THE ADVANCED ENERGY TECHNOLOGY GAP: A RESPONSE TO EDMONDS

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I am pleased to respond to Jae Edmonds' presentation. Edmonds has done seminal work integrating the role of energy technology into the economics of climate change (See, for example, Edmonds, et al, 2002). In my "response" to Jae Edmonds' paper/presentation, I will draw in part on research I have carried out with Doug Lightfoot as well as some of my own. I wish to make the following points:

1. Jae Edmonds' presentation and recent papers provide independent and elegant support for the technology focus that is the theme of Hoffert et al, <u>Nature</u> 1998, and <u>Science</u> (2002). Needless to say, I am in broad agreement with Edmonds.
2. An "Advanced Energy Technology Gap" (AETG) exists, one which I have estimated at 13-28 TW, drawing, in good part, on Lightfoot and Green (2001, 2002).
3. The AETG is defined as the amount of carbon-free energy required to stabilize atmospheric CO_2, over and above the maximum contribution from energy efficiency improvement, sectoral change, and terrestrial renewables (with current technologies).
4. The GDP cost of attempting to stabilize the atmospheric CO_2 concentration at 550 ppmv, by relying on energy efficiency improvement and renewables, could be <u>an order of magnitude or more higher</u> than the 1-3% range of estimates reported in Chapter 8 of IPCC WG III (2001).

The contents of my "Response" are distilled from the draft of a much longer paper entitled "The Developing Debate Over Climate Policy: Energy Efficiency, Renewable Energies and the Economic Cost of Stabilizing Climate Without Major New Technologies". (The paper is available at my McGill University website: www.mcgill.ca/economics/faculty/green .)
In that paper, I report the maximum physical (thermodynamic) increases in energy efficiency developed in Lightfoot and Green (2001) and then calculate what these imply for energy intensity decline. To this is added the effect on energy intensity decline of sectoral change away from

highly energy intensive industries. I then describe the estimates made by Lightfoot and Green (2002) of the maximum contribution of renewable energies, given the land availability estimates reported in IPCC WG III (2001), Ch. 3. I proceed to use the estimates of the maximum attainable average annual decline in energy intensity (1990-2100) and the maximum contribution of renewables, to estimate the magnitude of AETG. Finally, the "Developing Debate" paper asks the question: what would be the GDP cost to the generation living in 2100 if the present generation were to attempt to stabilize CO_2 by relying chiefly on improvements in energy efficiency improvement and the substitution of renewable energies for fossil fuels? To answer this question, I employ a "thought experiment" using a framework provided by the Kaya Identity.

In this paper, tables 1 and 2 summarize the findings of Lightfoot and Green (2001) with respect to the maximum long-term rate of energy intensity decline permitted by physical limits to energy efficiency improvement and economic limits to sectoral change. For the period 1990-2100, physical (thermodynamic) limits to energy efficiency imply an average annual contribution of energy efficiency improvement to energy intensity decline of between 0.8 and 0.9 percent. Adding in the average annual contribution of a substantial decline in the relative role of highly energy intensive sectors adds 0.16 to 0.30 percent to the long-term average annual rate of energy intensity decline. These estimates, together with some sensitivity analysis relating to the relative size of the electricity generating sector in 2100, produce a range of estimates for the maximum achievable average annual rate of energy intensity decline -1.0 to -1.24 percent. The rate of energy intensity decline actually experienced is likely to be lower.

Tables 3 and 4 summarize evidence from Lightfoot and Green (2002) on the contribution of three "new" renewable sources of energy: solar wind and biomass. Table 3, columns 1-3 indicates the number of Km^2 required to produce one EJ/yr of solar and wind electricity, and one EJ/yr of biomass energy, drawing on three different studies. Column 4 indicates the range of renewable energies that could be derived from the amounts of land IPCC WG III says are available for renewable energy production. The land availabilities are: (1) solar electricity – one percent of all "unused land" in the world; (2) wind electricity – four percent of all land with an average wind speed of at least 5.1 meters per second; and (3) biomass – 100 percent of all cropable land not used for crops.

Table 4 indicates the contribution renewable resources can make to atmospheric CO_2 stabilization. But the maximums far exceed what is likely, or really possible. Because of grid and resource, especially water, constraints, the maximum likely contribution of renewables is less than half of the amounts in column 1. Because solar and wind energy are intermittent, the electricity grid will permit only limited amounts of solar and wind electricity to be directly supplied to customers. Additional solar and wind energy to be useable would have to be stored in the form of electrolytic hydrogen. However, large scale electrolysis is an expensive and resource using process, requiring, among other things, very large amounts of fresh water of distilled quality. Biomass is even more heavily water using (Bernedes, 2002), so that water as well as land are likely to act as important constraints on the supply of renewable energy.

Figure 1 is based on the construct developed in Hoffert, et al (1998). It brings together the estimates of the maximum contributions from energy intensity decline and renewable energies. The latter includes 50 EJ/yr of hydroelectricity and 20 EJ/yr geothermal, ocean, and tidal power. With a range of energy intensity decline rates of -1.0 to -1.2% and renewable energy totals of 275 to 500 EJ/yr (9-16 TW), the AETG is 410 to 880 EJ/yr (13-28 TW) using the IS92a emission scenario. For stabilization at 450 ppmv, the AETG would be much higher.

Failing to recognize the existence of, and find solutions to, the AETG would be very costly. For example, attempting to stabilize the atmospheric CO_2 concentration by relying on energy efficiency improvement and renewable energies would sharply constrain the growth of GDP, with very large costs to future generations as well as the present. A "thought experiment" suggests how high would be the GDP cost of attempting to stabilize atmospheric CO_2 at 500-550 ppmv without first addressing the large AETG. Table 5 provides the relevant information for the "thought experiment". When the information in Table 5 is fed into the Kaya Identity, and an assumption is added that stabilization can be achieved if the average annual rate of growth in carbon emissions in the 21st century is zero, the GDP cost can be readily calculated.

With a 1.1% average annual rate of decline in energy intensity and an upper limit of 480 EJ/yr from renewable energies, which implies an 0.3% average annual rate of decline in the carbon intensity of energy, GDP growth is limited to an average rate of 1.4% per annum. If world GDP grows at a 1.4% rate in the 21st century, world GDP would grow from $32 trillion in 2000 to $128 trillion (in 2000 $) in 2100. Suppose, however, the long-term "trend" growth rate of GDP (i.e., the growth rate in the absence of a policy of stabilization) were 2.3%, the rate assumed in

the IS92a scenario, and at the lower end of the GDP growth rates in the SRES scenarios. At a 2.3% rate, GDP would grow to $311 trillion in 2100. Thus, a crude calculation of GDP cost to the generation living in 2100 would be $183 trillion ($311-128 trillion) or 58.8%, assuming GDP growth is sharply constrained by a climate policy that relies on energy efficiency improvement and renewable energies to achieve stabilization.

This huge "cost" hardly seems credible – and certainly would never be borne. Even at a much smaller cost, the policy of stabilization would be abandoned or the stabilization target raised substantially. Table 6 shows that the GDP cost calculations produced by a Kaya based thought experiment are quite sensitive to assumptions. Nevertheless, Table 6 indicates that for global energy intensity decline rates of less than 1.5%, and renewable energy supplies in 2100 of less than 700 EJ/yr, the GDP costs would be large – double digit in percentage terms, and as much as an order of magnitude higher than those reported by IPCC WG III.

Why do the results of the "thought experiment" diverge so greatly from cost estimates derived from economic models? There are, I think, two main reasons. One is that most economic models employ "neoclassical" production functions that allow for very substantial factor substitution elasticities, ones that may violate physical (thermodynamic) limits on the energy-to-output relationship as other factors (e.g., labour, capital) are substituted for energy. A second reason is that many economic models assume a "backstop" energy technology. A "backstop" technology is one in which, at some price, there is an unlimited supply of a resource – in this case carbon-free energy. But the contention of Hoffert et al (1998, 2002) is that no present technology (or set of technologies) can provide anything like the amounts of carbon-free energy required for stabilization. In short, a carbon-free backstop energy technology does not yet exist, and cannot be simply assumed to come into existence as a result of market forces.

To sum up, an "advanced energy technology gap" (AETG) exists. Edmonds' paper focuses on the importance of new technologies to stabilization, and the important role the technological issue should play in the IPCC's Fourth Assessment Report. As such, the Edmonds paper/presentation is an important contribution to the climate policy debate. It complements and elaborates on issues raised by Hoffert, et al (2002). It helps redirect the focus of climate policy toward new energy technologies where the climate policy debate belongs.

References

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Table 1: 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 2
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^2GCR Report 2001-7, October 2001, Table 9

Table 3

LAND INTENSITY AND RENEWABLE ENERGY POTENTIALS

	(1)	**(2)**	**(3)**	**(4)**
Energy Source	**Km^2/EJ**	**IPCC WG III (2001)**	**IPCC WG III Land Availability (Km^2)**	**Range of Energy Estimates (EJ/yr)**
Solar (electricity)	1,900 – 2,400	2,100 - 2,400	393,000	163 - 206
Wind (electricity)	16,700 - 25,100	16,700	1,200,000	48 - 72
Biomass			8,895,000	
Solid	19,000 - 48,000	33,000		234 - 275
Liquid	50,000-120,000	60,000-95,000		75 - 179
Total	N/A	N/A	N/A	326 – 481

Col.

(1) Range of Estimates based on: IPCC WG III (2001); Eliasson (1998); Lightfoot and Green (1992).

(2) Calculated by Lightfoot and Green (2002).

(3) IPCC WG III (2001): solar: 1% of unused land; wind: 4% of all land with average wind speed greater than 5.1 m/s; biomass: 100% of estimated (by Lightfoot and Green (2002)) cropable land not used for crops, in 2100.

(4) Lightfoot and Green (2002). The total assumes that biomass is 25% solid and 75% liquid.

Table 4

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, of Green (2003)

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, of Green (2003)

Table 5

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 6

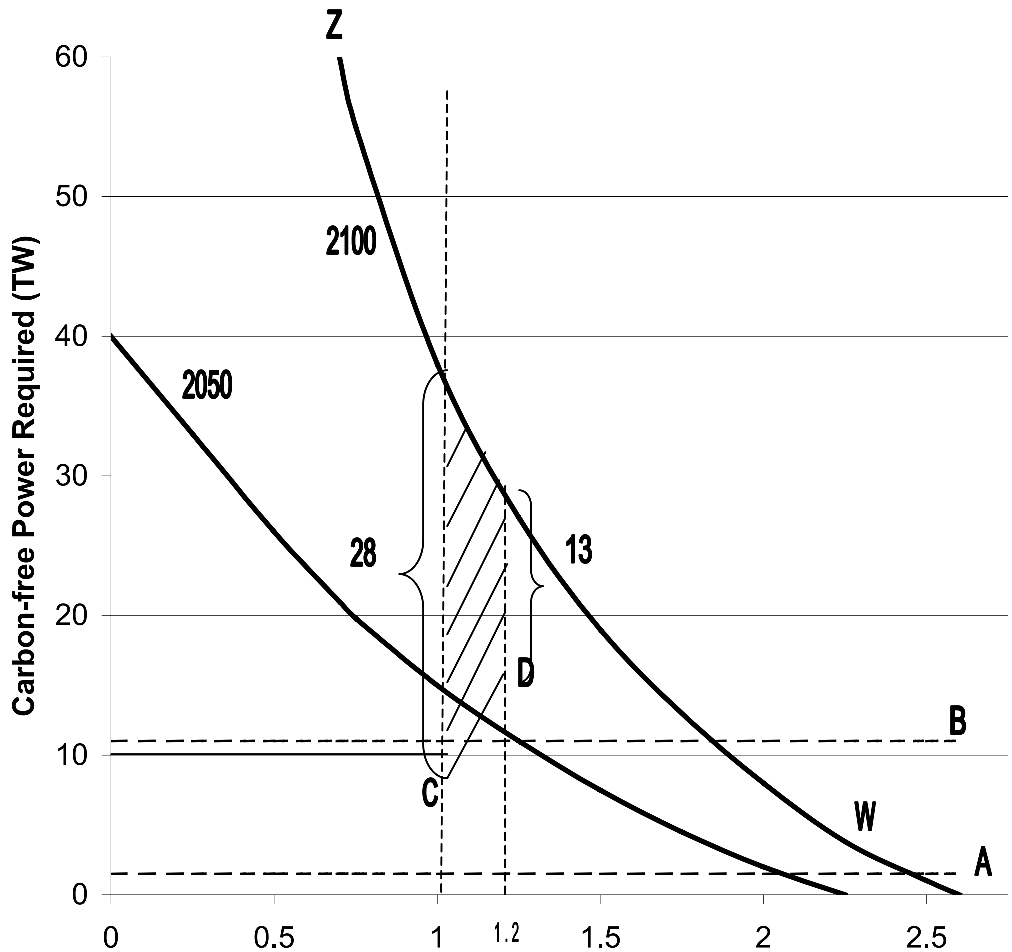
Percentage Reductions in GDP below Trend[a] in 2100 for Varying Rates of Energy and Carbon Intensity Declines

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.

Figure 1: Advanced Energy Technology Gap



Rate of Energy Intensity $\left(\frac{E}{GDP}\%/year\right)$ **Decline**

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.