20% of generating capacity without incurring significant penalty”. The same would apply to solar generated electricity because it, too, is intermittent.

Storage raises still another problem. The most likely form of storage for photovoltaic and wind generated electricity is, in the form of hydrogen. But conversion to hydrogen requires very large amounts of fresh water. One EJ/yr requires 21 billion gallons (enough to meet the annual needs of a city of 500,000 people). More than 600 billion gallons is required per TW of solar hydrogen energy. Such large amounts of fresh water would be very difficult to find in most areas of high insolation not already covered with tropical forests.

ECONOMIC COSTS OF STABILIZATION

Our assessments of (i) the SRES scenarios and (ii) of the potential contribution of renewables have some interesting implications for the economic (GDP) cost of stabilizing the atmospheric concentration of CO_2. Specifically, we have raised doubts about the rates of decline of energy intensity in the SRES scenarios. We have also raised doubts about the presumption, based on theoretical energy potentials, that renewables can be relied on in making the transition from a world in which most energy is in the form of fossil fuels to one in which most energy is from carbon-free sources. If, as we have suggested elsewhere (Lightfoot and Green, 2001b), there are (1) upper limits on the long-term rate of decline in energy intensity and if there are (2) limits on the extent to which we can rely on renewables for carbon-free energy, then the potential economic implications of these limits cannot be ignored. This is particularly so where climate policies rely on energy efficiency improvements and carbon-free renewables for climate stabilization. Such policies are the ones that are emphasized by the IPCC's WG III.

The problem can be posed in the following way. Suppose there are limits to the rate of improvement in energy efficiency (as we have shown, Lightfoot and Green, 2001b). Suppose further, that there are limits to the extent to which we can rely on renewables for carbon-free energy (as we have demonstrated above). Then these limits will tend to act as constraints (albeit "soft" over some limited range) in the Kaya identity (see equations (1) and (2) in the Appendix). Recall that the Kaya identity relates the growth rate of carbon emissions to GDP growth, energy intensity decline, and the rate of decarbonization (decline in carbon intensity of energy). Alternatively, we can think of GDP growth as being related to the growth rate of carbon emissions and the rates of decline in energy intensity and carbon per unit energy. The alternative formulation is derived from Appendix equation (2), which after cancelling out the population (P) variable in equation (1) can be written as:

$$\dot{C} = \dot{Y} + \left(\dot{E/Y}\right) + \left(\dot{C/E}\right) = \dot{C} = \dot{Y} + \dot{e} + \dot{f},$$

where $\dot{e} = \left(\dot{E/Y}\right)$ and $\dot{f} = \left(\dot{C/E}\right)$.

Rearranging, we have $\dot{Y} = \dot{C} - \dot{e} - \dot{f}$.

Now let us proceed with the following thought experiment. In Lightfoot and Green (2001b), we have estimated the long-term (100 years) upper limit to the global average annual rate of decline of (E/Y) to be 1.1%. (See Appendix B) Similarly, in Green and Lightfoot (2001b), we show that a reliance on renewables for carbon-free energy would effectively place a limit on the rate of decline of carbon intensity, C/E.

The economic implication of these limitations can be formulated as follows:

- Suppose the long-term trend rate of growth of GDP (Y) is, say, 2.3%.
- If the long-term rate of energy intensity decline, $\dot{e}$, is 1.1%, it follows that the rate of energy growth, $\dot{E}$, will be 1.2%. That is, $\dot{E}$ is equal to the GDP growth rate ($\dot{Y}$) minus the rate of energy intensity decline $\dot{e}$. In other words: $\dot{e} = \dot{E} - \dot{Y}$. Therefore, $\dot{E} = \dot{e} + \dot{Y} = -1.1\% + 2.3\% = 1.2\%$.
- With an upper limit on the energy that renewables can supply, carbon energy will have to grow to satisfy a 1.2% average annual rate of growth in energy consumption, unless, of course, non-renewable, carbon-free energy (such as nuclear) is used on a large scale.
- Based on our assessment of the energy available from renewables, including hydroelectricity, and an assumed tripling of electric energy from nuclear fission plants, we calculate that carbon energy would have to grow at an 0.9% rate in order to meet the remaining energy requirements associated with a long-term average annual energy growth rate of 1.2%.
- As a result, the long-term average annual rate of decline in carbon intensity, $\left(\dot{f} \equiv \dot{C} - \dot{E}\right)$, will be –0.3%, (0.9% growth in carbon energy minus 1.2 percent growth in energy.

- Now recall that the stabilization of atmospheric CO_2 by 2100 at 550 ppmv is more or less equivalent to maintaining, on average, CO_2 emissions at their current level of 6 to 7 GtC throughout the 21st century. In other words, stabilization of the atmospheric concentration of CO_2 at 550 ppmv implies a long-term average annual growth rate of CO_2 emissions equal to zero, i.e., %ΔC (or $\dot{C}$) = 0.
- If we put each of the elements together in equation (a) above, i.e., $\dot{C} = 0$, $\dot{e} = 1.1\%$, and $\dot{f} = 0.3\%$ (where both $\dot{e}$ and $\dot{f}$ are negative), we have a limit to the long-term average annual growth rate of GDP ($\dot{Y}$) of 1.4%.
- A 1.4% rate of growth of GDP over the course of the 21st century would imply that in 2100, GDP would be 58.8%, or $183 billion lower than it would be if the average annual growth rate of GDP were unconstrained at 2.3%.

In contrast to the above calculations, the IPCC, WG III reports much smaller estimates of the cost of stabilizing carbon emissions at 550 ppmv (Metz, et al, 2001: 545-549). WG III summarizes its findings as follows: "the average GDP reduction in most of the scenarios reviewed here is under 3 percent of baseline value (the maximum reduction across all stabilization scenarios reaches 6.1% in a given year)". When the six SRES reference scenarios are used as benchmarks, the global average GDP reduction in 2050 ranges from –0.25% to –1.75% for a stabilization target of 550 ppmv (Metz et al, 2001: 548).

What explains the huge differences between the estimated GDP costs of stabilization reviewed by WG III and the ones suggested by the thought experiment above? There are at least two different factors operating to produce a potentially very large difference. The first is that we imposed constraints on the long-term average annual rates of decline in energy intensity and on renewable energy-based carbon intensity. No such constraints are suggested, much less imposed, by WG III, as is clear from the rates of decline in energy and carbon intensities implied by the SRES scenarios (see Table 1). The second factor is that the SRES benchmark scenarios have already built in high rates of decline in energy intensity and large amounts of carbon-free energy. This means that the contributions of the SRES-mitigation scenarios to achieve stabilization has been reduced, and so therefore will their GDP cost estimates.

A third factor that could explain the difference in GDP reductions is that the economic models used to make the estimates presented in the report of WG III (Metz, et al, 2001, ch. 8), may have assumed a carbon-free backstop energy technology. A carbon-free backstop energy implies that at some price an unlimited amount of carbon-free energy becomes available. Many energy-economy models employ a backstop technology. A carbon-free backstop energy technology effectively removes the energy and carbon intensity decline constraints. With a backstop energy technology, the only effect on GDP comes through the economic cost (in the form of higher energy prices) of moving to the backstop.

We wish to underline that our discussion of the GDP costs of stabilization is by way of a thought experiment. We are not suggesting that the GDP cost of stabilization would be anything like 58% in 2100. In fact, we believe that in the face of potentially large reduction growth, it is predictable that it would not take long before the impact of the energy and carbon intensity constraints was substantially softened either by a refusal to adhere to the stabilization targets and/or by attempting to find and develop concentrated forms of carbon-free energy that would obviate reliance on renewables. In either case, there would likely be catch up, so that in the long-term average GDP would be closer to the trend rate, 2.3% in our example.

What we are saying is that if there are constraints of the sort we have suggested, and if the stabilization targets are strictly adhered to, the GDP cost of stabilization could be much higher than a few percent. Furthermore, our statement is robust to alternative values for the constraints. For example, even if the long-term global average annual rate of energy intensity decline could be raised to 1.3% (which we do not think is possible), and (ii) the long-term average annual rate of decarbonization can be raised to 0.7% (which we do not think is possible if reliance is placed on renewables), the GDP reduction (from a 2.3% trend rate) in 2100 would be 25.4%. Again, we would emphasize that this is no more than a thought experiment; but it is one that suggests that the estimates reviewed by WG III may provide a very incomplete picture of the possible GDP costs of stabilization.

In sum, by ignoring possible upper limits on the long-term rates of energy intensity and carbon intensity decline, the stabilization cost estimates reviewed by WG III may be substantially underestimated. If so, the estimated GDP reductions in the low single digits may not be reliable. To put it another way, the estimates of the cost of mitigation may not be "robust" to alternative assumptions about energy intensity decline, the availability of renewable energies, and what is encompassed in baseline (benchmarks) emission scenarios as Green and Lightfoot (2001b) show. Therefore, we should be very careful before adopting climate policies that rest heavily on the renewable energy figures and GDP costs of stabilization estimates presented in Chapters 3 and 8 of the TAR of WG III.

RECAPITULATION

In assessing the scope for stabilizing the atmospheric concentration of CO_2, we think it is useful to consider the following:

1. In the foreseeable future, the first two terms of the Kaya equation population (P) and real income $\left(Y/P\right)$ will tend for the foreseeable future, as they have in the past, to move in opposite directions. Cutting the rate of economic growth, especially in developing countries, is likely to have a perverse effect. All the socio-economic evidence of which we are aware indicates that reductions in the population growth rate, especially in developing

countries, is linked to improvement in economic well-being, broadly defined. Higher rates of growth of GDP per capita are likely to hasten the drop in the population growth rate, and vice-versa.

2. The long-term rate of reduction in energy per unit output will be limited by absolute energy efficiencies and the extent to which product substitutions convert the “basket” of goods and services that makes up GDP from more energy-intensive to less energy-intensive outputs. The combination of absolute energy efficiencies and product substitutions appear to limit the 110 year annual average rate of decline in energy per unit output (E/Y) to something close to 1.0 percent. (Lightfoot and Green, 2001b).

3. In considering the scope for producing carbon-free energy with existing technologies, particularly renewable energies, it is important to consider the <u>scale</u> on which such energies may be produced. Because the renewable energies are dilute and thereby highly land-intensive, what may be relatively low cost at small scales may well be very high cost on large scales. A critical issue here is land and its alternative uses including food production, living space, leisure space, ecological preserve, and resource stocks, all required for a growing, wealthier, and more environmentally sensitive population (Green 2000).

4. The <u>scale</u> issue applies as well to sequestration of streams of carbon dioxide. The sequestration of very large quantities of CO_2 in the ground, in the ocean or in biomass is a major problem which is part environmental, part energy using and part technology. Although there are some possibilities, there is still much technology to be discovered and developed before large scale sequestration can be considered as a viable and sustainable mitigation option.

5. Unless there is substantial upwards elasticity in the attainable rates of energy intensity decline and decarbonization, elasticities which need to be demonstrated, not simply assumed, the economic (GDP) cost of stabilization at 550 ppmv with known energy technology options, could be prohibitively expensive.

CONCLUSION

The views expressed by WG III, as they bear on the world's capabilities of achieving atmospheric stabilization of CO_2, require careful scrutiny. We have questioned the validity of claims that technologies are available to stabilize atmospheric CO_2 at 550 pmv, to say nothing of 450 ppmv. Because the claims made by WG III may have policy implications – particularly in the context of current climate policy agreements and negotiations - there is a predicament. If climate policy is framed on the assumption that existing technologies are sufficient to achieve stabilization when, in fact, they are not, the economic costs and time lost by pursuing policies based on this assumption could be substantial. This is not to say that policies to promote efficiency improvements and conservation should not be promoted. However, instead of policies directed to short-term emission reduction targets, it might be preferable for the leading industrial countries to commit to large and long-term research and development into new carbon-free energy sources and technologies capable of supplying the very large amounts of concentrated energy needed to stabilize the level of CO_2 in the atmosphere. If on the other hand, WG III is right that the real problem is to overcome the many political, economic, social and behavioral barriers to the adoption of mitigation options, rather than one of carbon-free energy sources and technologies, then the case for Kyoto-type targets would be stronger. However one looks at it, climate policy is at something of a crossroads.

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APPENDIX A

Limits on Long-Term Average Annual Rate of Energy Intensity Decline

In Lightfoot and Green (2001b), we investigated the question of maximum energy efficiencies and the implication of these maximums for the long term global average annual rate of energy intensity decline. The suggestion that there are limits to the long term rate of energy intensity decline is a potential source of misunderstanding. Because the role of energy efficiency limits plays a role in some of the analysis carried out in this paper, it is useful to summarize the motivation and main findings in Lightfoot and Green, 2001b.

We begin by noting that there are limits to energy efficiency set by the laws of physics. For example, the technology of water turbines has been well understood for more than half a century and the efficiency over the same period has been 90% when operating at more than 60% capacity. There are few, if any, further gains to be made, thus the potential for energy efficiency improvement is virtually nil and there is no technology of higher efficiency to replace water turbines in generating hydroelectric power. Similarly, the efficiency of coal fired generating stations is limited by thermodynamics to about 33%. However, coal fired generation can be replaced by combined cycle natural gas fired systems where the limit is around 60% efficiency, an increase of 82%. At the other end of the scale, residential space heating has a potential for large increases in efficiency before reaching a limit, on the order of 300%.

To avoid misunderstanding, we make the following points:

- The terms “long-term” and “global average” are crucial: to the issue of limits: we are interested in the average annual rates over periods of 50 to 100 years or longer, and to an average for the world. Moreover, we would not wish to argue that the limits are “hard”; within some limited range, they are perhaps better described as “soft” constraints.

• The limits which we posit, do not apply to the average annual rate of energy intensity decline over shorter periods, such as one, five, ten, or even 20 years. There is plenty of evidence of year to year (and decade to decade) variability. For example, the average annual rate of decline in energy intensity has substantially exceeded 1.1% in some countries for periods of a decade or longer. For example, for the U.S., the average annual rate of decline is estimated at 1.9% for 1980-1999, just about the highest in the industrialized world for this period. There is evidence, however, that in industrialized countries that have achieved low energy intensities, the rate of energy intensity decline has tended to diminish (C. Green and H.D. Lightfoot, 2001a).

• We do not wish to suggest that factor substitutability, including the energy factor, is unaffected by capital turnover. Still, what is implied by our analysis of energy intensity is that there are ultimate limits on the degree to which it is possible to substitute away from the energy factor. <u>The limits to energy efficiencies exist once we enter the domain of the laws of physics</u>. That is, for any given energy using activity, there is some maximum energy efficiency, one that is essentially impervious to improvements in technology – or at least any known technologies. In Lightfoot and Green (2001b), we investigated the maximum energy efficiencies for a wide variety of activities, including various forms of energy generation, various forms of transportation, various industrial activities, and residential uses.

Our calculations of the maximum contribution of energy efficiency improvement to the long-term average annual rate of energy intensity decline are summarized (from many individual tables in Lightfoot and Green 2001b) in the following table.

TABLE A.1

Sector	A Share of Energy Consumption (1995) %	B Maximum Estimated Average Increase in Energy Efficiency %	C Implied Energy Intensity in 2100 Relative to 1990 %	D Contribution to Energy Intensity in 2100 col. (A) x col. (C)
Electricity Generation	38	85[a]	54	20.5
Transportation	19	200[b]	33	6.3
Industrial	21.5	200[c]	33	7.2
Commercial	9.5	200	33	3.1
Residential	12.0	300[c]	25	3.0
Total:	100.0			40.1*

*Implied Average Annual Rate of Decline in Energy Intensity[d] (1990-2100) = 0.83%[e]

a) Mainly due to substitution away from coal to natural gas, using combined cycle generation at 60% efficiency compared to current fossil fuel thermal efficiency of approximately 33%.

b) Based on 100% increase in energy efficiency for trains, heavy trucks, ships, and airplanes; and 300% increase in energy efficiency for cars, light trucks, and "other" vehicles.

c) Average energy efficiency increases over a number of industrial activities and residential energy uses.

d) Attributable to energy efficiency improvements, excluding sectoral changes.

e) Calculated by setting energy efficiency in 1990 at 100; then a decline to 40.1 in 2100 implies an average annual rate of decline over the 110 year period of 0.83%.

As TABLE A.1 (see below) indicates, when all of the potential increases in energy efficiency for all of the uses of energy are combined, the result is a weighted average decline in energy intensity, over all energy applications, of 60 percent in 2100 relative to 1990, or to 40.1% of what it was in 1990. This amounts to an average annual rate of energy intensity decline attributable to energy efficiency increases of 0.83% for the period 1990 to 2100. When sectoral changes are factored in, the range of average annual energy intensity decline for the period 1990 to 2100 is from 1.0% to 1.1%.

The calculations in the table assume that the sectoral shares of energy use in 1995, as between energy production, transportation, and all other uses, will also apply in 2100. This is unlikely. However, since the energy shares of electricity generation and transportation are anticipated to rise (at the expense of industrial, commercial, and residential), the changes will tend to be offsetting, with little or no effect on the overall rate of energy efficiency improvement.

Sectoral shifts within the industrial, commercial, and residential sectors from highly energy intensive to less energy intensive industries/uses are treated separately. The impact of sectoral shifts on the global average annual rate of decline in energy intensity for the 110 year period 1990-2100, range from 0.15 to 0.30 percent, depending upon the magnitude of the shift. When the effect of sectoral shifts is added to the 0.83% for energy efficiency improvements, the total falls roughly in the range of 1.0 to 1.1%.

APPENDIX B

A KAYA EQUATION ANALYSIS OF THE ATMOSPHERIC CO_2 STABILIZATION PROBLEM

The Kaya equation capsulizes the factors that affect the growth of carbon emissions – and provides an excellent organizing framework around which analysis can proceed. The Kaya (1989) equation (in its identity form) is:

1) $C = P \cdot Y/P \cdot E/Y \cdot C/E$

Where, C = carbon emissions, in megatonnes

P = population in millions

Y = output in billions of 1990 dollars

E = energy in exajoules (10^{18} joules)

Over the course of the 21st century, the population (P) is expected to grow, but at a declining rate, with population leveling out at from 8 to 11 billion persons by the end of the century. Output per capita is expected to grow at a more or less constant rate, implying that the growth rate of GDP will decline more or less in proportion with the decline in the growth ratio of population. GDP growth is expected to be slower in developed countries than in developing countries, allowing some reduction in the inequality of income across countries. Offsetting the growth in GDP (output) and GDP per capita are: (a) anticipated declines in energy per unit output $\left(E/Y\right)$ due to improvements (increases) in what may be called "energy efficiency" and the transitions from energy-intensive activities to less energy-intensive ones; and (b) declines in carbon per unit of energy attributable to the use of less carbonaceous fuels (coal being the most carbonaceous; nuclear emitting zero carbon).

The Kaya equation can be converted into rates of change – a more useful form for analytical purposes. Taking logs and time derivatives of equation (1), we have:

2) $$\%\Delta C = \overset{(+)}{\%\Delta(P)} + \overset{(+)}{\%\Delta\left(Y/P\right)} + \overset{(-)}{\%\Delta\left(E/Y\right)} + \overset{(-)}{\%\Delta\left(C/E\right)}$$, or, more compactly

$$\dot{C} = \dot{P} + \dot{\left(Y/P\right)} + \dot{\left(E/Y\right)} + \dot{\left(C/E\right)}$$

The anticipated signs on each variable is indicated in parenthesis.

To stabilize the atmospheric CO_2 concentration (a stock) will first require stabilizing CO_2 emissions (a flow). Then it will require large cuts in the flow of carbon emissions to stabilize the stock of CO_2 in the atmosphere. Simply to stabilize the (flow) of carbon emissions will be no small task. It implies that the $\%\Delta C=0$ in equation 2, which means that it is necessary that the right hand variables in equation (2) add up to zero. For the right hand variables to add up to zero, the two variables with positive rates of change (P and Y/P) must be fully offset by the two variables with anticipated negative rates of change, E/Y and C/E.

We may add some numerical flesh to equation (2) by introducing the average annual rates of change of P, Y/P, E/Y, and C/E over the past two to three decades. Population (P) has recently grown at a rate of 1.3 percent (although it is showing some tendency to slow); output per capita (Y/P) has grown at a long-term average of 1.6 percent rate. Offsetting these "positives" are "negatives" in the form of an average annual decline in energy per unit output, (E/Y), of -1.0% and an average annual decline in carbon per unit energy (C/E) of –0.3 to –0.4 percent. The decline in E/Y (energy per unit output reflecting an improvement in energy efficiency) in recent years was spurred by the run up of oil prices in the 1970's and early 1980's, which helped squeeze out a lot of energy inefficiency that had built up in the low energy price, fast GDP growth, 1960's. The decline in C/E (carbon per unit output) in the past two or three decades has been spurred mainly by the coming on line of nuclear electric generating plants in the 1970's and 1980's, and the increasing popularity of less carbonaceous (than coal) natural gas since 1980, an energy source that had been literally treated as a "wasting asset", a few decades ago.

Putting together the rates of growth of these four variables yields: +1.3 + 1.6 – 1.0 – 0.4 = + 1.5, the average annual rate of growth of carbon emissions in the past 30 years or so. The rate of growth of carbon emissions slowed in the 1990's to the 1.3% rate reported by WG III, chiefly due to the economic collapse of the former Soviet and East European economies and the improvement in energy efficiency forced upon these countries as energy subsidies were replaced by market prices. To further reduce the rate of growth of carbon emissions will require some or all of the following: (1) a decline in growth rate of population (a large decline in the rate is expected over the course of the 21st century); (2) a decline in the rate of growth of GDP per capita (although a decline in the growth rate of GDP is anticipated, no decline in GDP per capita is forecast); (3) an increase in the rate at which energy per unit, E/Y, declines (an increase in the average annual rate of decline of energy intensity beyond 1.0 percent will be difficult to sustain over a century-long period); (4) a large increase in the availability of carbon-free energy permitting a substantial increase in the annual rate at which carbon per unit energy declines (the key to future success in first stabilizing CO_2 emissions and later making the cuts in CO_2 emissions required to stabilize atmospheric CO_2 concentrations).