CLIMATE CHANGE POLICY: THE ENERGY PREDICAMENT

Chris Green
Department of Economics
McGill University
and
H.D. Lightfoot
Mech.Eng. (retired)

ABSTRACT

In an important respect the climate change (global warming) problem is an energy problem. Any policy aimed at substantially reducing greenhouse gas (GHG) emissions will require large amounts of carbon free energy as substitutes for abundant fossil fuels. No conceivable rates of improvement in energy efficiency and/or changes in lifestyles will obviate the need for vast amounts of carbon free energy if GHG emissions are to be reduced and the atmospheric concentration of carbon eventually stabilized. Where will such large amounts of carbon free energy come from? The renewable energies (solar, wind, biomass) are dilute and enormously land-using. Their potential contribution is seemingly limited in a world in which competing demands for land for food production, living space, leisure activities, ecological preserve, and natural resource production are increasing. Nuclear energy is controversial (fission) or problematic (fusion). Fuel cells require hydrogen which must be produced using some other form of energy. Without abundant carbon-free sources of energy, reduction in GHG emissions will be much more costly than is indicated by current models. The aim of climate policy should be to spur a decades long search for and development of new carbon free energy sources and technologies capable of displacing fossil fuels and of eventually meeting the world's baseload energy requirements.

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Introduction

More than two decades have elapsed since serious study of greenhouse warming was initiated in scientific circles and more than a decade since the concept of the greenhouse effect became a household term. During the past decade, the world's leading climate scientists have issued two major reports (IPCC 1990; IPCC, 1996) on climate change. Another is expected in 2001. In 1992, and again in 1997, most of the nations in the world (including all developed countries) met to hammer out a global policy in the form of a climate convention (Rio, 1992) and a protocol for achieving targeted reductions in greenhouse gas (GHG) emissions (Kyoto, 1997). Looked at as a whole, a lot of progress has been made in understanding the sources and processes of climate change attributable to the build-up of GHGs in the atmosphere and in recognizing the global nature of the problem and solutions to it.

But as one looks more closely, it is evident that important fissures appear in the fabric of acceptance that global warming is an important problem, with important implications for humankind. While it is incontrovertible that there is a build-up of GHGs in the atmosphere and that the main source of that build-up is from burning fossil fuels for energy production, disagreement begins over how much warming will occur, whether there is already evidence of a "human imprint", what the impact of climate change will be, and how large the damage will be, if any. Almost out of sight altogether is the important question of where the world will get the energy to meet the needs of a modern global society if it attempts to greatly reduce its reliance on fossil fuels.

This paper is an attempt to tackle the energy side of the global climate change problem. It is not far fetched to say that in many respects the climate change problem is an energy problem. It is also likely that some of the division over climate change policy arises because of a failure to understand how and why the climate change problem is an energy problem. Energy is essential – and the need for energy will grow. Given the current limitations of alternative energies, blaming fossil fuels for the climate problem comes close to blaming energy use for the problem. This, in turn, almost certainly creates resistance to carbon emission abatement policies that would have the effect of substantially curtailing energy availability and use. Once it is acknowledged that abundant and affordable energy is crucial to humankind, and that it will be no simple task to find and to develop adequate alternatives to fossil fuels, it will be easier to achieve a consensus on appropriate climate policy.

The paper proceeds as follows. Section 1 briefly outlines current climate policy initiatives. Section 2 explains the development of atmospheric carbon concentration stabilization paths, their meaning, and their implications for future energy requirements. Section 3 takes up the important question of energy alternatives to fossil fuels and the reasons why, at present, these alternatives appear limited. In section 4, the paper briefly considers some implications of the analysis. Section 5 concludes.

1. Climate Policy Initiatives

Since the publication, in 1996, of the Second Assessment Report (SAR) of the International Panel on Climate Change (IPCC), there has been a stepped-up effort to frame policy initiatives to curb the emission of GHGs. These efforts culminated in agreements reached at Kyoto in December 1997, calling for most industrialized nations to reduce their GHG emissions relative to 1990 levels by

2008-2012. A number of mechanisms for emission reduction were set out in the Kyoto Protocol, including tradeable emission permits and credit for a developed country's actions that reduces emissions in a developing country (the Clean Development Mechanism). But even if all of the emission targets agreed to at Kyoto are reached, global GHG emissions are still anticipated to rise, reflecting the growing share of GHG emissions contributed by developing countries. Moreover, many of the developed country targets are suspect in as much as their achievement would require a 15 to 20 percent reduction from current emission levels to be achieved in the next, growth conscious, decade. Finally, even if stabilization of global emissions were achieved, the atmospheric concentration of GHGs – the factor influencing climate - will continue to increase because of the long-lived nature of GHGs. Stabilization of atmospheric concentration would require a 60 to 70 percent reduction in global emissions relative to current emission levels.

2. Stabilization Paths

The key question is how much carbon free energy will be needed to reduce carbon emissions and eventually stabilize the atmospheric carbon concentration. This issue has been tackled in a series of steps beginning with the construction of GHG emission scenarios by the IPCC (1992) and culminating in a paper by Hoffert, et al (1998).

The IPCC (1992) defined several GHG emission scenarios for the 21st century. These scenarios are based on assumptions about population growth, real income (output) growth, improvement in energy efficiency, and the availability of non-carbon energy. One of these scenarios, denoted IPCC 1992a, was viewed as the central estimate of GHG emissions growth over the next century assuming "business as usual" (BAU) conditions, that is, in the absence of policy intervention designed to mitigate or abate GHG emissions.

The assumptions underlying IPCC 1992a imply that GHG emissions would reach between 18 and 19 gigatons of carbon equivalent (GtC) by 2100, roughly three times the current level of emissions. Under IPCC 1992a assumptions, the carbon content of the atmosphere would reach 550 ppmv a little after 2050, double the pre-industrial levels of 275 ppmv (the current level in 365 ppmv). By 2100, the carbon content would be closing in on triple the pre-industrial level. Such concentration levels, according to most climate scientists, would be likely to trigger important climate changes. Yet, as Schmalensee, et al (1998) show, projections of historically-based trends of carbon emission are "much higher" than five of the six IPCC 1992 scenarios, including 1992a. The Schmalensee, et al results suggest therefore that the task of curbing carbon emissions is even more daunting than is implied by IPCC.

The IPCC Working Group I (WGI), made up of climate scientists, proceeded to construct GHG emission paths leading to stabilization of the atmospheric concentration of GHGs at various levels ranging from 750 ppmv (roughly triple the pre-industrial level) down to 350 ppmv (roughly the atmospheric concentration in 1990). These paths would, of course, diverge from the IPCC 1992a GHG emission path. As such, the paths served as more or less stringent policy targets, depending on the level it was agreed that atmospheric concentration of GHGs should or could be stabilized.

In a widely cited paper published in Nature, Wigley, Richels, Edmonds (WRE) point out that there are many (in principle, an infinite) number of emission paths to any given atmospheric stabilization target, and that it is important for policy makers to choose the most efficient (least cost) path. The least cost path would be influenced by such factors as: (a) the length of life of existing energy equipment and infrastructure; (b) the pace of technological change in producing new energy technologies and sources; and (c) a positive marginal productivity of capital, implying that with a positive return on capital, the further in the future is an economic burden, such as emissions reduction, the smaller the set of resources that must be set aside to finance the burden (WRE, 1996: 242).

Whereas the pathways to stabilization of GHGs employed by IPCC WGI all diverged almost immediately from the BAU (1992a) path, the WRE paths do so only after some time has elapsed. While WGI did not intend that their analysis serve as a policy recommendation, some persons interpreted WGI as implying that an immediate reduction in GHG emissions is required to achieve any of the stabilization targets. In contrast, WRE not only demonstrate that other paths to stabilization are possible, but the paths that follow the BAU path for the next 10-20 years may be more efficient or cost minimizing than ones that immediately diverge from BAU. The WRE analysis not only clarified the issue of stabilization paths, but has served as the basis for other recent assessments of the stabilization path issue.

In their paper, WRE stress that “to ensure sufficient quantities of low-cost, low carbon substitutes in the future requires a sustained commitment to research, development, and demonstration today” (1992: 242). Despite their appropriate stress on the importance of research, WRE did not consider whether their paths were a realistic transition from the present fossil-fuel based system of energy supply. This gap is noted in another paper in Nature, by Hoffert, et al (1998) (which includes Wigley as one of its eleven co-authors). The Hoffert, et al paper employs the WRE stabilization paths in estimating the amount of carbon-free energy that would be needed to stabilize the atmospheric concentration of CO_2. As the IPCC (1992) and WRE (1996) had done, Hoffert, et al employ stabilization targets ranging from 350 to 750 ppm. In making their assessment, Hoffert, et al employ the population and income growth assumptions of IPCC 1992a (as WRE had done) and then show how the required amounts of carbon-free energy depend critically on the pace of improvement in energy efficiency (decline in energy per unit output).

Hoffert, et al show that very large amounts of carbon-free energy (measured in terms of terrawatts (TW) of power) will be needed by 2050, if the atmospheric CO_2 concentration is to be stabilized at 550 ppmv (i.e. at twice its pre-industrial level of 275 ppmv by the end of the century). The amounts of carbon-free energy required depend critically, as noted, on the pace of energy-efficiency improvement. Hoffert, et al use a one percent annual rate of improvement (decrease) in energy per unit of output as their central case. The one percent per annum rate is the historic rate of decline in energy per unit of output achieved in developed countries after their initial stages of industrialization. Figure 1 (drawn from Hoffert, et al) shows the amount of carbon-free energy needed at various dates between 2000 and 2100, for varying levels of energy efficiency improvement, if the WRE path to stabilization at 550 ppmv is to be achieved. Table 1 indicates the amount of carbon-free energy (terrawatts of power) needed at 2050 and 2100, assuming annual rates of energy efficiency improvement of 1.0 percent and 1.5 percent, respectively.

In order to grasp the dimensions of the carbon-free energy (or power) requirements needed to substantially reduce dependence on fossil fuels, it is important to know that, in 1990, the world required about 11 TW of primary power, of which about 1.5 TW was carbon-free (nuclear, hydro, solar, wind, biomass). Given the energy requirements implied by IPCC 1992a, 16 TW of carbon-

free power would be required by 2050 and 37 TW by 2100, to stabilize atmospheric CO_2 concentration at 550 ppmv, assuming the average rate of energy improvement is 1 percent per annum throughout the 21st century. The requirements are 7 and 18 TWs, respectively, if the rate of energy improvement can somehow be pushed up to 1.5 percent per annum.

Table 1: Required Amounts of Carbon-Free Power[a] and Energy[b]

RATE OF ENERGY INTENSITY DECLINE		CARBON FREE POWER (ENERGY)			TOTAL POWER (ENERGY)
		Current	**Required[c]**		
		1990	**2050**	**2100**	**1990**
1.0%	TW	1.5	16	37	11
	EJ	47	505	1168	347
1.5%	TW		7	18	
	EJ		220	568	

a) measured in terrawatts (TW) of power. A TW = 10^{12} watts

b) measured in exajoules (EJ) of energy per year. An EJ = 10^{18} joules

c) These are the amounts of carbon free power (energy) needed to stabilize the atmospheric CO_2 concentration at 550 ppmv

Another way to comprehend the point made by Hoffert et al (1998) is to manipulate the Kaya equation that underlies that paper's calculations. The Kaya equation (or identity) is:

$$(1) \quad C = P \bullet Y/P \bullet E/Y \bullet C/E$$

The Kaya equation is usually presented in terms of rates of growth or decline per time period (equation (2)).

$$(2) \quad \dot{C} = \overset{(+)}{\dot{P}} + \overset{(+)}{\dot{\left(Y/P\right)}} + \overset{(-)}{\dot{\left(E/Y\right)}} + \overset{(-)}{\dot{\left(C/E\right)}}$$

where a dot $(\bullet)$ indicates the relative time rate of change, i.e. the percentage change over a specified period of time, such as a year, and the anticipated signs (direction of change) are in ( ).

If we feed the annual rate of change of population (0.8 percent); of output per capita (1.3 to 1.8 percent, where $\left(\dot{\left(Y/P\right)} = \dot{Y} - \dot{P}\right)$, and energy intensity decline (0.8 percent to 1.4 percent) into equation (2), one can learn how crucial is the rate of decarbonization (decrease in C/E) for the level of carbon emissions C. For the 21st century, projections for average annual rates of population and income growth are $\dot{P} = 0.8$, and $\dot{Y} = 2.3$ (implying $\left(\dot{Y/P}\right) = 1.5$). If $\left(\dot{E/Y}\right) = -1.0$ per annum, then

$$(3) \quad \dot{C} = .8 + 1.5 - 1.0 + \left(\dot{C/E}\right)$$

With the rates of growth of population, income, and energy intensity decline in equation (3), stabilization of carbon emissions, C (i.e., $\dot{C} = 0$), would require an annual rate of decarbonization (i.e., an annual rate of decline in C/E) of –1.3 percent. Such a rate is more than three times the current annual rate of decline in carbon per unit energy of –0.4 percent. If the average annual rate of energy intensity decline $\left(\dot{E/Y}\right)$ can somehow be raised to 1.5 percent, it would still take an average annual rate of decarbonization of energy of -0.8 percent per annum (or twice the current annual rate), to stabilize carbon emissions. (Keep in mind that achieving stabilization of carbon emissions at current levels would still result in a doubling of the atmospheric CO_2 concentration by 2100.)

Where would such large amounts of carbon-free power come from? This question has been largely ignored. Yet it is a question that needs to be answered if we are to say we "can" (if we decide we "should") stem the growth of GHG emissions and eventually stabilize the atmospheric CO_2 concentration, albeit at a level substantially above the current one of 365 ppmv. Hoffert, et al make a major contribution by establishing that stabilization will require very large amounts of carbon-free power. But, except for suggesting that "researching, developing, and commercializing carbon-free primary power technologies capable of 10-30 TW by 2050 could require efforts, perhaps international, pursued with the urgency of the Manhattan Project or the Apollo space program," Hoffert, et al do not directly address the question of where vast amounts of carbon-free energy will come from (1998: 884).

3. Limitations of Existing Energy Alternatives

The question of where very large amounts of carbon-free energy will come from is, we believe, the crucial issue surrounding any attempt to reduce greenhouse gas emissions and stabilize their atmospheric concentration. It is an issue that has not been given the attention it deserves, although it has now been given a needed push by the Hoffert, et al paper. (Also see Hoffert and Potter, 1997, and Nakicenovic, et al 1998.) It is, in any event, the issue that has governed most of our own research in recent years. Our work has centered on two rather different questions. What is the scope for employing renewables such as solar, wind, biomass, and hydro energies as replacement for fossil fuels? What will it take to stimulate a long-term energy technology race into research and development of new energy sources and technologies? The answer to the second question is made all the more important by our answer to the first question, but only the first question is considered in this paper.

Throughout the debate over climate change, there has been a quiet optimism that if the use of fossil fuels is curtailed, via regulation, carbon taxes, or tradeable permits, other sources of energy would appear to take their place. Many have argued that these sources are already available – but are simply not economically competitive with fossil fuels, the abundance of which, has kept their prices low. By artificially raising the price of fossil fuels or otherwise curtailing and regulating their use, so the argument goes, new energy sources and technologies waiting in the wings will rapidly replace fossil fuels. What are these sources? Most are the renewables mentioned above: solar (in its various forms), wind, and biomass. To these may be added a non-renewable, hydrogen – a component of water and of fossil fuels, particularly oil and natural gas. Much is already being made of the decline in the cost of harnessing these energy sources. In this view, it would not take very long, and not that much of an increase in the price of fossil fuels, before greatly increased amounts of renewable energies could become economically competitive. But is this really the case?

With nuclear fission under its own environmental cloud, renewables are at the core of energy alternatives to fossil fuels. But, there is reason for doubt about how much we can rely on renewables once we take into consideration the scale on which non-carbon energy is needed. Whereas fossil fuels and nuclear are highly concentrated forms of energy, renewables are very dilute. Fossil fuels are stored solar energy, stored over hundreds of millions of years. Solar, wind, and biomass energies are provided by the current flow of solar energy. A large current flow implies renewable energies must be gathered over a very large area. In short, the renewables are highly land using – in a world in which land almost surely will become an increasingly scarce resource.

To give some idea of just how land using the renewables are, we draw attention to Table 2. This table is an updated summary of the main findings contained in Lightfoot and Green (1992 and 1998) and in Green (1994, 2000). What Table 2 shows is that it would take thousands (in many cases tens of thousands) of square kilometers to produce an energy equivalent to three large oil refineries. The unit of energy used here is an exajoule, or 10^{18} joules. The world currently uses about 400 exajoules of energy – about eighty percent of which is supplied by fossil fuels. Table 2 shows that it would take a very large amount of land of the right type in the right locations to meet a substantial fraction of the world's current requirements for energy, much less its future requirements. Table 2 also indicates that if solar photo voltaic energy is to be stored in some form to use at night, in winter or when it is cloudy, large amounts of fresh water will be needed to turn it into hydrogen through the electrolysis process.

The key idea to be drawn from Table 2 is that to convert from a world dependent on fossil fuel energy to one based on renewables will require large amounts of another scarce resource: land. It would amount to making land our chief source of energy production in the same way as it is vital to food production. But land has many alternative uses, and the demand for it will inevitably increase even in the absence of using it to produce energy.

Suppose we are fortunate enough that increased agricultural productivity continues to outstrip population growth, thereby reducing the demand for cropland and forage. Still, increasing amounts of land will be required for living space, recreation and leisure, other resources such as lumber, and environmental preserve, including the preservation of ecosystems that provide among other things, water purification, species habitat, and nutrient cycling. To add energy production to the demands placed on land would almost certainly add to upward pressure on the price of this scarce resource – making it increasingly expensive. As an example, let us consider how much land might be needed if biomass is to become a major factor in the energy picture. It is estimated that it would take 571 million hectares (or 41 percent of the world's current cropland) planted in short rotation trees and other energy crops to produce 325 exajoules of energy. But by 2100, the world will need between 700 and 1200 exajoules of energy. (Watson, et al, 1996). So, by the time such a huge

conversion of land is achieved, biomass could provide for only 25 to 40 percent of the world's energy need. Moreover, conversion of such large amounts of land to energy production may not be economic at all. To determine whether it would be economic requires including land costs in the estimates of the cost of producing renewable energy on a large scale (Green, 2000). This has not been done.

The foregoing should not be interpreted as writing off a future energy role for renewables. In a recent paper, Turner (1999) paints a less pessimistic view of the land requirements of a renewable energy future, one that is based on a solar photo voltaic energy source and hydrogen technologies. Although Turner's estimate of land requirements per EJ are similar to ours, his estimates of total land requirements are lower than what one would presume on the basis of current US production and consumption of energy. One reason for his lower estimates is that Turner's analysis accounts for only one third of U.S. energy consumption (electricity consumption plus automobiles), not, as he says, to all U.S. energy needs (1999: 687). Another, is Turner's implicit assumption that the combination of photo voltaics and hydrogen would reduce the total amount of energy needed to meet end use consumption by somehow bypassing efficiency losses at the production level. There is also an assumption of huge improvements in energy efficiency -- with advanced fuel cell technology allowing an automobile fuel economy equivalent to 106 miles per gallon (Turner, 1999: 689 n 15.) These leaps of faith also ignore evidence that the large scale application of photovoltaic energy technology still has huge hurdles to overcome (Shah, et al, 1999).

Hydrogen based fuel cells are getting a lot of attention, but hydrogen must be produced, and this too requires energy. If the energy is supplied by solar photo voltaics, as Turner (1999) assumes, it also requires very large amounts of fresh water – something typically in short supply where solar energy is most plentiful. As well, there are still big hurdles to overcome in hydrogen-fuel cell or hydrogen-substitute technologies. (See Scientific American, July 1999: 78-79, 86, 91, and Science, July 3, 1999: 680-685.) Electric cars are often cited as a possibility – but it takes energy to charge the batteries. A possible alternative is Toyota's ingenious electric – internal combustion (gasoline) car, where the engine operates at peak efficiency whether running the car or charging the battery. Toyota's innovation essentially increases energy efficiency – while still using fossil fuels. But even in the case of Toyota's innovation, there are no short cuts to freeing ourselves from dependence on fossil fuels.

What is clear is that fossil fuel energy replacement technologies are not only not in place, they do not now exist in a form capable of displacing the dominant role now played by fossil fuels. Although Romm, et al (1998) discuss a number of readily available technologies that would help countries (especially the U.S.) meet their Kyoto targets by 2008-2012, nothing that they describe solves the problem of moving from a Kyoto target of slowing the growth of global emissions of GHGs to a post-Kyoto target of actual reduction of emissions on a global scale. The latter is a necessary step in the direction of ultimately stabilizing the atmospheric CO_2 concentration. Moreover, even if there is unexpectedly great and rapid progress in photovoltaic and hydrogen technologies, this step may well wait upon the successful development of some new, concentrated sources of energy such as nuclear fusion.

There is, however, a possible alternative approach. Technical progress in carbon management (CM) – the linked processes of separating carbon dioxide when fossil fuels are burned and collecting it for sequestration in the ocean or ground – "may transform the political economy of abatement policy" (Parson and Keith, 1998: 1054). But even CM may create important environmental problems. According to Parson and Keith (1998: 1053), CM's "technical progress is outpacing consideration of its limitations and potential risks". The problem is storage. Barring solutions to the sequestration problem (and carbon dioxide storage is considerably more problematic than the safe sequestration of nuclear wastes), we are still stuck with the issue of what can be done to eventually displace fossil fuels.[1]

Fundamentally, then, the issue of what will happen to carbon emissions in the 21st century is an energy supply question. Attempts to reduce global carbon emissions must surely fail in the absence of alternative energy sources. Moreover, the "quality" of energy sources also matters. To adequately replace fossil fuels, about one half of the new energy must have similar or better energy densities and energy release rates than fossil fuels. Thus, the main issue is whether energy technologies and sources can be developed which will obviate current dependence on fossil fuels. There are no assurances. While CO_2 emission constraints may add incentives to find and develop new technologies, imposing carbon emission constraints is not a sufficient condition that the required amounts of carbon-free energy will be found and developed. In fact, carbon emission constraints could get in the way by generating political resistance to any costly course of action to reduce emissions.

4. Some Implications

The discussion in the preceding two sections calls into question (a) the feasibility of Canada's commitment to reduce GHG emissions to 6% below its 1990 level by 2010, and (b) the vast majority of GHG emission cost estimate which suggest that each 20% reduction in GHG emissions from baseline would cost approximately about 1.0 percent of GDP. We begin with a brief analysis of the likelihood that Canada can meet its commitment under the Kyoto Protocol.

a. Canada's Kyoto Commitment

The Kaya equation can be used to evaluate the likelihood that Canada will achieve its commitment of a reduction, by 2010, in GHG emissions to 6 percent below 1990 levels. Based on projections of uncontrolled emission-levels in 2010, the Analysis and Modelling Group of Canada's Climate Change Process estimated that carbon emissions must decrease at annual average rate of 2 percent between 2000 and 2010 in order to meet this target (Canada's Emissions Outlook, 1999: 58-59). With population and GDP per capita projected to grow at annual average rates of 0.9 percent and 1.4 percent, respectively, achieving the GHG emission target would require that the rate at which $\overset{\bullet}{\left(C/Y \right)}$ declines, where $\overset{\bullet}{\left(C/Y \right)}$ is equal to the sum of $\overset{\bullet}{\left(E/Y \right)}$ and $\overset{\bullet}{\left(C/E \right)}$, is -4.3%. If $\overset{\bullet}{\left(E/Y \right)}$ declines at its "historic" annual average rate of -1.0%, $\overset{\bullet}{\left(C/E \right)}$, the rate decarbonization, must decline at a -3.3% rate. This can be seen in equation (4) where equation (2) has been rearranged to solve for $\overset{\bullet}{\left(C/E \right)}$. Even if, somehow, the rate of energy intensity decline can be raised to -1.5%, it would

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[1] Under study, however, is a proposal for "zero coal" in which carbon dioxide would be converted to a solid when placed in serpentine, or limestone deposits.

still take an average annual rate of decline in $\left(\dot{C/E}\right)$ of 2.8 percent, or seven times the “historic” rate of decarbonization of 0.4%, to meet Canada’s Kyoto commitment. These required rates of decarbonization are unimaginable given existing energy sources and technologies. One is inevitably led to the conclusion that Canada will not come close to meeting its Kyoto commitment, at least by reductions in GHG emissions at home.[2]

(4)

$$\left(\dot{C/E}\right) = -\dot{C}^{*} - \dot{P} - \left(\dot{Y/P}\right) + \left(\dot{E/Y}\right),$$
$$-3.3 = -2.0 - 0.9 - 1.4 + 1.0$$

where $-\dot{C}^{*}$ is the annual rate of decline in GHG emissions required to meet Canada’s Kyoto target

b. Emission Reduction Cost Estimates

The analysis and discussion of sections 2 and 3 above also casts doubt on estimates of the cost, in terms of reduced GDP, of substantially reducing GHG emissions. Economists have employed aggregative economy-energy (so-called “top-down”) models to estimate the cost of reducing GHG emissions. These studies employ neoclassical production functions, many of the Cobb-Douglas or some other constant elasticity of substitution type. These models are typically used within a general equilibrium framework. By the mid-1990's, a large number of cost of GHG reduction studies had been carried out. These are nicely summarized in Figures (9.1, 9.9, and 9.22) and Tables (9.1, 9.9 and 9.24) of Chapter 9 of the International Panel on Climate Change (IPCC) Working Group III report issued in 1996. (See Bruce, et al, 1996).

Table 3 summarizes the range of findings (ignoring a few outliers) of studies reported in the IPCC (WG III) survey. The Table includes the numerous U.S. studies and the not-so-numerous global studies. There is a range of estimates for any given percentage reduction in GHG emissions. To aid the reader, Table 3 reports in parentheses mid points of the range of estimates. Generally, these rise at a rate of approximately one percentage point of GDP per 20 percent point increase in the control rate for GHG emissions.

The third column of Table 3 reports the range of estimates that one would predict if one assumed a Cobb-Douglas production function with a coefficient on the energy variable equal to energy’s share of U.S. GDP and an energy elasticity of fossil fuels of .7. Energy’s share lies in the 6 to 8 percent range of U.S. GDP. The output elasticity of fossil fuel reduction predicted by a Cobb-Douglas production function is therefore equal to energy’s share in national output times the percentage reduction in energy due to the percentage reduction in fossil fuel use (the energy elasticity of fossil fuels). The relationship between the percentage change of GDP and the percentage reduction in carbon emissions is given in equation (5).

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[2] If the world adopts internationally tradeable carbon permits as its GHG reduction instrument of choice, it might be possible for Canada to meet its Kyoto commitment by massively buying permits from former parts of the USSR (which will temporarily have an excess of permits) and from less developed countries which, under the Kyoto Protocol, are not obligated to meet a GHG emission target. With full international trading of emission permits, Canada would have a temporary respite from the high cost of reducing GHG emissions at home.

$$\%\,\Delta GDP = \%\,\Delta C \cdot \epsilon_{YE} \cdot \epsilon_{EC} \qquad (5)$$

, where C = carbon emissions, ϵ_{YE} is the output elasticity of energy and ϵ_{EC} is the energy elasticity of carbon (fossil fuels)

The estimates in col. 3 of Table 3 are disturbingly similar to those in columns (1) and (2). We use the words “disturbingly similar” because the analysis in section 2 and the discussion in section 3 above implicitly suggest that a Cobb-Douglas production function, with its assumptions of a constant elasticity of substitution and an output elasticity of energy equal to the latter’s share in GDP, should be a very poor predictor of how output would vary as we substitute away from, and reduce the use of, fossil fuel energy. Our ability to substitute away from energy use on a large scale is limited. What might be relatively costless at the margin should become exponentially costly in terms of reduced GDP, as the scale of GHG/energy reduction becomes much larger. Thus, the ability to substitute away from energy, once one moves beyond marginal reductions, is likely to be low, and that beyond some point, energy and capital may become complements rather than substitutes.

The only way to reconcile the estimates in economy-energy (top-down) models with “reality” is if there is some carbon-free energy backstop. If there is a carbon-free backstop, the elasticity of energy with respect to carbon (fossil fuels) declines toward zero, thereby disconnecting fossil fuel decline from energy- dependent GDP. This paper has argued however that, with the possible exception of nuclear fission (currently viewed by many as a “cure worse than the disease”), there is now no carbon-free energy backstop, nor is one on the horizon. The implication is that current estimates of the output (GDP) cost of reducing GHG emissions are too low, probably very substantially so. For example, even if the energy elasticity of fossil fuels (ϵ_{EC}) is only .5, a more realistic output elasticity of energy (ϵ_{YE}) of .3 to .4 would imply, according to equation (5), that a 50 percent reduction in carbon emissions from baseline would reduce GDP by 7.5 to 10 percent, rather than 2.0 to 3.0 percent as indicated by current models. If this is the case, there is added reason to direct climate policy toward facilitating investment in a long-term race to innovate and develop new carbon-free energy sources and technologies.

5. Conclusion

In 1987, W.W. Kellogg published a paper entitled “Mankind’s Influence on Climate: The Evolution of Awareness.” Twelve years later that awareness is widespread. But there is neither sufficient awareness of the vast amounts of carbon-free energy that will be required if fossil fuels are to be displaced, nor that there are currently no alternatives to fossil fuels on anything like the scale needed. In the meantime, the focus of climate policy seems to be on somehow curbing fossil fuel use and on improving energy efficiency. The Hoffert, et al paper makes clear that very large amounts of carbon-free energy will be needed as well.

Table3

Cost of GHG Emission Reductions: U.S. and Global Studies in Comparison to Predictions Based on a Cobb-Douglas - Production Function (% decrease in GDP)

% Reduction in Emissions	U.S. Studies	Global Studies	Prediction Based On a Cobb-Douglas Prod. Function[a)]
20	0.2-1.0 (0.6)	0.2-1.0 (0.6)	0.8-1.1 (0.95)
40	0.5-2.9 (1.7)	0.5-2.9 (1.7)	1.7-2.2 (1.95)
60	2.5-3.2 (2.8)	2.1-2.8 (2.5)	2.5-3.4 (2.95)
80	2.4-4.2 (3.6)	3.0-5.7 (4.4)	3.4-4.5 (3.95)

[a)] Energy's share of GDP is in the range of .06 to .08 for the U.S. The energy elasticity of fossil fuels is assumed to be 0.7. (Mid points are in parentheses)

Source: Bruce, et al (1996), Ch. 9, Figures 9-1, 9-22; Tables 9-1, 9-24.

Hoffert, et al get it right when they seek solutions in new energy technologies and sources. But, in the best of circumstances, an energy technology-based climate policy will take money and a lot of time to develop. If, in the meantime, climate policy is based on artificially raising fossil fuel prices sharply and limiting energy use, the result is likely to be political resistance and denial rather than a meaningful reduction of carbon emissions. Moreover, it is not clear that using political and economic resources to negotiate and enforce artificial reductions in the demand for and/or supply of abundant fossil fuel energy, will reduce the time it takes to innovate and develop new energy sources and technologies capable of displacing fossil fuels.

Economists interested in climate change policy have focused on the gains from employing efficient (market based) instruments of policy. Inadequate attention has been paid to where the required amounts of carbon energy free will come from. (An exception is Chakravorty, et al (1997); but these authors nevertheless overlook the scale issue discussed above.) It is fortunate, then, that the findings of The Impact of Climate Change on the United States Economy (Mendelsohn and Neumann, 1999) suggest that because of our ability to adapt to 2 to 3°C of warming, climate policy can buy some time. Buy time for what? This paper suggests that if carbon emissions are to be curbed, new energy technologies must be devised and new energy sources must be found -- ones that can provide huge amounts of carbon-free power. Unfortunately, in the past decade, government funding of energy technology research and development has been declining in the U.S. and in many other International Energy Association Countries (Margolis and Kammen, 1999). It is time to reverse these trends.

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