How Robust are IPCC Estimates of the GDP Costs of Climate Stabilization?

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ABSTRACT

The paper addresses estimates of the economic cost of reducing carbon emissions sufficiently to stabilize the atmospheric CO_2 concentration. Stabilization of CO_2 in the atmosphere is a key ingredient in stabilizing climate and eliminating the main anthropogenic influence in climate change. In its recent report, the Intergovernmental Panel on Climate Change (IPCC) reviews estimates of the economic costs of stabilization. It finds these costs to be relatively small – a few percentage points of GDP, at most. When its own reference emission scenarios are used, the estimated GDP reduction lie between 0.25 and 1.75 percent in 2050 for stabilization of atmospheric CO_2 concentration at the widely adopted stabilization target of 550 ppmv. We use a thought experiment to show that if there are limits on the long-term global average annual rates of decline in (1) energy intensity (due to eventual upper limits on energy efficiency) and (2) carbon intensity (due to a policy of relying on renewable forms of carbon-free energy), the economic cost of stabilization may be more than an order of magnitude higher than the estimates presented in the IPCC report. We trace the difference between the estimates reviewed in the IPCC report and the results of our thought experiment to three factors:
(a) the large amounts of carbon-free energy and the high rates of energy intensity decline built into the IPCC's reference scenarios; (b) the failure to distinguish "potential" and attainable energy derived from carbon-free renewable energies; and, (c) cost estimates derived from energy economic models that are characterized by large factor substitutabilities and backstop energy technologies.

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One of the key issues for the 21st century is coping with the build-up of carbon dioxide and other greenhouse gases in the atmosphere. The build-up is predicted to produce global warming and other long-term climate change. One of the main topics tackled by the Intergovernmental Panel on Climate Change (IPCC) is what will it cost to stabilize the atmospheric concentration of carbon dioxide (CO_2). Because CO_2 is the main greenhouse gas (GHG), and burning fossil fuels in the main source of CO_2, a policy goal is cutting carbon dioxide emissions sufficiently to eventually stabilize climate, i.e., free it from further anthropogenic interference. A widely adopted target is the stabilization of atmospheric CO_2 at 550 ppmv – twice its pre-industrial (and long-term) level of 275 ppmv.

The concentration of carbon dioxide has increased in the last 150 years from 275 to 370 ppmv. With population still growing and GDP per capita expected to grow in the 21st century at something like its long-term rate of 1.6 percent per annum, carbon dioxide emissions are expected to increase substantially during this century. Since current emissions of CO_2 from fossil fuel burning is equal to 6 billion tons carbon equivalent, and CO_2 has an atmospheric lifetime of 100 years or more, the growth in emissions is expected to raise the atmospheric CO_2 concentration in 2100 to well beyond 550 ppmv in the absence of stringent controls. Even if carbon emissions could be maintained at their current level throughout the 21st century, the atmospheric concentration of this long-lived gas would rise to something close to, but slightly below, the 550 ppmv level.

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The Cost of Stabilizing Climate

One of the issues addressed by the IPCC Working Group III is the GDP cost of stabilizing atmospheric CO_2 at 550 ppmv (Metz, et al, 2001: 545-549). WG III reports the results of several studies that tackled this question. It summarizes the 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 reached 6.1% in a given year)." WG III then provides estimates of the reduction in GDP in 2050 for each of the six "baseline" (or SRES reference) scenarios developed for it by an IPCC task force (IPCC, 2000). The global average GDP reduction in 2050 for a stabilization target of 550 ppmv ranges from .25% to 1.75 percent across the six emission scenarios. For five of the six SRES reference scenarios, the GDP cost in 2050 is less than 1 percent from baseline (Metz, et al, 2001: Figure 8-18: 548).

WG III does not provide estimates for the GDP cost of stabilization at 550 ppmv in 2100 – a more typical date set by analysts for achieving atmospheric CO_2 stabilization. It is reasonable to assume, however, that the stabilization of population that is anticipated to occur in the second half of the 21st century and the longer period over which technological changes can occur would tend to reduce, not raise, the GDP reduction in 2100, as compared to 2050. We focus on 2100 because that is the earliest date at which stabilization is likely to be achieved. If the GDP reduction in 2100 is significantly different (higher) than for 2050, we would question the reliability or "robustness" of the latter.

Why do we raise the issue of robustness of the estimates presented by WG III? We are concerned that the stabilization cost estimates reported by WG III are heavily dependent on (implicitly assumed) rates of decline in energy intensity and the carbon intensity of energy that may not, in fact, be achievable – at least not with known technology options. In contrast, WG III claims that "--- known technological options could achieve a wide range of atmospheric CO_2

stabilization levels, such as 550 ppmv, 450 ppmv or below, over the next 100 years or more" with no "drastic technological breakthroughs" (Metz, et al, 2001: 8).

A related concern is that the stabilization cost estimates are derived from neoclassical economic models that put a premium on substitutabilities – substitutability between factors of production and substitutability between fossil and carbon-free energy sources. If there are limits to the rate of decline in energy intensity, then there may be limits to interfactor substitutability, at least where the energy factor is concerned. If there are limits to carbon-free energy supplies, then there may be limits to the rate of decline in the carbon intensity of energy. Together, these two limitations – or constraints – could impose limits on the rate of growth of GDP, assuming there is continued adherence to climate stabilization targets.

A Framework for Stabilization Cost Analysis

To check the robustness of estimates of the GDP cost of stabilization, we employ the Kaya identity, which relates carbon dioxide emissions (C), to the product of GDP (Y), the average energy intensity of GDP, E/Y, and the carbon intensity of energy, C/E. We have

(1) $C = Y \cdot E/Y \cdot C/E \equiv Yef$, where $e \equiv E/Y$ and $f \equiv C/E$

Because we are interested in growth rates over time, we convert (1) by taking logs and time derivatives to get:

$$\overset{(+)}{\dot{C}} = \dot{Y} + \overset{(-)}{\dot{\left(E/Y\right)}} + \overset{(-)}{\dot{\left(C/E\right)}} = \dot{Y} + \dot{e} + \dot{f}, \quad \text{where } \cdot = \left(1/x\right) dx/dt, \tag{2}$$

x being the variable in question and ( ) is expected sign of change

Re-arranging terms we have:

$$\dot{Y} = \overset{(+)}{\dot{C}} - \overset{(-)}{\dot{e}} - \overset{(-)}{\dot{f}} = \dot{C} + |\dot{e}| + |\dot{f}| \tag{3}$$

A further set of relationships used below is

$$\dot{e} = \dot{E} - \dot{Y}. \quad \text{Therefore } \dot{E} = \dot{e} + \dot{Y} \tag{4}$$

$$\dot{f} = \dot{C} - \dot{E}. \quad \text{Therefore } \dot{C} = \dot{f} + \dot{E} \tag{5}$$

Because the atmospheric concentration of CO_2 can be stabilized at 550 ppmv by maintaining carbon dioxide emissions, C, at their current level (on average) over the course of the 21st century, stabilization implies setting the rate of change of carbon emissions, $\dot{C}$ equal to zero in equation (3). In other words, if the average annual rate of growth of carbon dioxide emissions is zero over the next one hundred years, stabilization at 550 ppmv can be achieved by 2100. From equation (3), we see that $\dot{C}=0$ implies that GDP growth will then depend on the average annual rates of decline in energy intensity $\left(E/Y\right)$ and carbon intensity, $\left(C/E\right)$.

WG III did not consider whether there are upper limits to the attainable rates of decline in $\left(E/Y\right)$ or $\left(C/E\right)$. Essentially, these two key variables are treated as unconstrained, implying that there is no necessary upper limit on GDP growth in an atmospheric CO_2 stabilization scenario. But precisely because the estimated GDP costs of stabilization reviewed by WG III do not appear to be constrained by imposed upper limits on the long-term values of $\dot{e}$ or $\dot{f}$, they may be subject to substantial error if there are, in fact, upper limits on these variables. Moreover, to the extent that the economic models included a carbon-free backstop energy technology, modellers are implicitly assuming that the energy-intensity $\left(E/Y\right)$ or carbon intensity $\left(C/E\right)$ variables will not impose a constraint on the rate of growth of GDP.

We have two reasons for investigating the constraint issue. First, recent research (Lightfoot and Green, 2001b) leads us to believe that there are indeed upper limits on the long-term (50 to 100/year) average annual rate of decline of energy intensity $\left(E/Y\right)$. Second, our work , and that of some other researchers, leads us to believe that a combination of technical and land limitations constrain the long-term average annual rate of decline in C/E, <u>if</u> reliance for supplying carbon-free energy is placed on <u>renewable energies</u> such as solar, wind, and biomass. (Green, 2000, Lightfoot and Green, 1992, 2001a, 2002; Eliasson 1998; Cassedy, 2000; Hoffert et al, 2001).

Lightfoot and Green (2001b) investigated the question of whether there are upper limits to attainable energy efficiencies, using known technologies, limits which would constrain the long-term average annual rate of energy intensity decline. They found that indeed there are limits, although not sharp, that would tend to constrain the global average annual decline in energy intensity over the course of a century to between 0.8 and 0.9 percent. The limits arise because beyond some point, energy efficiencies simply cannot be increased – they have reached their potential maximum. After the impact on energy intensity of sectoral, or structural, shifts from highly energy intensive to low energy intensive industries are added in, the attainable global average annual rate of decline in energy intensity in the 21st century is raised to between 1.0 and 1.1%. The estimates are briefly developed in the Appendix.

Lightfoot and Green (2002), have also investigated the amount of renewable energy that might be supplied by the end of the twenty-first century from renewable energy sources, given assumptions about available land and conversion efficiencies. They estimate that the attainable, as opposed to the theoretically potential, amount of energy from wind, solar, and biomass technologies, taken together, to be about 340-350 EJ/yr (Green and Lightfoot, 2002). Another carbon-free renewable energy, hydro-electricity, is limited by available sites to at about 45-50 EJ/yr, compared to the current production of hydro electric energy of 27 EJ/yr. Electric energy from nuclear fission is likely limited by uranium supplies and, more importantly, by political resistance. Even a tripling of the current 25 EJ/yr contributed by nuclear energy may be difficult to achieve unless the problem of storing radioactive waste is resolved. Finally, relatively small amounts of carbon-free energy, perhaps 10-15 EJ/yr in total, might be supplied by a combination of geothermal, ocean thermal, and tidal sources. Adding together the potential contribution from carbon-free renewable energies plus nuclear fission is about 480 EJ/yr.

We regard the 480 EJ/yr of carbon-free energy as optimistic, given the very important hurdles each of these energy sources face if developed on a large-scale. As we shall see, 480 EJ/yr is less than half of the amount of carbon-free energy needed to stabilize the atmospheric CO_2. To substantially expand the amount of carbon-free energy available by 2100, will probably require <u>long-term</u> commitments to develop new energy sources and technologies, such as nuclear fusion, tapping the earth's mantle for heat, and the development of other, more exotic, energy sources.

<u>Cost Implications of Constraints: An Example</u>

The aim of the paper is to consider the economic (cost) implications if there are upper limits on the long-term average annual rates of decline in energy intensity and carbon intensity. The former is predicated on limits to improvements in energy efficiency, the latter to the limitations of a policy that relies on renewables to provide carbon-free energy. We proceed by way of a thought experiment. The following example illustrates.

Suppose that the anticipated growth of GDP over the 100 year period, 2000 to 2100, averages 2.3 percent annually. A 2.3 percent average rate of growth of GDP is arbitrary, but it can be rationalized on the ground that the 1.6 percent average annual rate of growth in per capita income (output) in the 20th century is sustained throughout the 21st century, while the growth rate in world population, currently at 1.3 percent, slows to a crawl by the latter half of the 21st century, with an average over the whole period of 0.7 percent.

In 2000, the world GDP was approximately $32 trillion. Total energy consumed in 2000 was 400 EJ/yr, of which about 57 EJ/yr was from non-carbon sources. Aggregate energy intensity in 2000 was 400 EJ/yr divided by $32 trillion, or 12.5 EJ/yr per trillion dollars of GDP. Likewise, the aggregate ratio of carbon-free energy (57 EJ/yr) to total energy (400 EJ/yr) was 14.25 percent. While the ratio of carbon-free to total energy is not an accurate measure of carbon intensity (e.g., fossil fuels vary in the degree to which they are carbonaceous), the ratio can provide a reasonably good measure of the change in carbon intensity over time.

We can now bring the pieces together in both point and tabular (see Table 1) form.

- If GDP grows for 100 years at a 2.3 percent rate, it will reach $311 trillion in 2100 (Table 1).
- If the average annual rate of decline in energy intensity $(\dot{e})$ is at what we have estimated as its attainable long-term maximum of –1.1%, a 2.3% growth rate of GDP implies that total energy consumption $(\dot{E})$, which was 400 EJ/yr in 2000, will rise to 1322 EJ/yr in 2100. This represents an average annual rate of increase of 1.2 percent (row 3). (Note from equation (4) above, that the rate of increase in energy (1.2%) minus the rate of increase in GDP (2.3%) is the rate of decline in energy intensity of –1.1% (row 2).
- If carbon-free energy increases from 57 EJ/yr in 2000 (almost all of which was hydro and nuclear) to 480 EJ/yr in 2100 (three quarters of which would be solar, wind and biomass energy), the implied increase in carbon energy (including "old" biomass) is from 343 (out of 400) EJ/yr in 2000 to 842 (1322-480) EJ/yr in 2100 (row 4).

- The rise in carbon energy from 343 EJ/yr to 842 EJ/yr implies an average annual rate of growth in carbon energy from 2000 to 2100 of 0.9% (row 5). In turn, from equation (5) above, the implied average annual rate of decline in carbon intensity ($\dot{f}$) is –0.3% (0.9% rate of growth in carbon energy ($\dot{C}$), minus 1.2% growth in energy ($\dot{E}$), or the same as the rate of decline experienced over the past 30 years.
- If the implied average annual rates of decline in energy intensity (E/Y) and carbon intensity (C/E) over the course of the 21st century are -1.1% and –0.3% respectively, and if carbon emissions are stabilized by setting the average annual rate of growth of emissions at zero (i.e., $\dot{C} = 0$), then the attainable rate of growth of GDP is, according to equation (3), 1.4%.
- If world GDP grows at a 1.4% average annual rate over the next 100 years, then a GDP of $32 trillion in 2000 will grow to $128 trillion (in 2000 dollars) by 2100. (row 6)
- A world GDP of $128 trillion is a lot – but it is, nevertheless, $183 trillion (row 7) less than the $311 trillion that GDP would reach in 2100 if the average annual growth rate in the 21st century is 2.3%. A GDP of $128 trillion in 2100 is 58.8% below the unconstrained level of $311 trillion (row 8).
- Thus, if there are constraints on the average annual rates of decline in energy intensity (due to upper limits on energy efficiency) and to carbon intensity (if reliance is placed on renewable energies to supply carbon-free energy), then attempts to stabilize the atmospheric concentration of CO_2 may have very large impacts on GDP.

The example above is illustrative at best. It is nothing more than a thought experiment. Most readers will find a 59 percent reduction in GDP (in 2100), a figure that reflects the power of compounding, too fantastic to accept, even as a thought experiment. For this reason, we think it is useful to modify the constraints in our thought experiment – a sort of sensitivity analysis. Table 2 indicates the percent by which GDP in 2100 would differ from the level that would be attained at a 2.3 trend rate under alternative assumptions about the constrained values for the long-term rates of energy intensity and carbon intensity decline. The reader will note that as long as the combination of rates of decline in energy intensity and carbon intensity add up to less than 2.3%, "attainable" GDP (for a carbon emission growth rate of zero) must fall below the 2.3% trend. That is not surprising. What may be surprising is the substantial amount (in percentage terms) that GDP will be less than trend in 2100, even if the combined total of energy and carbon intensity decline rates is only two or three tenths of a percentage point below the 2.3% GDP trend rate.

Even more surprising is the very large amounts of carbon-free energy that will be required by 2100 to raise the average annual rate of decline in carbon-intensity above the -0.3 percent rate of decline of the last half century. The amounts of carbon-free energy in 2100 associated with a given average annual rate of decline in carbon intensity are shown in parentheses in the first column of Table 2. For example, in our thought experiment (see above) the global consumption of energy in 2100 is 1322 EJ/yr. An average rate of decline in carbon intensity of –0.7 percent implies that 760 EJ/yr – or 57.8% of total energy -- must be in the form of carbon-free energy.

There is, however, one important qualification. The amounts in parentheses overstate the amount of carbon-free energy required to achieve a given rate of reduction in carbon intensity if there is continued scope for substituting the relatively low carbon fuel (natural gas) for the two high carbon fossil fuels, oil and especially coal. But, if as anticipated, natural gas supplies cannot meet most of the increased demands for carbon fuels in the 21^{st} century, requiring an eventual more back to coal among the carbon fuels (as some believe will be the case by mid-century), the amounts of carbon-free energy in the table may not be overstated at all. (The capacity to sequester streams of carbon dioxide, in gaseous, liquid, or solid form would be a further qualification to the figures in Table 2).

Table 1

Tabular Summary of Calculation of GDP Reduction Below Baseline in 2100: Case of Baseline GDP Growth Rate of 2.3%, Energy Intensity Decline Rate of 1.1% and Carbon-Free Energy of 480 EJ/yr in 2100

Variable	**2000**	**2100**	**Average Annual Rate of Change 2000-2100**
1) GDP (in trillions of 2000 $)	32	311	2.3 percent
2) Energy Intensity (EJ/yr per trillion$)	12.5	4.25	-1.1%
3) Energy EJ/yr	400	1322	1.2 percent
4) Carbon Energy	343	842	+0.90
5) Carbon Intensity	.857	.637	-0.3
6) GDP attainable (if $\dot{C} = 0$ and $\dot{e} = -1.1$ and $\dot{f} = -.03$)	32	128	1.4%
7. GDP differential (6) ÷ (1)	0	-183	-
8. Percent Difference (7) ÷ (1)	-	-58.8	-

TABLE 2

Percentage Reductions in GDP Below Trend[a] in 2100 for Varying Rates of Energy and Carbon Intensity Declines

Average Annual Rate of Decline in Carbon Intensity, C/E	Implied EJ/yr carbon-free energy	Average Annual Rate of Decline in Energy Intensity (E/Y)			
		-1.1	-1.3	-1.5	-1.7
-0.3	(480 EJ)	-58.8	-49.7	-38.7	-25.4
-0.5	(635)	-49.7	-38.7	-25.4	-9.3
-0.7	(760)	-38.7	-25.4	-9.3	NR[b]
-1.0	(905)	-17.6	NR[b]	NR[b]	NR[b]
-1.2	(980)	NR[b]	NR[b]	NR[a]	NR[b]

a) Assumes 100 year trend growth rate of 2.3%.

b) NR = no reduction. However, to the extent that carbon-free energy is more costly to supply than carbon energy, there will be a "cost" reflected in the impact of higher energy costs on GDP.

Assessment of WG III Stabilization Cost Estimates

The question arises: how can the estimated costs of stabilization, in terms of reduced GDP, reviewed by WG III, differ so fundamentally from those in our thought experiments? The estimates of GDP reductions for the SRES emission scenarios ranged for 0.25 to 1.75 percent in 2050. In other stabilization scenarios, some cost estimates were higher, with one outlier at six percent. In contrast, our thought experiment GDP reductions range from 0 to 60 percent for a 550 ppmv target. Why did the WG III review not reveal a larger range of estimates with at least some double digit reductions in GDP for stabilization at 550 ppmv?

We think we can provide insight into, if not a definitive answer to, this question. Our analysis suggests three factors that may contribute to the potentially large differences in stabilization cost estimates. These are : (a) the rates of energy intensity and carbon intensity decline that are built into the IPCC's emission reference scenarios; (b) the calculated renewable energy "potentials" reported by WG III; and (c) the use of economic models in which a premium is placed on factor substitutabilities, both among energy sources and between energy and non-energy sources.

a) SRES Scenarios

For its Third Assessment Report, the IPCC constructed new baseline or SRES reference emission scenarios (IPCC 2000). There are four "families" of scenarios, A1, A2, B1 and B2, each based on a "storyline", or scenario descriptor containing a number of such scenarios. The A1 family is broken into three parts with the result that there are six basic scenarios, each summarized by a "marker" scenario. None of the new SRES scenarios is officially considered more probable than the others; thus none have the centrality given to IS92a in the IPCC's Second Assessment Report. The scenarios can be briefly described as follows:

A1 Family: In this scenario, global population is assumed to peak around 2050 and declines thereafter. New technologies are rapidly introduced and at the same time economic disparities between regions are substantially reduced. The A1 family is broken into A1F1 (fossil fuels continue to supply most of the energy); AIT (carbon-free energy sources dominate); and A1B (energy supply is balanced among fossil fuel and carbon-free energy sources).

A2 Family: In this scenario, global population continues to increase throughout the 21st century. Technological change and economic growth occur more slowly and global economic disparities persist.

B1 Family: As in A1, global population peaks around 2050 and declines thereafter. Most economies in the world rapidly become service and information oriented, requiring much less energy , and what is required is increasingly supplied from non-fossil fuel technologies. Economic growth is somewhat slower than A1, but income disparities decrease.

B2 Family: As in A2, global population continues to increase throughout the 21st century, but not as rapidly. Economic growth is slower and less concentrated in the service or information sectors than in A1 and B1. Decreases in economic disparities occur primarily at the regional and local levels rather than at the global level.

Table 3 presents some characteristics of the six basic SRES reference scenarios. The table also includes the Hoffert, et al (1998) result based on the IS92a baseline carbon emission scenario and the Wigley, Richels and Edmonds (1996) stabilization path. Among the salient characteristics of the six SRES scenarios are:

- Three are high GDP growth rate scenarios (the A1 series), including the fossil fuel dominant (A1F1); technology dominant (A1T), and “balanced” (A1B) scenarios.

- What clearly distinguishes the two relatively low GDP growth rate scenarios, A2 and B2, are their assumptions about the average annual rate of decline (1990-2100) in energy and carbon intensities. A2, is the more pessimistic of the two on both counts (col. 2).
- One scenario, B1, combines a medium growth rate of GDP of 2.53 percent with an extraordinarily high average annual rate of decline (1990-2100) in energy intensity of 2.13 percent. The result is a relatively low carbon-free energy requirement for atmospheric CO_2 stabilization.
- Four of the six scenarios have average annual rates of decline in energy intensity that exceed (in absolute terms) the –1.1% rate which we have calculated as the maximum attainable average rate of decline over the course of the 21st century (col. 3).
- Four of the six scenarios have built in amounts of carbon-free energy that exceed the 480 EJ/yr, which we have calculated as the atainable level in our thought experiment (col. 5).
- Two of the SRES reference scenarios, B1 and A1T, will stabilize by themselves at 550 ppmv, or less; B1 by 2100, A1T sometime in the 22nd century (col. 6).
- The B2 scenario, which WG III claims is closest to the baseline that was employed in many of the mitigation scenarios, <u>builds in</u> 665 EJ/yr of carbon-free energy, 185 EJ/yr more than we have estimated is achievable from a 21st century <u>policy</u> of emphasizing the development of the renewable energies, solar, wind, and biomass (col. 5).
- Five of the six SRES scenarios require average annual rates of decarbonization (reduction in carbon intensity, C/E) for CO_2 stabilization that are four or more times greater than the –0.3% experienced in the past thirty years (col. 8).

The rates of decline in energy intensity and the amounts of carbon-free energy built into most of the SRES emission scenarios are, on the whole, very large by historical standards. Four of the six scenarios <u>build in</u> average annual rates of decline in energy intensity that exceed what our own work indicates is possible over the course of the 21 century. Four of the six scenarios build in amounts of carbon-free energy that exceed what we believe is plausible if reliance is placed on renewables. In other words, the SRES scenarios provide CO_2 emission benchmarks or references that include unaccountably high rates of improvement in energy efficiency and availability of carbon-free energy. The implication, then, is that the mitigation scenarios, cited by WG II, had less “work” to do than would have been the case, had the energy intensity decline and carbon-free energy built into the reference scenarios been lower. To this extent, there is a tendency to underestimate the GDP cost of mitigation.

We can illustrate by adding some constraints of our own to the SRES scenarios. Specifically, we subject each of six basic SRES scenarios to combinations of average annual energy intensity (-1.1% and -1.3%) and carbon intensity (-0.7, -1.0, -1.2) decline limits. Table 4 indicates what happens. In only two cases, when the rates of energy intensity decline limits and carbon intensity decline are set at the very high levels of –1.3% and –1.2% respectively, were the SRES GDP’s for 2100 achievable, and then only for the low growth scenarios, A2 and B2. In all other cases (22 in all), the constraints on the energy and carbon intensity decline rates reduced GDP in 2100 below the levels in the SRES scenarios by amounts ranging from 3.1% (the only single digit reduction) to 72.9 percent (one of ten that were 50 percent or higher). Again, we emphasize that the calculations are only illustrative. They do, however, suggest that the GDP reductions in the range of 1-2 percent for the SRES scenarios, are not robust to alternative assumptions about energy and carbon intensity decline rates.

(insert Table 3 here)

Table 4

GDP in 2100 and Relative Reduction from SRES Scenarios for Varying Rates of Energy and Carbon Intensity Decline

Scenario	**GDP Growth Rate**	**GDP in 2100 (trillions of 1990$)**	**GDP in 2100 if Energy Intensity Decline Rate is –1.1% and Carbon Intensity Decline Rate is**		**GDP in 2100 if Energy Intensity Decline Rate is –1.3% and Carbon Intensity Decline Rate is**	
			-0.7% [760 EJ/yr]	-1.0% [905 EJ/hr]	-0.7% [760 EJ/yr]	-1.2% [980 EJ/yr]
(1)	**(2)**	**(3)**				
A1F1	2.97	525	149 (-71.6)	207 (-60.6)	185 (-64.8)	318 (-39.4)
A1B	2.98	529	149 (-71.8)	207 (-60.9)	185 (-65.0)	318 (-39.9)
A1T	3.01	550	149 (-72.9)	207 (-62.4)	185 (-66.4)	318 (-42.2)
A2	2.25	243	149 (-38.7)	207 (-14.8)	185 (-23.9)	318 (NR[a])
B1	2.53	328	149 (-54.6)	207 (-36.9)	185 (-43.6)	318 (-3.1)
B2	2.22	235	149 (-36.6)	207 (-11.9)	185 (-21.3)	318 (NR[a])

( ) = percent below GDP in 2100 (see col. 3)

a = no reduction

b. Renewable Energies

A second reason why the GDP cost reductions reported by WG III and those produced by our thought experiment are so different has to do with the renewable energy "potentials" calculated by WG III. In its report, WG III gives energy potentials for biomass, wind, and solar energies. (Metz, et al 2001, Tables 3.31, 3.32 and 3.33b, pp. 244, 246, 248). These potentials are 396 EJ/yr for biomass, 636 EJ/yr for wind, and 1575 EJ/yr for solar energies. The three energy potentials total to 2600 EJ/yr, more than enough for stabilization at almost any level, even at constrained levels of energy intensity decline.

Unfortunately, none of the renewable energy potentials reported by WG III is close to what could be available. There is, in fact, a substantial gap between the tables themselves and what might be inferred from WG III textual statements. Table 5 summarizes. Column (1) shows the "potential" amounts of solar, wind, and biomass energy, in EJ/yr, reported by WG III. Col. (2) indicates the assumptions, some implicit, behind these "potentials". In col. (3), we present adjusted figures to take into consideration various factors that differentiate WG III "potentials" from actual final energy that could be delivered. The bases for our adjustments are indicated in Col. (4). As a comparison of columns (1) and (3) indicates, taken together the "adjusted" potentials are lower than those reported by WG III by as much as a factor of nine. The adjusted figures present a very different picture of the effective renewable energy potential than that suggested by WG III.

There are a number of reasons why adjustments to the renewable energy "potentials" reported by WG III had to be made. These include the following: (a) the biomass and wind

Table 5

Renewable Energy "Potentials" Reported by WG III and "Adjusted" Potential

	(1)	(2)	(3)	(4)
Energy Source	**WG III Annual (Primary) Renewable Energy Potential**	**Basis for WG III Calculation**	**Range of Estimates of (Secondary) Renewable Energy Potentially Attainable**[a]	**Basis for Adjustment**
Biomass	396 EJ/yr (Table 3.31, p. 244)	100% of all land with crop production potential that is not used for crop production	94-179 EJ/yr (liquid biomass fuels)	80% of the available land is in Africa and South America; biomass crops must be adjusted to land type; substantial energy is needed to produce, harvest, transport and/or convert biomass into a liquid form for use in world energy markets
Wind	636 EJ/yr (Table 3.32, p. 246)	10.6% of land with average wind speeds of 5.1 m/s or more (see Table 3.32, p. 246)	48-72 EJ/yr[b,c]	Corrected for 0.3 conversion efficiency; WG III said that as a "practical matter" only 4% of land with average wind speed of 5.1 m/s is available (Metz, et al, 2001, p. 246)
Solar	1575 EJ/yr (Table 3.33b, p. 248)	1 percent of 39.3 million km^2 of "unused land". (This calculation made no adjustment for energy conversion efficiency or spacing between solar arrays.)	118-206 EJ/yr[c]	Corrected for 15% conversion efficiency, and a ratio of land to collector area of 2. Based on average 200 W/m^2 insolation reported by WG III (Metz, et al, 2001, p. 248)
TOTAL	2607 EJ/yr		270-457 EJ/yr	

a) Based on Lightfoot and Green (2002), Metz, et al (2001), and Eliasson (1998)

b) Assuming 1 EJ of wind generated electricity requires 20,000 km^2/EJ/yr

c) Most of this energy could not be used to directly produce electricity for the grid. As the capacity of intermittent energy sources to supply electricity directly to the grid is limited to 20% of the capacity of the electricity grid, only a fraction of the available wind and solar energy can displace fossil fuels in the generation of electricity. A small amount of the wind and solar electricity can be used to supply remote locations. Although the use of solar electricity to produce hydrogen through electrolysis is often mentioned, technical barriers and the very large amount of fresh water of distilled water quality required to produce an EJ of solar hydrogen limits the amount of usable solar electricity.

potentials are based on the unrealistic assumptions that 100% and 10.6% of relevant types of land, respectively, are used for energy production; (b) the solar energy potential implicitly assumes a 100 percent energy conversion efficiency, when the current levels (15%) and maximum levels (30%) are only a small fraction of 100%; (c) the solar energy estimate fails to adjust for spacing requirements; (d) the wind energy estimate needs to be adjusted for a .3 conversion factor; and (e) the biomass energy potential fails to distinguish between net and gross energy.

That adjustments have to be made to the "potentials" is clear. In its text, WG III states that, as a "practical matter", only four percent of land with an average wind speed of 5.1m/s or greater would be available for production of wind energy, but it did not factor this into its calculation. From several sources, including the WG III text (Metz, et al.2001: 246), we calculate maximum attainable wind energy at 48-72 EJ/yr. The solar energy potentials (Tables 3.33 and 3.33b: 247-248), when adjusted for energy conversion efficiencies and spacing requirements, are reduced by almost an order of magnitude. Even if one accepts the unreasonable assumption that all potentially cropable land not used for food production is used for biomass energy, it is still necessary to adjust for the energy intensive conversion of biomass into liquid form for world wide and flexible use.

As the bottom row of Table 5 indicates, the difference between the potentials reported by WG III and what we have calculated as maximum attainable levels is between a factor of six and nine. The difference is not only huge, but its implication for estimating the GDP cost of stabilizing the atmospheric CO_2 concentration is very important. With 2600 EJ/yr of renewable energy in 2100, it is perfectly reasonable to include in economic models a carbon-free, renewables backstop energy technology. With a carbon-free backstop energy technology, constraints on the rate of increase in energy efficiency (decline in energy intensity), really do not matter. If on the other hand, a maximum of 300-450 EJ/yr of solar, wind and biomass energy could be available in 2100, then the assumption of a non-carbon backstop energy technology based on renewables is not reasonable. Without some other energy sources capable of providing large amounts of carbon-free energy, or, the capability of sequestering very large amounts of CO_2 in a geologically stable and safe manner, there will be a limit to the attainable rate of decline in carbon intensity, one which could matter a lot for the (GDP) cost of stabilizing the atmospheric CO_2 concentration.

c. Neoclassical Models and Substitutabilities

A third possible reason why the GDP cost reductions reported by WG III are small may be attributable to the type of models used in making the cost estimates. In general, economists begin their modelling with production functions. To our knowledge, most, if not all, of the economic models used in making estimates of the cost of mitigating CO_2 emissions include production functions of a "neoclassical" sort. An important characteristic of neoclassical production functions is their substitutability among factors of production, land, labour, capital, energy, as well as between energy fuel types.

Neoclassical functions are a powerful and useful means of modelling economic behaviour and activity. They capture two key ideas in economics: choice and substitutability. Moreover, these functions have some interesting – and telling – properties. For example, one of the most convenient forms of production function, the Cobb-Douglas, implies that the output elasticities of the inputs into production are equal to their factor share in GDP. This means that if an input accounts for a small (large) share of GDP, restricting its use has a small (large) effect on output (GDP).

Let us pursue the Cobb-Douglas case further. Because the energy factor constitutes only a relatively small share of GDP (relative to labour and capital), the output elasticity of energy tends to be relatively small. In a Cobb-Douglas production function, a small output elasticity for energy implies that a large reduction in the energy input would have only a small impact on output. If energy accounts for only 8 percent of GDP (as is the case in the U.S.) the Cobb-Douglas production function implies that a 50% reduction in energy availability would reduce output (GDP) by only 4 percent. Other inputs, labour and capital would "substitute" for energy in the production of output.

Since climate policy aims at reducing carbon emissions, energy use need not be curbed if there is abundant non-carbon energy. What is crucial, then, is the elasticity of carbon energies with respect to carbon-free energies. If the amount of the latter is large, then the assumption of high substitutabilities and elasticities is reasonable. But, if supplies of the latter cannot be easily and quickly increased, then high factor substitutabilities and elasticities are in doubt.

The Cobb-Douglas production function, as with most neoclassical models, does not in itself imply any particular rate of energy intensity decline. In effect, the scope, over time, for improvements in energy efficiency are effectively unlimited – unless the user of the model chooses to introduce an exogenously constrained rate of energy intensity decline. But, even a limitation on the long-term rate of decline in energy intensity is not necessarily an effective constraint. As long as large amounts of carbon-free energy are available, an energy-intensity decline constraint is not going to have much impact on achievable rate of increase in GDP. That is, if the technological potential to produce very large amounts of carbon-free energy exists, there is effectively a carbon-free backstop energy technology. Then the cost of stabilization will be attributable to the price differential between carbon-free and carbon energies, not to technological limits on the ability of GDP to grow. In turn, if it is higher prices, not output limits, that act as the economic “constraints”, the implication for GDP cost reduction may be small, particularly if land costs are ignored.

But if there are limits to both the long-term rates of both energy intensity and carbon intensity decline, then a Cobb-Douglas production function, and neoclassical production functions in general, may misrepresent the actual degree of substitutability that is possible. Limits to the rate of decline in energy-intensity imply that there will be limits to the substitutability between energy and other inputs into production. If there are limits to the availability of carbon-free energy supplies, particularly as a result of a policy aimed at relying on renewable energy sources, then there will be limits to substitutability among carbon and non-carbon energies. Taken together, these limitations can have implications for estimates of the impact on GDP of climate stabilization policies, when those estimates are derived from economic models that place a premium on the assumption of interfactor and intrafactor substitutabilities.

The argument we are making can be summarized as follows. There are three reasons why neoclassical models, when they are used to estimate the economic cost of climate stabilization, may substantially underestimate GDP reductions. The models: (1) are based throughout on substitutabilities; substitutabilities among inputs, substitutability among different types of energy inputs, and substitutabilities that are influenced by the factor shares of the inputs themselves; (2) typically introduce a carbon-free backstop energy technology; and (3) usually do not impose constraints on the long-term rates at which energy intensity can decline or on the rate at which decarbonization can proceed. The paper has focussed on the third of these factors, emphasizing that upper limits on energy efficiency and limitations of a policy that relies on renewable energies may have important implications for estimates of the cost of stabilizing atmospheric CO_2.

We wish to be clear. We are <u>not</u> criticizing neoclassical models as such. On the contrary: neoclassical production functions are a powerful and useful tool in economic analysis. However, their heavy dependence on substitutability makes them a dubious tool for analyzing the impact of movements away from dependence on fossil fuels (which are abundant) to carbon-free energies which are currently not abundant and which face important limits to their expansion. When combined with long-term limits on the average annual rate of decline of energy intensity, limits on attainable levels of renewable energies may act as constraints in production of output. They will tend to do so, unless there is a very high substitutability between energy and other inputs such as labour and capital (which is doubtful); new concentrated carbon-free energy sources are found and developed; or technologies to strip and effectively sequester carbon dioxide from fossil fuels can be developed on a large scale. We think that any economic model that does not take explicit account of such long-term constraints – if they exist – may provide incorrect, misleading or incomplete estimates of the cost of stabilizing atmospheric CO_2 concentration.

Conclusion

In this paper, we have attempted to demonstrate the implications of imposing constraints on the (a) long-term rates of decline in energy intensity and (b) the attainable rate of decline in carbon intensity when the supply of carbon-free energy is made to rely upon renewable energy from solar, wind, and biomass. We have shown that if there are limits on the rates of decline of energy intensity and carbon intensity, these can make a big difference in terms of predicted GDP reductions associated with atmospheric CO_2 stabilization. In Lightfoot and Green (2001), we estimated an upper limit of -1.1% to the attainable rate of decline in energy intensity over the course of the twenty-first century. That estimate is based on engineering limits to energy efficiency and to economic limits on the contribution of sectoral share shifts from energy intensive to non energy intensive activities. In Lightfoot and Green (2002) and in this paper, we have shown that, however large the renewable energies potential may seem, the actual energy that can be made available from these sources are both a small fraction of potential and what will be needed to stabilize climate.

If there are constraints on the rates of energy intensity decline and on the renewable energies contribution to the rate of decline in carbon intensity, as we have argued, then these constraints cannot be ignored. If these constraints are factored into the economic estimation of the cost of stabilizing atmospheric CO_2 concentration, then the robustness of the estimated GDP reductions reported by WG III are placed in doubt. In a sense, we have used the Kaya identity as a check on the predictions of economic models used to make the estimates reported by WG III. We have shown that the small and relatively narrow range of estimated GDP reductions predicted by these models do not appear to be robust to alternative assumptions about what is achievable in terms of energy efficiency and renewable energies.

But the thought experiment we have carried out does not mean that the atmospheric CO_2 concentration cannot be stabilized. Stabilization certainly may be achievable. What our analysis indicates is that stabilization may be very costly if the world held tightly to a policy that relies on a combination of energy efficiency improvements and renewable energies. But a concerted (albeit long-term) effort to find and develop new carbon-free energy sources and technologies (Green, 2000), including an effective and safe means of sequestration of CO_2 on a large scale (Lackner, et al, 1998; Lackner, 2001), may allow stabilization by 2100 at relatively little economic cost.

Moreover, our thought experiment in no way implies a prediction about what GDP would be in 2100 (or any other distant year) as a result of carrying out a policy to stabilize climate. If, in fact, a policy that relies on energy efficiency improvements and renewable energies to achieve stabilization at 550 ppmv proves to be too binding on global economic growth, such a policy will almost surely be abandoned in favor of discovering and/or developing more concentrated carbon-free sources of energy (e.g. nuclear fusion), or on setting the stabilization target at a higher level (e.g. 650 or 750 ppmv). Once the constraints on GDP growth are relaxed, GDP can be expected to rebound, even surpassing trend rates for a time as GDP catches up to its long-term potential.

Thus, even in the face of constraints, policies to mitigate GHG emissions may not lead to GDP reductions in 2100 (or 2050) that are far from those reviewed by WG III. But, if so, it would not be because of consistency with the energy efficiency-renewable energy story told by WG III. Either new carbon-free energies and technologies are developed, or the stabilization targets are abandoned. In the end, the view that self-correcting mechanisms tend to dominate non-correcting ones is a more robust prediction of the future than is the view that technological options now exist to achieve climate stabilization at a relatively low cost.

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APPENDIX

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

Lightfoot and Green (2001b) investigate whether there are limits to the long-term global average annual rate of energy intensity decline. The reason for asking this question is 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%.

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%.

To avoid misunderstanding, we make the following points:

- The terms "long-term" and "global average" are crucial: they refer to average annual rates over periods of 50 to 100 years or longer, and to an average for the world. The limits 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.

- 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, 2001).

- We would not wish to argue that the limits are "hard"; within some limited range, they are perhaps better described as "soft" constraints. Nor do we wish to suggest that factor substitutability, including the energy factor, is unaffected by capital turnover.

- 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. The limits to energy efficiencies exist once we enter the domain of the laws of physics. 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 making our calculations, 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

	A	B	C	D
	Share of Energy Consumption (1995) %	Maximum Estimated Average Increase in Energy Efficiency %	Implied Energy Intensity in 2100 Relative to 1990	Contribution to Energy Intensity in 2100 col. (A) x col. (C) %
Sector				
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%.

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%.

We have carried out some sensitivity analysis with regard to energy efficiency improvements and shifts in energy use sectoral shares. Assume the share (in total energy use) of the electricity generation sector, the sector experiencing the smallest improvement in energy efficiency, declines from 38 percent to 30% in 2100. Assume further, that the share in total energy use of residences, the final use energy use sector experiencing the greatest improvement in energy efficiency (300%) increases from 12 percent to 20 percent in 2100. Finally, let us assume that improvements in energy efficiency of cars and light trucks, the transportation component accounting for 60 percent of transportation sector energy use, increases by 500% rather the 300% calculated in Lightfoot and Green (2001b). All of these assumed changes are favorable to an increase in energy intensity decline. The combined impact of these changes reduces energy intensity in 2100 (relative to 1990) from 40.1 (see Table A.1, Col. D) to 35.98. The implied 110 year (1990-2100) average annual rate of decline in energy intensity attributable to energy efficiency improvements rises from 0.83% (see note to Table A.1) to 0.93% -- or by 0.1 percentage point per year. When the effect of sectoral shifts is added in, our estimate of the attainable long-term average annual rate of energy intensity decline rises from the 1.0 to 1.1% range to the 1.1 to 1.2% range. We conclude that our estimates of the upper limits on the 110 year average annual rate of decline in energy intensity are robust; that is they are relatively insensitive to alternative assumptions about energy efficiency improvements and energy use sectoral changes.