THE DEVELOPING DEBATE OVER CLIMATE POLICY: ENERGY EFFICIENCY, RENEWABLE ENERGIES, AND THE ECONOMIC COST OF STABILIZING CLIMATE WITHOUT MAJOR NEW TECHNOLOGIES

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I. INTRODUCTION

What will it take to stabilize climate – i.e., to stabilize the atmospheric concentration of CO_2 and other greenhouse gases? This important question is often obscured in debates over short-term emission cutting and the costs of meeting the Kyoto targets. Yet emission cuts will mean very little if stabilization of CO_2 at a level that would avoid a "dangerous interference" with climate is unachievable.

Currently, there is a vibrant debate over whether or not the means to achieve stabilization are at hand. On the one side are those who believe that a combination of energy efficiency improvements and renewable energies would provide most of what is needed to achieve stabilization – that no "drastic technological breakthroughs" are needed (Metz, et al, 2001: 8). Moreover, this view holds that stabilization of atmospheric CO_2 is achievable at relatively low costs (0.5 to 3% of global GDP), and that the main barriers to stabilization are socio-political and institutional in nature. The most prominent examples of this view are the members of WG III of the Intergovernmental Panel on Climate Change (IPCC), especially those who were responsible for writing that report's Summary for Policy Makers and its third chapter on the technology and economic potential for greenhouse gas reduction (Metz, et al, 2001; O'Neill, et al, 2003; Swart, et al, 2003)). It is also a view widely espoused by environmental groups. It has even found its way into the energy plans of some EU countries for curbing CO_2 emissions (e.g. U.K. Energy White Paper, 2003).

A quite different view, one that emphasizes major, long-term, energy technology breakthroughs is found in Hoffert, et al (1998, 2002, 2003), Edmonds, et al (2002), and is implied by Cadeira, et al (2003). The Hoffert, et al papers make clear that stabilization of atmospheric CO_2 concentration will take huge amounts of carbon-free energy and that no current technology or combination technologies are up to the task. Without long-term commitments to research and development of energy sources and technologies capable of supplying concentrated carbon-free power on a scale sufficient to meet the world's baseload energy requirements by 2100, stabilization of CO_2 at 550 ppmv – or twice the pre-industrial level – will not be possible; certainly not at any acceptable cost.

The view persists, however, that a combination of energy efficiency improvements and reliance on renewables is sufficient – or almost so – to achieve stabilization. The issues of what can be achieved by energy efficiency improvement and what renewable energies can contribute were tackled in reports by Lightfoot and Green (2001, 2002). One of the purposes of this paper is to explain as briefly and succinctly as possible what was done in these reports to answer the question of how much (a) energy efficiency and (b) renewable energies could contribute to stabilization of atmospheric CO_2: Another aim is to summarize and extend the chief findings of these reports; and check the robustness of the findings to alternative assumptions about the composition of energy consumption in 2100 and the future availability of resource-intensive renewable energies. A third objective is to provide an estimate of what I term an "advanced energy technology gap", the existence of which is maintained in Hoffert, et al, 2002. A final, and important, objective is to report and discuss the results of a "thought experiment" (Green and Lightfoot, 2002a, 2002b) about the economic (GDP) cost implications of a policy that relies on energy efficiency improvements and renewable energies to stabilize climate. The first two objectives are carried out in section II and III of the paper. The third objective is the subject of section IV and the final in section V of the paper. Section VI presents some conclusions

II. ENERGY EFFICIENCY IMPROVEMENT

Lightfoot and Green (2001) tackled the question of energy efficiency improvement in a series of steps. First, for each use of energy, a maximum physical (thermodynamic) efficiency is determined. That is, the paper begins with what engineering physics tell us about maximum energy efficiencies in the generation of electricity, the means of transport, and in the use of energy by residences, commercial establishments, and by industrial enterprises. Second, it establishes where we are “now”, as a global average, in terms of energy efficiency for each energy use. Third, on the assumption that the maximum energy efficiencies would be achieved by, or before 2100, it calculates the implied average annual rate of decline in energy intensity for the period 1990-2100. To this rate is added the implied rate of energy intensity decline attributable to a worldwide shift within the industrial sector from energy intensive to moderate to low energy intensive industries and activities.

a. Methodology

It is important to be clear about the procedures followed in Lightfoot and Green, 2001. In that paper we were concerned only with the maximum average annual rate of energy intensity decline that is (theoretically) achievable over the course of the 21st century. What is theoretically achievable depends on the laws of physics (second law of thermodynamics). To determine the maximum average annual rate of decline in energy intensity that is possible, we break the problem into two parts: the contributions to energy intensity decline of (i) maximum energy efficiency improvement and (ii) maximum achievable sectoral shift from high to low energy intensive economic activities.

To calculate the maximum average annual improvement in energy efficiency, one needs to know two things; (a) where we are now (on average) in terms of physical energy efficiencies, and (b) the maximum energy efficiency that is physically possible (given the laws of thermodynamics). Then we calculate the (maximum) average annual rate of energy efficiency improvement that would, by 2100, take us from where we are now to the physical, or thermodynamic, maximum efficiency in each energy using sector or subsector. This maximum long-term rate of improvement in energy efficiency is then converted to a rate of energy intensity decline.

The next step is to consider the maximum contribution to energy intensity decline from shifts in activity from highly energy-using industries and activities (excluding those that generate energy or provide transportation, which are treated separately). We find that highly energy intensive industries, other than electricity generation and transportation, currently comprise about a third of all industrial activity. The highly energy intensive industries have, on average, energy to output ratios (energy intensities) ten times greater than all other industrial activities. We make the assumption that the share of activity accounted for by these highly energy intensive industries declines from 33 percent of industrial GDP to 5 percent by 2100. We then calculate the average annual energy intensity decline that is associated with the virtual disappearance of these highly energy intensive industries. Because virtual disappearance is unlikely, we conduct sensitivity analysis.

We can then combine the maximum average annual rate of energy intensity decline made possible by moving to the physical (thermodynamic) maximum energy efficiency with the maximum rate of decline attributable to sectoral shifts away from highly energy intensive industries. These give us the maximum average annual rate of energy intensity decline achievable in the 21st century. Our calculations show this to be 1.18%, consisting of an average annual 0.88% contribution from energy efficiency improvement and a 0.30% contribution from sectoral change.

To fully comprehend what we are attempting to do, it is important to understand that:

(1) the measures of energy efficiency and energy intensity are in physical terms: megajoules of electricity; real, price-adjusted, output;

(2) the rate of energy intensity decline consistent with achieving maximum energy efficiencies and sectoral shifts over a specified long period of time 1990-2100. We are not concerned with the achievable rate of decline in energy intensity over shorter periods, such as 5, 10, 20, or even 40 years, before physical maximums are achieved.

An important implication of the methodology is that factors such as energy prices that may be very important role in influencing the infra-maximum rates of change in energy efficiency and sectoral changes may play no role in our calculations. The case of energy prices bears discussion. To be sure, energy prices are important, in some cases they are the most important, determinant of the actual rate of improvement in energy efficiency and the relative importance of highly energy intensive activities and industries. There is abundant empirical evidence to support the influential role of prices in spurring improvements in energy efficiency and movement away from energy-intensive activities in the past, particularly in the mid and late 1970's. But, energy prices by themselves cannot change the physical maximum energy efficiencies governed by the laws of thermodynamics, nor can they push beyond same minimum (zero is a limit) the relative importance of highly energy-intensive industries.

While energy prices can influence the time it takes to achieve maximum energy efficiencies, and thereby the rate at which energy efficiency improves while moving to the maximum, energy prices will not affect the average annual rates of improvement in energy efficiency (energy-intensity decline) over the 100-110 year period considered in this paper. In the paper, Lightfoot and Green assumed that the energy efficiency maximums can be achieved by, or before, 2100. They focused on a specified period, and end date of 2100, because the interest is in the maximum contribution of energy intensity decline to the stabilization of atmospheric CO_2. The operative assumption is that the atmospheric concentration of CO_2 would not be stabilized before 2100.

It may help to think about the role of energy prices in the following way. Energy prices influence the process of change: they act as an incentive to improve energy efficiency and reduce the importance of energy-intensive activities. Energy price changes thereby move the world toward the maximum energy efficiencies and minimum shares of energy intensive industries that are the object of our interest. Energy prices may also influence the rate at which energy efficiency increases and sectoral shifts occur. But energy prices cannot affect the limits of those changes or shifts. In effect, the question addressed in the paper is equivalent to asking what is the maximum rate of energy efficiency that can be achieved as energy prices approach infinity. If the maximum is achieved by, or before, 2100, it is straightforward to calculate the (maximum) 100-110 year average annual rate of energy intensity decline for each energy use. The same thought experiment applies to sectoral shifts away from energy intensive industries.

Because energy prices play no apparent role in our calculations, it is important to guard against the tendency to conclude that we are assuming energy prices are either constant, or an unimportant influence on energy intensity. In this paper, we are able to ignore the role of energy prices because we are only interested in two points; where we are now in energy efficiency terms, and the physical (thermodynamic) energy efficiency maximums, and energy-intensity sectoral minimums, however attained. Then we calculate the implied rate of change between now and 2100, assuming the maximums are achieved by, or before, that date. But prices are surely a, if not, the mechanism that may move us to the maximum.

An example may help illustrate. Transportation is an important user of energy, and many have observed there are important ways in which energy efficiencies can be increased for various forms of transportation. In the case of automobiles, Lightfoot and Green (2001) estimate that the maximum energy efficiency in terms of miles per gallon of gasoline-equivalent energy is 110 mpg. This estimate is based on calculations of energy needed to move a minimum vehicle mass at a reasonable velocity, including the energy requirements of moving from a stop position to the required speed. With a current global average energy efficiency of 27 to 28 mpg, a move to 110 mph. 110 mpg represents a four-fold, or 300%, increase. A 300% maximum increase in energy efficiency of automobiles implies a fall in energy intensity to 25% of its current level. Over a 100 year period, a decline in energy intensity to one-quarter its current value implies an average annual rate of decline of 1.39%. This sort of exercise is carried out throughout the paper for five sectors and several subsectors within each sector (except commercial). It goes without saying, that estimating maximum efficiencies for many activities is a major undertaking. The estimates of other researchers, and their comparisons with the findings presented below, are welcomed.

A final word on the energy price issue seems appropriate. Maximum energy efficiency is probably never actually achieved, much less is achievable directly or indirectly through the price mechanism. Maximum energy efficiency is, in most cases, very expensive to achieve. So would be a total shift away from energy intensive industries. An attempt to achieve a theoretical minimum energy intensity through the price mechanism, albeit working through energy efficiency improvement and sectoral change, could prove to be unacceptably costly in economic terms. Nevertheless, it is useful to consider the most favorable case; that maximum energy efficiencies are achieved and energy intensive industries virtually disappear by, or before, 2100. In effect, we consider the limits, even when it is clear that, at best, only an asymptote is achievable.

b. Energy Efficiency/Intensity Findings

Tables 1 through 4 summarize the main findings regarding maximum attainable energy efficiency increases and energy intensity declines. Table 1 indicates the maximum potential increase in energy efficiency in electricity generation. The current shares of each electricity generating source are shown in column A. The maximum potential increases are shown in col. B. Behind col. B lies a substantial body of research which is spelled out in some detail in Lightfoot and Green (2001). Two points are noteworthy. The 100% maximum increase in energy efficiency for natural gas is based on moving to combined-cycle technology. The 70% increase for “other renewables” (which includes, solar, wind, and biomass) has a wide margin of error, errs on the high side, and depends as well on the relative contribution of each of these renewables among other renewables. Biomass and solar may have more scope for energy efficiency increase than does wind.

In col. C, it is assumed that by 2100 electricity will be generated by carbon-free energy sources or by natural gas (the least carbonaceous of the fossil fuels) using combined-cycle technology. What differentiates cases 1 and 2 is the relative contribution of other renewables to electricity generation. Case 1 uses the 6% figure employed in Lightfoot and Green (2001). Case 2 uses 35%, with the intermittants contributing, at most, 15 to 20% (because of limits on the amount of intermittent supply the electricity grid can accommodate); the other 15 to 20% comes from biomass used as boiler fuel or electrolytic hydrogen. The weighted contribution to energy efficiency improvement of each of these energy sources is shown in col. D for both cases 1 and 2. Overall, the maximum energy efficiency increase in the generation of electricity for cases 1 and 2 are 73% and 69%, respectively.

Table 2 presents the maximum increases in energy efficiency attainable in electricity generation and four other broad sectors. As with electricity generation, the figure for maximum energy efficiency increases in the transportation, residential, industrial, and commercial sectors are built up from estimates for many subsectors or specific categories of energy usage. (For details, see Lightfoot and Green, 2001). Col. D of Table 2 indicates the weighted contribution of each broad sector to energy efficiency increase, 1990-2100, assuming the energy consumption patterns of 2100 are the same as in 1990. For cases 1 and 2, these energy efficiency increases are 164.5% and 163.0%, respectively. As it is unlikely that energy consumption patterns will remain the same, an alternative energy pattern, in which electricity generation accounts for 50% of energy consumption is 2100, is indicated in col. E. (Most scenarios indicate an increase in the share of energy consumption accounted for by electricity. See IPCC, 2000, and Appendix Table B, below). A higher share for electricity generation reduces the overall increase in energy efficiency from 164.5% (163.0%) to 151.5%

(149.5%) as indicated in the third row from bottom of Table 2. The smaller increase is attributable to the fact that the scope for energy efficiency increases is considerably smaller in electricity generation than in other sectors.

The rows below the main part of Table 2 indicate: (i) the weighted average energy efficiency increase in each of the two cases and the two alternative distributions; (ii) the resultant decline in energy intensity in 2100 relative to 1990 in each of these cases, and (iii) the implied average annual rates of energy intensity decline attributable to energy efficiency increase, if the theoretical energy efficiency maximums are reached by 2100. The theoretical maximum rates of average annual energy intensity decline for each of the two cases (1 and 2) and the current and “alternative” distributions of energy consumption fall into a narrow range of 0.83 to 0.88%. Table 3 summarizes these results and for purposes of sensitivity analysis, includes a second (and unlikely) alternative distribution of energy consumption in 2100. In the second alternative distribution, the share of electricity generation in energy consumption declines from 37.5% in 1990 to 30% in 2100. The results of such a decline is to raise the maximum average annual rate of decline in energy intensity to 0.94.

Table 4 brings together two sets of findings: (a) the maximum attainable rates of energy intensity decline that are attributable to achieving the theoretical energy efficiency maximums, and (b) contribution to energy intensity decline attributable to sectoral or structural change. The potential contribution of sectoral or structural change in the industrial sector to energy intensity decline is not unimportant. In addition to the energy intensive electricity generating and transportation sectors, five broad industry groups within the industrial sector, pulp and paper, iron and steel, non-ferrous metals; non-metallic minerals (e.g. cement and glass) and chemicals and petro-chemicals, have energy intensities that, on average, are an order of magnitude higher than the average of all the other industries within the manufacturing sector. These five broad industry groups account for one-third of GDP produced in the industrial sector.

On the assumption that the GDP share of very energy intensive industries will decline, not just in developed nations but globally, sectoral change is shown to contribute materially to energy intensity decline (Lightfoot and Green, 2001). Table 4 considers two cases: one in which the GDP share of the highly energy intensive industries in the industrial sector declines from its current level of 33% to 15% in 2100; the other to 5% in 2100. A decline in the GDP share of highly energy intense industries to 15% and 5%, adds 0.16% and 0.30, respectively to the average annual rates of energy intensity decline. Together with the 0.83 to 0.94 range for the maximum possible contribution of energy efficiency improvement, the 0.16 to 0.30 range for the contribution of sectoral change yields a range for the maximum rate of energy intensity decline of 0.94% to 1.24%. A "robust" central figure is a 1.1% average annual rate of energy intensity decline. This central figure will be used in section IV below.

III. RENEWABLE ENERGIES

It is widely believed by many, environmentalists among them, that renewable energies are feasible substitutes for fossil fuels. It is also believed that renewable energies, particularly solar and wind energies, and to a lesser extent biomass, are so abundant or potentially so, that in combination with energy efficiency improvement they are capable of stabilizing the atmospheric concentration of CO_2 at levels that avoid a "dangerous interference" with climate. This could require stabilization of atmospheric CO_2 at levels as low as 450 ppmv (O'Neill and Openheimer, 2002).

The belief that renewables can supply most, if not all, of the carbon-free energy required to stabilize the atmospheric CO concentration has been reinforced by the Third Assessment Report of the IPCC's Working Group III (Metz, et al, 2001). In Chapter 3 of its report, entitled "Technological and Economic Potential of Greenhouse Gas Emission Reduction" (see Appendix Table B, col. 1), WG III reports amounts of renewable energy that ostensibly are sufficient for stabilization. Moreover, the subgroup of WG III responsible for developing the IPCC's new emission scenarios, built into most of these scenarios very large amounts of renewable energy even in the absence of any policy intervention (see Appendix Table A, col. 3).

These claims and scenarios are built on a very weak foundation indeed. For example, the presentation by IPCC WG III of the "technical potentials" of three main "new" renewables, solar, wind, and biomass, shown in Appendix Table A, is misleading. The presentation does not make clear the huge difference between IPCC "technical potentials" and actual useable energy (e.g. in the form of electricity) from these sources once energy conversion efficiencies are taken into account. Further, the WG III report fails to account for a number of other factors that affect the useable energy to land ratios: These include the (a) required spacing of solar panels to avoid shading and to provide for servicing, and (b) the large amounts of energy used in the planting, fertilizing, harvesting, and transporting of biomass. These and other defects in IPCC WG III's presentation of renewable energies are the subject of a report by Lightfoot and Green (2002). Lightfoot and Green use the land availability assumptions employed by IPCC WG III, and proceed to systematically calculate attainable secondary (or final) energy yielded by each of the renewables. They do so by calculating the average amounts of land (Km^2) required to produce an EJ/yr of electric energy (solar, wind) or biomass fuel (both solid and liquid).

Tables 5-8 summarize the findings of Lightfoot and Green (2002). In each table, col. A reports the amount of land (in Km^2) to produce an EJ/yr of electricity (solar, wind) and biomass fuel. For purposes of comparison, Lightfoot and Green report estimates from Eliasson (1998) and the land area per Km^2 implied by WG III's textual discussion (although not its tables). The basis for each of the land per EJ/yr estimates is discussed in detail in Lightfoot and Green (2002: pp. 5-16).

In col. B of Tables 5-8, Lightfoot and Green (2002) report amounts of solar and wind electricity and biomass (solid and liquid) fuel, given the calculations in col. A of the tables and the amounts of land that IPCC WG III assumed could actually be made available for energy production (see Appendix Table B, col. 3). These amounts are respectively, 393,000 Km^2, or 1% of 39 million Km^2 of unused land (solar energy); 1,200,000 Km^2, or 4% of 30 million Km^2 of land with average wind speed greater than 5.1 m/s (wind energy); and 8,895,000 Km^2, or 100% of cropable land not used for crops in 2100 (biomass). Lightfoot and Green use a land calculation for biomass that diverges from the 11,900,000 Km^2 that is reported by IPCC WG III (Metz, et al, 2001, Table 3.31). Because WG III's land estimate is based on population in 2050, Lightfoot and Green use approximately 8.9 million Km^2 of biomass land availability in 2100, based on mid-range population estimates for the end of the 21st century. (However, some population estimates now predict that population will be lower in 2100 than in 2050.) The substantial difference between solid and liquid biomass reflects the 50% conversion efficiency loss when solid biomass is converted to liquid fuel. The Lightfoot and Green estimates are also net of the costs of planting, harvesting, and transporting biomass (Cassedy, 2000).

Tables 9 brings together in col. (1) the renewable energy potentials reported in IPCC WG III (Metz, et al, 2001), Ch. 3, and in col. 3 presents the calculations reported in Lightfoot and Green (2002). The latter estimates are for the amounts of renewable energies in electricity or biomass fuel form that are actually attainable using IPCC land assumptions (col. 2). The main factors that drive a wedge between the Lightfoot and Green calculations and what is reported by WG III are reported in col. 4 of Table 9.

The resultant estimates of renewable energy, in electricity or fuel form, range from 11 to 17 percent of the 2607 potential reported by IPCC WG III. In Table 10, col. A shows the attainable renewable energy potential based on WG III's own land assumptions, using equal amounts of solid and liquid biomass. If the attainable potential is achieved, solar, wind, and biomass might supply as much as 35 to 40 percent of the carbon-free energy required to stabilize the atmospheric concentration of CO_2 at 550 ppmv. (See section IV). However, for reasons explained below, achieving anything like 400 EJ/yr of solar, wind, and biomass energy per year is highly unlikely.

It is generally overlooked, or unknown, that the renewable energies, solar, wind, and biomass, are not only highly land using, but will draw heavily on available water supplies as well. In addition, the production of solar and biomass energy are highly energy intensive activities. The reasons for the water and energy intensity of renewables are as follows:

- Because solar and wind energy are intermittent, only a small proportion of these energies, when fully developed, can be supplied directly to the electric grid. Because the electric grid must be able to supply electricity on demand, at most only 20 percent of the electricity it carries can be supplied from intermittent sources. Beyond that fraction, any further supply by intermittents must be backed up by operable and operating baseload energy supply not subject to natural variation.

- The implication of intermittency means that most solar and wind energy, when developed on large-scale, must be converted to a storable form of energy. The usual form is hydrogen produced via electrolytic means, with solar and/or wind supplying the electric current and freshwater, of distilled water quality, supplying the hydrogen.
- It takes 21 billion U.S. gallons (or approximately 80 billion litres) of freshwater of distilled water quality to produce an EJ/yr of hydrogen from solar and wind electricity. This is enough water to meet the needs of a city of 500,000 persons. Supplies of freshwater of this magnitude are scarce, and becoming more scarce, in many areas of high solar insolation, such as the U.S. southwest. For this reason, wind-based electrolytic hydrogen, much of which comes from areas with somewhat larger supplies of fresh water, may be a better bet than that which is solar-based. Still, housing tens of thousands of large wind turbines presents its own logistic (and environmental?) problems.
- Biomass is even more water-intensive than electrolytic hydrogen. It is estimated by Bernedes (2002), that 150 to 300 EJ/yr of solid biomass (75-150 EJ/yr of liquid biomass) could use as much water as does all current cropland. Since world agriculture, particularly that which is irrigated, currently accounts for a large fraction of world water withdrawals, and given concerns about future water demands and scarcity, adding a huge new element to future world water demand in the form of biomass energy crops is highly questionable. Worse, the 150-300 EJ/yr figure is gross of energy use in planting, harvesting and transporting and conversion to liquid fuel. The net biomass energy from the use of such

large amounts of water would be much smaller (see above). At the very least, water, as well as land, must be counted among the scarce resources in the resource intensive energy crop equation.

- Harnessing solar energy is both materials and energy intensive. A recent article in *Nature* (2002), entitled "Materials for Sustainability", uses solar cells as an example of a supposedly "sustainable resource" which is both materials and energy intensive. According to the article:

  > "… it has been estimated that solar cells take between three and eight years to pay back their energy costs. Significant energy input stems from the aluminum or steel frames in which the cells are placed. Additional costs come from the manufacture of solar cells, the disassembly and recycling of components, and finally from chemicals that might pose occupational health risks to workers and are difficult to dispose of".

- The energy intensity of the inputs into renewable energy production has implications for the potential long-term shift away from energy intensive activities discussed at the end of section II. Consider what may be implied for the share of energy intensive activities if the world actually attempts to move to large scale production of renewables. As shown by Lightfoot and Green (2001), and indicated in Table 4, the ability to shift away from energy intensive activities in the industrial sector has an influence on the attainable long-term average annual rate of energy intensity decline. A large increase in the share of energy from renewables may prevent the GDP share of highly energy intensive industries from declining as sharply as is assumed in Table 4. If so, the maximum long-term average annual rate of energy intensity decline is likely to be, at best, at the low end of the 1.0-

1.2% range shown in Table 4. As we shall see, this would increase the amount of carbon-free energy required for stabilization, and decrease the share of this total that could be contributed by renewable energies.

Because of their land, water, and energy intensity, the scope for large scale production of energy from the "new" renewables, solar, land and biomass, appears limited. Thus the assumption that the world will produce solar energy on 393,000 Km^2 of land, wind on 1,200,000 Km^2, and biomass on approximately 9 million Km^2, the land assumptions used by IPCC WG III and that underlie the calculations in Tables 5-10, is highly questionable. It is more reasonable to assume that the amounts of renewable energy produced will be sharply resource (water, energy, as well as land) constrained. Thus, in col. C of Tables 5 through 8, a stab is taken at what might be a more realistic maximum production of renewable energies, once all the resource (land, water, energy) constraints, and the grid-related ones, are taken into account. The underlying assumptions are noted in the tables themselves with the textual discussion above serving as background. When these modified amounts are combined, the maximum energy from the three renewables is more likely to be around 200 EJ/yr in 2100 year (see Col. B of Table 10), instead of the approximately 400+ EJ/yr that is indicated by the figures in col. B of Tables 5-8. Realistically, then, the "new" renewables, solar, wind and biomass, are unlikely to contribute much more than a sixth, or perhaps at a maximum a fifth, of the carbon-free energy required for stabilization.

IV. ADVANCED ENERGY TECHNOLOGY GAP

The two preceding sections provide us with rough indicators of (i) the maximum long-term rates of energy efficiency improvement and energy intensity decline on the one hand,

and (ii) the <u>maximum</u> amounts of carbon-free energy from three "new" renewables that can be expected. To the estimates for solar, wind, and biomass in columns A and B of Table 10, we may add 50 EJ/yr from hydro and about 20 from geothermal, ocean, and tidal power. Thus, carbon-free renewable energies could supply anywhere from 280 to 500 EJ/yr, or from 9 (278 EJ/yr) to 16 TW (500 EJ/yr) of power. Hoffert, et al (1998), using the IS92a carbon emission scenario, develop a framework indicating the amount of carbon-free energy (EJ/yr)/power (TW) required to stabilize the atmospheric CO_2 concentration at 550 ppmv can be derived. Figure 1, focusing on the tradeoff curve, ZW, for 2100, employs the Hoffert, et al (1998) framework.

The rate of energy intensity decline is indicated on the abscissa in Figure 1 and required amounts of carbon-free power on the ordinate. Table 4 places the <u>maximum</u> attainable average annual rate of energy intensity decline in the range of 1.0 to 1.2 percent. (In actuality, the actual long-term average annual rate of decline in energy intensity may well be less than 1.0%.) The range of all renewable energy, 9-16 TW (278-500 EJ/yr) is also indicated. The hatched area brings together the combinations of energy intensity decline and attainable renewable energies with the carbon-free energy stabilization requirements to indicate an "advanced energy technology gap" (AETG). If the attainable rate of energy intensity decline is 1.0% and the attainable amount of renewable energy is approximately 275 EJ/yr, the AETG is 28 TW, or about 880 EJ/yr. If in the unlikely event the attainable rate of decline is 1.2% and 500 EJ/yr of (all) renewable energies can be produced, the AEGP is 13 TW, or about 410 EJ/yr. These figures are for stabilization of the atmospheric CO_2 concentration at 550 ppmv. For stabilization at 450 ppmv, the AETG would be much larger.

What are the consequences of failing to realize that there is a large "advanced energy technology gap"? The most likely consequence is that stabilization will not be achieved, at least not at a level of 550 ppmv or below. But, there are also important economic consequences of attempting to proceed on the assumption that energy intensity decline and renewables are sufficient to achieve stabilization. To demonstrate why such attempts could be very costly, a thought experiment is employed to examine the robustness of the stabilization cost estimates reported by IPCC WG III in Chapter 8 of their report, Climate Change 2001: Mitigation (Metz: et al, 2001: 544-549).

V. THE COST OF STABILIZING CLIMATE

What would be the cost of stabilizing climate if the world followed the policies suggested by IPCC WG III? To be more specific, what would be the cost of attempting to stabilize atmospheric CO_2 by relying on energy efficiency improvement and renewable energies to do so? According to IPCC WG III, economic costs, in GDP terms, would be very modest indeed, a few percentage points, at most, in a 250-550 trillion dollar economy in 2100. According to IPCC WG III, the main problem is overcoming socio-political and institutional barriers to change. But, a very different picture appears if the findings on energy intensity decline and renewable energy reported in this paper are considered. To get an idea how much different, it is useful to begin with the GDP cost estimates reported by IPCC WG III.

IPCC Working Group III reported the results of several studies that tackled the question of the GDP cost of stabilizing atmospheric CO_2 at 550 ppmv (Metz, et al, 2001: 545-549). WG III, summarizes their 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)." For the six representative SRES reference scenarios developed for the IPCC by a task force of WG III members, the range of estimates of global GDP reduction in 2050 is from .25% to 1.75 percent for a stabilization target of 550 ppmv. 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 did not provide estimates for the GDP cost of stabilization at 550 ppmv in 2100. It is reasonable to assume, however, that longer period over which technological changes can occur would not raise materially, and might even reduce, the percentage GDP reduction in 2100, as compared to 2050. Here the focus is on 2100 because that is the earliest date at which stabilization is likely to be achieved.

The stabilization cost estimates reported by WG III appear to be 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. 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 long-term limits to interfactor substitutability, at least where the energy factor is concerned. In the absence of a carbon-free backstop technology(ies), the resultant limits to carbon-free energy supplies will impose limits on the long-term 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, unless radically new carbon-free or emission-free energy technologies are brought forth to fill the “advanced energy technology gap”.

We proceed, however, by asking what would be the economic consequences of accepting the IPCC WG III propositions about available energy technologies. Specifically, a “thought experiment” is used to carry out cost calculations for a policy that attempts to stabilize the atmospheric CO_2 concentration at 550 ppmv by relying on energy efficiency improvements and renewable energies alone. The thought experiment will provide a check on the credibility of stabilization cost estimates in Chapter 8 of Metz, et al. (2001), as well as on WG III claims about the capabilities of exiting technological options and the potential contribution of renewable energies to achieve stabilization.

(a) 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) $C \equiv Y \cdot E/Y \cdot C/E \equiv Yef$, 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 derivations to get:

(2) $\dot{C} = \overset{(+)}{\dot{Y}} + \overset{(-)}{\dot{\left(E/Y\right)}} + \overset{(-)}{\dot{\left(C/E\right)}} = \dot{Y} + \dot{e} + \dot{f}$, where $\cdot = \left(1/x\right)\ dx/dt$, x being the variable in question and ( ) is expected direction of change. Re-arranging terms we have:

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

A further set of relationships used below is

(4) $\dot{e} = \dot{E} - \dot{Y}$. Therefore $\dot{E} = \dot{e} + \dot{Y}$

(5) $\dot{f} = \dot{C} - \dot{E}$. Therefore $\dot{C} = \dot{f} + \dot{E}$

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, $\left(C/E\right)$.

As described in section II above, Lightfoot and Green (2001) investigated the question whether there are physical upper limits to attainable energy efficiencies, limits which would constrain the long-term average annual rate of energy intensity decline. There are indeed limits 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. Once the impact on energy intensity sectoral, or structural, shifts from highly energy intensive to low energy intensive industries is added in, the attainable global average annual rate of decline in energy intensity in the 21st century is raised to between 1.0 and 1.2 percent.

How much renewable energy and conventional nuclear (fission) energy might be available by the end of the century? As Table 10 indicates, the maximum attainable amount of energy from wind, solar, and biomass technologies, taken together, is in the range of 206-436 EJ/yr. For purposes of further analysis, it is assumed that solar, wind and biomasss might be able to supply 350 EJ/yr of primary energy by the end of the century – a figure that is substantially higher than the amount that realistically can be anticipated (see section III). Another carbon-free renewable energy, hydro-electricity, is limited by available sites to 50 EJ/yr, about twice the current capacity. Electric energy from nuclear fission is likely limited by uranium supplies and, more importantly, by political resistance. Even an approximate doubling of the 27 EJ/yr of primary energy currently contributed by nuclear energy to 60 EJ/yr may be difficult to achieve unless the problem of storing radioactive waste is resolved. Finally, relatively small amounts of carbon-free energy, perhaps 20 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.

The 480 EJ/yr of carbon-free energy from renewables and conventional nuclear is highly optimistic, given the very important technical, land, water, and environmental hurdles that renewable energy sources face if developed on a large-scale. Even 480 EJ/yr is less than half of the amount of carbon-free energy needed to stabilize atmospheric CO_2 in most emission scenarios.

(b) The Thought Experiment

What are the economic (cost) implications of stabilization if there are upper limits on the long-term average annual rates of decline in energy intensity and the carbon intensity of energy? The former limit is introduced because there are ultimate physical 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 (Green and Lightfoot, 2002b). The following example illustrates.

Suppose that the anticipated growth of GDP over the 100 year period, 2000 to 2100, averages 2.3 percent annually. While an assumed 2.3 percent average rate of growth of GDP is arbitrary, it can be rationalized on the ground that it is at the lower end of the GDP growth rates employed by IPCC WG III in its SRES emission scenarios. It is also the 110 year average annual GDP growth rate underlying the earlier benchmark emission scenario, IS92a.

In 2000, world GDP was approximately \$32 trillion. Total primary energy consumed in 2000 was 400 EJ/yr, of which about 57 EJ/yr was from non-carbon sources. Only "modern" or new biomass, not old biomass, is included in the 57 EJ/yr. 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 primary energy from carbon-free sources (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.

The pieces of the thought experiment are brought together in Table 11. The elements of Table 11 can be summarized as follows:

- If GDP grows for 100 years at a 2.3 percent rate, it will reach \$311 trillion in 2100 (Table 11).
- If the average annual rate of decline in energy intensity $(\dot{e})$ is set at what Lightfoot and Green (2001) estimated is its attainable long-term maximum of 1.1 percent, a 2.3 percent growth rate of GDP implies that total energy consumption (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

consumption (1.2 percent) minus the rate of increase in GDP (2.3 percent) is the rate of decline in energy intensity of -1.1 percent (row 2).

- If carbon-free primary 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 percent (row 5). In turn, from equation (5) above, the implied average annual rate of decline in carbon intensity $\left(\dot{f}\right)$ is –0.3 percent (0.9 percent rate of growth in carbon energy $\left(\dot{C}\right)$, minus 1.2 percent growth in energy $\left(\dot{E}\right)$), 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 percent and –0.3 percent 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 percent.
- If world GDP grows at a 1.4 percent 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 still it is $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 if 2.3 percent. A GDP of $128 trillion in 2100 is 58.8 percent 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, in theory, have very large impacts on GDP.

The example above is illustrative at best. As already indicated, the exercise is only a thought experiment. It works backward to calculate the GDP cost and cannot be considered a formal cost estimate. Even then, readers will naturally and inevitably find a 59 percent reduction in GDP (in 2100), a figure that reflects the power of compounding, beyond the realms of credibility. It contrasts too starkly with the GDP cost reductions reported in IPCC WG III and other fora. It is useful, therefore, to modify the constraints in the thought experiment and carry out a sort of sensitivity analysis.

Table 12 indicates the percent by which GDP in 2100 would differ from (fall below) 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 percent, "attainable" GDP (for a carbon emission growth rate of zero) must fall below the 2.3 percent trend. That is not surprising. What still is surprising is the substantial amount (in percentage terms) that GDP will be less than trend in 2100, even if the combined total of the energy intensity and the carbon intensity decline rates is only two or three tenths of a percentage point below the 2.3 percent 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 average rate of decline in carbon intensity are shown in parentheses in the first column of Table 12. 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 percent 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 will be insufficient to meet more than a fraction of the increased demands for energy fuels in the 21st century, requiring an eventual move back to coal among the carbon fuels, 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, however, be a further, and potentially major, qualification to the figures in Table 12).

(c) Opportunity Cost of Not Investing in Advanced Energy Technologies

It should be clear now that there is a huge opportunity cost in not directly and aggressively tackling the “advanced energy technology gap”. The opportunity cost will either take the form of a large reduction in GDP (economic well being), or a failure to effectively address the build-up in atmospheric CO_2, and the resultant changes in climate and its consequences. The thought experiment demonstrates that there is likely to be a very large opportunity cost of relying on energy efficiency and renewable energies to stabilize the atmospheric CO_2 concentration. The thought experiment, and accompanying sensitivity analysis, strongly suggest that the GDP cost of relying on energy efficiency improvements and renewables to stabilize that atmospheric CO_2 concentration would be far higher (perhaps by an order of magnitude or more) than the estimates reported by IPCC WG III. Another way to put it is that there would be a large GDP cost of attempting to stabilize in the absence of advanced, and still uncertain, carbon-free energy technologies.

But the GDP cost of stabilization without advanced energy technologies does not tell the whole story and tends to overstate opportunity cost. First, we must take into consideration the long-term investment cost in researching and developing advanced energy technologies. Second, the GDP costs are gross; they do not include the economic costs of climate change (or the benefits of avoidance/mitigation). Nevertheless, it is unlikely that taking account of investment and environmental costs would do much to narrow the huge gap between the GDP cost estimates in our thought experiment and those reported by WG III (2001: 545-549).

VI. CONCLUSION

Currently, there is a major debate over climate policy among those who agree that unchecked GHG induced climate change poses a major environmental and human problem for the 21st century and beyond. This is not a debate about whether action on climate change should be undertaken, but what sort of action; in particular what kind of policies will be required in order to avoid "dangerous anthropogenic interference" with climate. Make no mistake: the disagreements about requisite means are deep and fundamental. They represent a deep divide between those who think a combination of energy efficiency and terrestial renewable energies can do the job of stabilization and those who believe that such reliance cannot come remotely close to stabilizing climate.

This paper reviews evidence indicating that there are: (a) limits on the long-term rates of decline in energy intensity; (b) limits on the supply of carbon-free energy that can be expected from renewable energy sources such as solar, wind, and biomass; and (c) economic implications of these limits for a policy of relying on energy efficiency improvements and renewable energies to stabilize the atmospheric CO_2 concentration. It is demonstrated that limits, physical or resource on the rates of decline of energy intensity of output and the carbon intensity of energy, can make a big difference in terms of predicted GDP reductions associated with atmospheric CO_2 stabilization, depending on the nature of climate policy. The investigation of these limits is critical to a rational climate policy.

Lightfoot and Green (2001) and section II of this paper, provide estimates of an upper limit of approximately –1.1 percent to the attainable rate of decline in energy intensity over the course of the twenty-first century. The estimates are based on physical or engineering limits to energy efficiency and to economic limits on the contribution of sectoral share shifts from energy-intensive to non-energy intensive activities. Lightfoot and Green (2002), and section III of this paper, demonstrate that, however large the renewable energies *potential* may seem, the actual energy that can be made available from these sources are a fraction of what will be needed to stabilize climate. When the findings of sections II and III are combined in section IV, they indicate the magnitude of the large “advanced energy technology gap”, that Hoffert et al, (2002) have shown to exist.

The existence of long-term limits on the rates of energy intensity decline and the overall contribution of renewable energies cast in doubt the robustness of the estimated GDP reductions reported by WG III. To assess robustness, the Kaya identity was used in section V as a check on the predictions of economic models used to make the sorts estimates reported by WG III. It is shown that the low and relatively narrow range of estimated GDP reductions predicted by these models do not appear to be robust to alternative, and much more realistic, 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 mistaken policy that relies chiefly on a combination of energy efficiency improvements and renewable energies to achieve stabilization. In contrast, policies that effectively address the large advanced energy technology gap estimated in section IV, can make stabilization possible, and at potentially relatively modest cost. A concerted (albeit long-term) effort to find and develop advanced carbon-free energy sources and technologies (Hoffert et al., 2002), including an effective and safe means of sequestration of CO_2 on a large scale (Herzog (2001), Lackner, et al, 1998; Lackner, 2001), may, if successful, allow stabilization of atmospheric CO_2 at an acceptable level, and at relatively modest economic cost.

A caveat is in order. The calculations produced by the thought experiment in section V should not be used as <u>estimates</u> of what GDP would be in 2100 (or any other distant year) as a result of <u>attempting</u> to carry out a policy to stabilize climate. If 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), as called for by Hoffert, <u>et al</u> (2002), 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, although great climate damage will be done.

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 as Hoffert et al (1998, 2002) urge, 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, enunciated by IPCC WG III, that technological options now exist to achieve climate stabilization at a relatively low cost.

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Table 1
Maximum Potential Increase in Primary Energy Efficiency, World Electricity Generation

	A	B	C		D	
Type of Energy	**Primary Energy Consumed in Electricity Generation in 1990** [1] (%)	**Maximum Potential Increase in Energy Efficiency** (%)	**Primary Energy Consumed in Electricity Generation in 2100** (%)		**Contribution to Increase in Energy Efficiency, 1990-2100** (%) (B X C)	
			Case 1	Case 2	Case 1	Case 2
Oil	10.9	52	0.0	0.0	0.0	0.0
Natural Gas	15.4	100	60.0	40.0	60.0	40.0
Coal	37.9	52	0.0	0.0	0.0	0.0
Nuclear	15.7	33	25.0	16.0	8.3	4.0
Hydro	17.4	5	9.0	9.0	0.5	0.5
Other Renewables	2.6	70	6.0	35.0	4.2	24.5
Total	100.0		100.0	100.0	73.0	69.0
a) Energy Efficiency Increase, 1990-2100 (%)					73.0	69.0
b) Energy Intensity in 2100 as % of 1990 (%)					57.8	59.2

1) Department of Energy, Energy Information Agency

Table 2: Calculation of Maximum Average Annual Rate of Energy Intensity Decline, 1990-2100

A	B	C		D		E	
World Energy Use, by Sector	**% Distribution, World Energy Consumption, 1990**	**Energy Efficiency in 2100 relative to 1990** (%)		**Contribution to Energy Efficiency Increase 1990-2100, with 1990 Energy Consumption Share** (%) (B X C)		**Contribution to Energy Efficiency Increase 1990-2100, with Alternative Distribution** [a] (%)	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Electricity Generation	37.5	73	69	27.4	25.9	36.5	34.5
Transportation	18.6	200	200	37.2	37.2	40.0	40.0
Residential	12.1	300	300	36.3	36.3	45.0	45.0
Industrial	21.9	200	200	43.8	43.8	30.0	30.0
Commercial	9.9	200	200	19.8	19.8		
Total	100.0			164.5	163.0	151.5	149.5
Energy Efficiency Increase, 1990-2100 (%)				164.5	163.0	151.5	149.5
Energy Intensity in 2100 relative to 1990 (%)				37.8	38.0	39.8	40.1
Average Annual Rate of Energy Intensity Decline, 1990-2100				0.88	0.87	0.84	0.83

a) Alternative Distribution of Energy Consumption (%)

Electricity Generation	50
Transportation	20
Residential	15
Industrial/Commercial	15
Total	100

Table 3
Average Annual Rate of Energy Intensity Decline, 1990-2100, if Maximum (Physical) Energy Efficiencies Achieved by 2100

Share of "Other" Renewable Energy Share in Electricity Generation in 2100	**Same as 1990**	**Alternative # 1**	**Alternative # 2**
"Small" (6%)	0.88	0.84	0.94
"Large" (35%)	0.87	0.83	0.94

"Other" includes all non-hydro renewables

Sectoral Share of Energy Consumption in 2100:

Sector (%)	Same as 1990	Alternative 1	Alternative 2
Electricity	37.5	50	30
Transportation	18.6	20	25
Residential	12.1	15	23
Industrial/Commercial	31.8	15	25
Total	100	100	100

Table 4
Maximum Attainable Average Annual Rate of Energy Intensity Decline: 1990-2100

Average energy intensity decline from energy efficiency improvement	0.83 - 0.94
Average energy intensity decline due to structural change	0.16[a] - 0.30[b]
Estimated total average energy intensity decline	0.99 - 1.24

a) Share of energy intensive industries decline from 33% to 15% in 2100

b) Share of energy intensive industries decline from 33% in 1990 to 5% in 2100

Source: Based on Lightfoot and Green, C^2*GCR Report 2001-7, October 2001, Table 9*

Table 5: Solar Electricity - area/EJ and total EJ from 1% of unused land

		A	B	C
		Area/EJ of electricity delivered **km^2/EJ/yr**	**Solar electricity from 1% of unused land, 393,000 km^2** **EJ/yr**	**Solar electricity if grid & storage limited** [a] **EJ/yr**
1	Lightfoot and Green, horizontal plate data, 2.12x spacing	2,078	189	80
2	Eliasson, horizontal plate data, 2x spacing	1,905	206	80
3	WG III, horizontal plate data, 2x spacing, Table 3.33a, p 247	2,413	163	80
4	WG III, (393,000 km^2) / (1,575 EJ), 15% efficient solar cells, horizontal plate data, 2x spacing (WG III min)	3,327	118	80
5	WG III, (3,930,000 km^2) / (49,837 EJ), 15% efficient solar Cells, 2-axis tracking, 5x spacing (WG III max)	2,629	150	80
6	WG III, horizontal plate data, 2x spacing, text, p 247	2,116	186	80

a) See note b to Table 6

b) Assumes equal amount of direct electricity and solar hydrogen

Source: Lightfoot and Green, C^2GCR Report 2002-5, Table 1, November 2002, for cols. A, B

Table 6: Wind Generated Electricity - area/EJ and total EJ/yr

		A	B	C
		km^2/EJ/yr	**Wind electricity from 1,200,000 km^2** [a] EJ/yr	**Wind electricity in 2100 if grid constrained** [b] EJ/yr
1	Lightfoot and Green	20,000	60	40
2	Eliasson	25,079	48	40
3	WG III: from WEC data in text, p 246	16,670	72	40

a) 4% of all land with average wind speed of 5.1 m/s or greater

b) A maximum of 20% of the electricity supplied to the electric grid can be supplied from intermittent sources, such as wind & solar. The assumptions here are that:
(1) electricity demand in 2100 will be 10 times that in 1990, or 400 EJ/yr, and
(2) the two intermittents, solar and wind energy, contribute equally to the grid

Source: Lightfoot and Green, C^{2}GCR Report 2002-5, Table 2, November 2002, for cols. A, B & C

Table 7: Solid Biomass - area/EJ and EJ/yr from 8,950,000 km^{2} [a]

		A	B	C
		Km^2/EJ	**Solid biomass fuel** EJ/yr	**Water availability constrained** (0.5 x col. B)
1	Lightfoot and Green - average for short rotation trees	19,000 – 46,000	195 - 470	98 - 235
2	Eliasson - average for hybrid poplar (short rotation) trees	28,802 – 47,642	188 - 311	94 - 156
3	WG III - trees	33,333	268	134

a) 100% of estimated cropable land not used for crops in 2100

Source: Lightfoot and Green, C^{2}GCR Report 2002-5, Table 4, November 2002, for cols. A & B

Table 8: Liquid fuels from biomass - area/EJ and EJ/yr from 8,950,000 km^{2} [a]

		A	B	C
		Land area km^2/EJ	**Liquid biomass fuel** EJ/yr	**Water availability constrained** (0.25 x col. B)
1	Lightfoot and Green - average for methanol of 50,000 to 120,000 km^2	50,000 - 120,000	75 - 179	18 - 45
2	WG III - trees to liquid fuels	66,666 - 95,000	94 - 134	24 - 34

a) see note to Table 7

Source: Lightfoot and Green, C^{2}GCR Report 2002-5, Table 5, rows 1 & 2, November 2002, for cols. A & B

Table 9: Renewable Energy "Potentials" Reported by WG III and Actual Potentials

	(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 Calculations in col. (3)**
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 (50% conversion efficiency for solid to liquid)
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.

Table 10: Renewable Energies[a] that Could Potentially be Available in 2100, Under Two Different Sets of Assumptions

	A	B
	WG III Land Availability [b]	**A Resource and Grid Constrained World** [c]
EJ/yr in 2100	436 EJ/yr	202 EJ/yr
% of carbon free energy needed to stabilize at 550 ppmv IS92a scenario	37%	17%

a) total solar, wind, biomass

b) sum of rows 3, col. C of Tables 5 & 6, plus 50% of rows 3 & 2 of col. B of Tables 7 & 8, Respectively

c) sum of rows 3, col. C of Tables 5 & 6, plus 50% of rows 3 & 2 of col. C of Tables 7 & 8, Respectively

Table 11

Tabular Summary of Calculation of GDP Reduction Below Baseline in 2100: Case of Baseline GDP Growth Rate of 2.3 percent, Energy Intensity Decline Rate of 1.1 percent 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 $)	32	311	2.3%
2) Energy Intensity (EJ/yr per trillion$)	12.5	4.25	-1.1%
3) Energy EJ/yr	400	1322	1.2%
4) Carbon Energy	343	842	0.9%
5) Carbon Intensity	0.857	0.637	-0.3%
6) GDP attainable (if C=0 and e = -1.1 and $\dot{f} = -0.03$)	32	128	1.4%
7) GDP differential (6) – (1)	0	-183	-
8) Percent Difference (7) ÷ (1)	-	-58.8	-

Table 12

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	-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[b]	NR[b]

a) Assume 100 year trend growth rate of 2.3 percent.

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 energy costs on GDP.

Appendix Table A: Some Energy-Related Characteristics of the 40 IPCC (SRES) Emission Scenarios

1	2	3	4	5	6
Quartile	**Average Annual Rate of Energy Intensity Decline 1990-2100** %	**Average Share of Electricity in Final Energy** %	**Renewable Energies in 2100** EJ/yr	**Primary Energy in 2100** EJ/yr	**Final Energy in 2100** EJ/yr
Highest	1.59 - 2.18	49.6 - 60.8	582 - 1,609	2,040 - 2,737	1,436 - 1,765
Second	1.27 - 1.55	45.3 - 48.9	432 - 579	1,370 - 2,021	1,117 - 1,432
Third	1.09 - 1.26	40.7 - 44.6	318 - 427	1,114 - 1,357	891 - 1,092
Fourth	0.57 - 1.06	16.1 - 40.7	103 - 307	514 - 1,077	452 - 843
Mean (2100)	1.32	42.9	509	1,542	1,141
Median (2100)	1.265	45.0	430	1,360	~ 1,100
Mean (1990)	1.0[b]	15.0	26[c]	347[d]	~ 260

a) prepared by IPCC WG III for the IPCC Third Assessment Report, 2001
b) Average 1970 – 2000
c) excluding old biomass. About 98% is hydroelectricity
d) 400 EJ/yr in 2000

Source: IPCC, *Special Report on Emission Scenario*, 2000

Appendix Table B: IPCC WG III Renewables Potential Estimates

	1	2	3
	Renewable Energies Reported in IPCC WG III (2001) Tables 3.31, 3.32 & 3.33b EJ/yr	**Renewable Energy Reported by Jose Moreira[a] to Delegates at COP 6(II) in Bonn, July 2001 (Long Term Technical Potential)** EJ/yr	**Land-Use Assumptions, IPCC WG III Ch 3, p 244-249** km^2
Solar	1,575	> 1,600	393,000
Wind	636	> 630	1,200,000
Biomass	396	> 440	11,900,000
Total Renewable	2,607	> 2,800[b]	~ 13,500,000
Range of Total Energy Demand in 2100, SRES Scenarios: 515 - 2,737 EJ/yr			

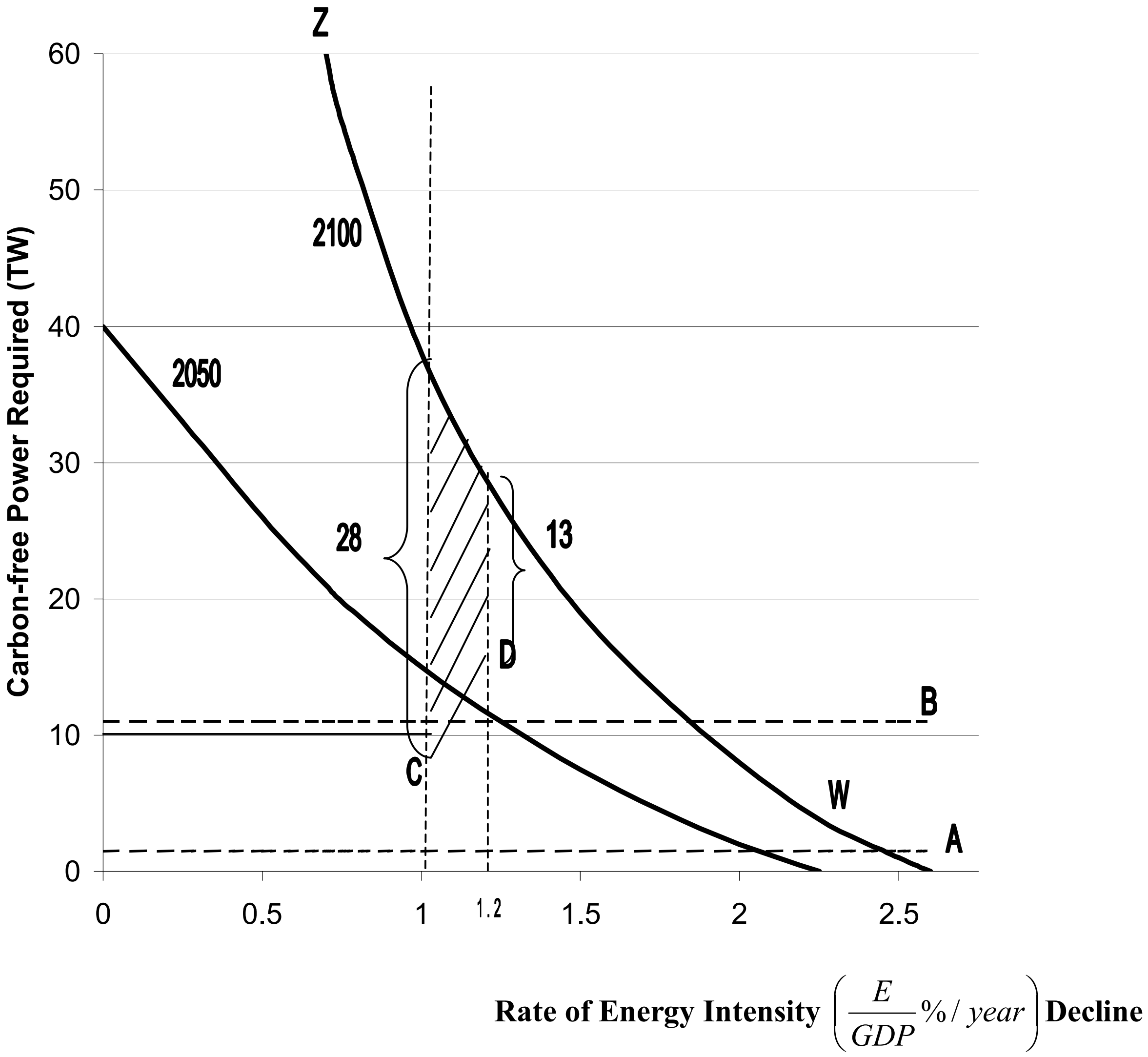
a) One of the two chief authors of Ch 3 IPCC WG III (2001)

b) Includes hydro (> 50); geothermal (> 20); ocean (> 20)

c) The Earth's land area is approximately 130,000,000 km2, not including polar areas

Source: Intergovermental Panel on Climate Change, Report of Working Group III, *Mitigation*, Cambridge University Press, 2001, Ch 3, and IPCC website: www.ipcc.ch

Figure 1: Advanced Energy Technology Gap



Line A => 1990 Carbon-free Power

Line B => 1990 Total Primary Energy "Burn Rate"

Estimated magnitude of "Advanced Energy Technology Gap" is indicated by hatched area.

Based on Hoffert, et al. (1998) Figure 3. 21st century trade-offs, between carbon-free power required and "energy efficiency", to stabilize atmospheric carbon at twice the pre-industrial CO_2 concentration.