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Influence of Economic Factors on Future Global Emissions

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Summary

The climate change debate is really about economics, and reducing greenhouse gas (GHG) emissions and climate change potential at a reasonable and acceptable cost for everyone.

In this paper, we examine the major economic factors behind defining climate change policies that relate to reducing GHG emissions, and the value to be placed on CO_2. We examine the impacts and the "cost of carbon" based on the studies of GHG reduction strategies in the US and the European Union (EU). We show that a series of self-defeating assumptions have been used in the latest analyses regarding relative future energy and power costs, and hence future GHG emissions. We estimate:

1. the "natural value" of GHG emissions based on world economic factors,
2. the value of electricity and energy based on world data,
3. the cost advantage of using a given new technology, and
4. the value of avoided GHG emissions in future global and national climate change projections.

The use of electricity is shown to be key in aiding economic growth for the entire world. Using the latest Intergovernmental Panel on Climate Change (IPCC) 2000 climate change projections as a base, we reflect the impacts of differing energy prices on future global climate conditions and GHG reductions. We conduct a similar analysis for Canada using the latest "Energy in Canada 2000" projections.

We show how the use of advanced technology for the traditional production of electricity, and for hydrogen-based transportation fuels, can stabilize global emissions and assist in managing adverse climate change conditions without causing economic penalties. The method we develop is sufficiently general that it can be used for valuing the economic impact of the emission reductions for any technology. We estimate the embedded value and potential economic benefit of nuclear technology and electric contribution for both the world economy to 2100, and for the latest projections for Canada to 2020.

1. INTRODUCTION: THE ECONOMIC DEBATE

Carbon dioxide (CO_2) is the GHG of largest concern among anthropogenic emissions. Before the industrial age, the concentration of CO_2 in the Earth's atmosphere is generally agreed to have been about 280 ppm. In 1960, the CO_2 concentration at Mauna Loa, the remote Hawaiian site considered representative of tropospheric composition, stood at 321 ppm. In 1996, it had passed 360 ppm. In other words, the increase in CO_2 concentration over the two centuries from the start of the Industrial Revolution in 1760 had been matched in just 36 years in the last half of the 20^{th} century. Today, the concentration has passed 370 ppm.

The global and national debates about Climate Change are no longer about the science and whether there is a real problem; these are now largely accepted. Now, the discussion and disagreements are about the cost of needed emissions reduction, and whether or not it is actually affordable, in both economic and political terms. In this paper, we try to demonstrate the economic case.

In all economic analyses and projections of the future, the answers are only as good as the input assumptions on supply and demand, and the projected market cost variations. Malthus, for example, in his famous "An Essay on the Principle of Population" in 1798 assumed exponential growth in demand and linear growth in supply and so inevitably modelled disaster [1]. Today, with large computer simulations of future developments, key, underlying assumptions of comparable impact to Malthus's are sometimes unobvious. Examining the most recent studies, we find there is a set of self-defeating assumptions regarding the future costs of advanced technologies.

To date, people have paid no attention to the levels of GHG emissions, treating them as a free entitlement. If we are now to mitigate emissions of GHGs, establishing a cost of these emissions is essential for modelling and informed debate. Only with a basis for costing/valuing emissions, does it become possible to let market forces act for their reduction though trading, within companies, within nations, or internationally. This cost would also provide a benchmark to weigh against the cost of reduction using any technology or approach.

The World Bank has a Prototype Carbon Fund of some $15 M for lending money that states that the estimated cost of emission reductions should preferably be less than $10 US/tC[1], which is equivalent to about $3 US/tC of CO_2 [2]. The only actually funded activity is the Liepaja Solid Waste Management Project on methane capturing, which has an "assigned" and very speculative value of $20 /t CO_2. This is close to the value applied to the use of forests for temporary carbon sequestration.

So, what is the real value of any technology used to reduce carbon emissions? To answer that question, we must first try to establish a range of values for the cost of the GHG emissions and of their avoidance.

[1]Throughout this report, « t » is used for metric tonnes, either as « tC » for tonnes of carbon or « tCO_2 » for tonnes of carbon dioxide or as « toe » for tonnes of oil equivalent.

2. THE VALUE OF CO_2, ENERGY AND ELECTRICITY

Only recently in human history have attempts been made to estimate the value of carbon when used as an energy source and the cost when emitted as CO_2. Typical possible approaches to estimate a value, a cost or a price are:

1. the implied value in expanding the world and/or national economies by using carbon energy (a macroscopic value),
2. the extra cost of avoidance or reduction in emissions or carbon energy use by using emissions reduction technologies and/or substituting other non-carbon energy sources (an avoidance value),
3. the market price of trading credits nationally and/or internationally for carbon emissions "rights" based on an assumed market which allows for limits or caps in total amounts (a trade or credit value), and
4. "natural" value

We can look at these approaches in turn to see if these values are comparable and make sense, noting that the whole world is conducting an experiment here of potentially very large importance.

2.1 The Implied "Natural" Value

Unconsciously, the world has already valued its CO_2 emissions, via the "natural capital" that it has invested in releasing today's levels of GHGs into the atmosphere. Since global and national wealth are produced naturally by using energy, and energy is largely produced today by burning fossil fuels, and burning fossil fuels produces CO_2 emission, all aspects are very tightly correlated.

Table 1 summarizes data from the World Bank for a typical year (1997) for global wealth, energy use and levels of CO_2 produced.

Table 1
Gross World Product and Energy Use (1997)

Gross World Product (current US$)	**2.62×10^{13}**
Commercial energy use (tonnes oil equivalent - toe)	**9.43×10^{9}**
Energy equivalent (GJ)	2.8×10^{11}
CO_2 emissions (tonnes)	2.4×10^{10}

Primary input information is in **bold**.

To estimate the price of energy, information was compiled from the BP *Statistical Review of World Energy* [3], for proportions of fuels used worldwide; from Oilnergy [4], for approximate price information for oil and gas energy in North America; and from the United States Energy Information Administration [5], for approximate price information for coal energy in North America. This is imperfect in the sense that prices will vary somewhat by region, especially for natural gas, but it provides a reasonable approximation for a macroscopic value of CO_2 (Table 2). The price also varies with time. The year 1997 was a typical one but data for 2000, when oil and gas prices rose sharply, are also shown.

Table 2
Approximate Value of Energy Inputs [1]

	Oil	Gas	Coal	Weighted Average	Total
1997 Data					
Price (US $/primary price unit specified) [2]	**17 $/bbl**	**2.4 $/GJ**	**19 $/short ton**	11.7 $/bbl	
Weight of Primary Price Unit (kg/unit) [3]	111		908		
Conversion Value (GJ/primary price unit) [4]	5.17	1.00	29.54		
Energy per weight (GJ/tonne of fuel)	46.5	55.3	32.53		
Emissions per Energy (tCO_2/GJ) [5]	0.068	0.050	0.104		
Price (US $/GJ)	3.29	2.40	0.64	2.27	
Energy Consumption in 1997 (Mtoe) [6]	**3395.5**	**1977.3**	**2293.4**		7666.2
Energy Consumption 1997 (actual tonnes)	3395.5	1661.6	3276.3		
Cost ($/toe)	153	112	30	105	
Total value ($)	5.2E+11	2.2E+11	6.9E+10		8.1E+11
CO_2 Emissions (10^6 tCO_2) [5]	10672	4569	11089		26330
Proportion of total costs	64%	27%	8%		
Proportion of energy	44%	26%	30%		
2000 Data					
Price (US $/unit specified)	**27 $/bbl**	**3.6 $/GJ**	**16 $/short ton**		
Price (US $/GJ)	5.23	3.60	0.54	3.40	

Notes:
(1) Primary input information is in bold
(2) Sources: Oilnergy [4] (oil, gas); US Energy Administration Information [5] (coal)
(3) Crude oil density = 0.7
(4) Oil = 20 000 Btu/lb; coal = 14 000 Btu/lb
(5) Basis: oil = 1C:2H; gas = 1C:4H; coal = 1C:1H
(6) Source: BP Statistical View of World Energy, 1998 June. We note that the energy use estimated by this BP source is about 10% lower than the World Bank's estimate.

Table 2 provides a cost estimate of \$105 US per toe for energy in 1997. This implies an approximate value for the Commercial Energy Use in Table 1 of 0.99 x 10^{12} US\$ or \$26.5 of GWP for each dollar of energy input. The calculated emission of 26.3 x 10^9 tCO_2 produced \$1000 of GWP per tCO_2.

One can make further use of the data in Table 2 to consider the low value placed on coal on a per toe basis, even though coal emits about 53% more CO_2 than oil on a per-unit-of-energy basis[2]. Table 3 shows the total estimated costs for the three carbon-based fuels in 1997 and then gives a redistribution of the total between the three fuels so that each is priced at equal cost of CO_2 emission per gigajoule of energy content, while the total cost is maintained at the level of the original estimate.

Table 3
Actual Fuel Costs and Redistributed Fuel Costs

	Oil	Gas	Coal	Average	Total
Tonnes CO_2/GJ	0.06762	0.04972	0.104036		
Actual Cost (\$/toe)	152.9	111.5	29.9	105.4	
Ratio actual cost	2261.01	2243.26	287.3327		
1997 amounts (Mtoe)	3395.5	1977.3	2293.4		7666.2
Total actual cost (M\$)	519164	220552	68557		808272
Equal CO_2 basis (\$/toe)	96.5	70.9	148.4		
Costs redistributed to an equal CO_2 basis (M\$)	327594	140270	340407	808272	

Looking at the ratio of actual fuel costs (US \$/toe) to the tonnes of CO_2 emitted by each for the same energy content, oil and gas appear almost perfectly matched. Coal, however, is priced far below its equivalent CO_2 emission. The second last row of Table 3 gives a redistribution of costs between the three fuels in which they are now priced equally on the basis of CO_2 emissions. The absolute values have been set to give the same total energy bill. The result would be a drop in oil and gas prices of a little over one-third and a rise in coal price by a factor of almost five (an increase of 118.5 US \$/toe or 83 US \$/tonne or 75 US \$/short ton).

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[2] Table 2 shows the tonnes of CO_2 emitted per gigajoule for each of the three carbon-based fuels. Relative to natural gas, oil emits 36% more CO_2 for the same energy release. Coal releases 208% more CO_2 than natural gas for the same energy release.

In terms of GHG effects, considering only CO_2 is not entirely satisfactory since it neglects the effects of CH_4 releases to the atmosphere – CH_4 being a very potent greenhouse gas. Release of less than 2% of CH_4 in the production and distribution of natural gas would offset its apparent advantage over oil. Coal mining, on the other hand, can also release substantial quantities of CH_4 to the atmosphere, adding to its relative disadvantage as a fuel.

On this basis, coal ought to carry a US \$25/tCO_2 surcharge to neutralize its undesirably greater contribution to CO_2 emissions.
While we do not see this as a number of exceptional definitiveness, it is one interesting indicator of an appropriate value to assign to the hitherto free CO_2 emissions. For the range of values suggested for a "carbon-tax", this is a somewhat high-end value. We note that applying it to coal would level the playing field from coal's current advantage of having an excess of unpriced CO_2 emissions.

Beyond re-weighting energy prices to comparable levels on the basis of CO_2 emissions, some mechanism has to be put in place to encourage either the use of non-emitting technologies or to make CO_2 sequestration economic. Using the average fuel price of \$105 per toe, each tonne of CO_2 emitted is associated with \$37-worth of fuel. Since one would prefer measures that do not seriously disrupt the global economy, one can compare average prices for oil, gas and coal in 1997 and 2000 (Table 2). The weighted average increase between 1997 and 2000 is 50%. This appeared to have little effect on either inflation or global growth. So, a market-driven mechanism that added 50% to the 1997 cost of energy (i.e., the equivalent of adding 13.5 \$/tCO_2 to carbon-based energy costs) has been demonstrated to be innocuous and easily absorbed by the world's economies. As an aside, in the context of the global GHG problem, we suggest that allowing the cost of energy to the end-user to revert below 2000 levels is irresponsible.

2.2 Overall Global Correlation

Measured atmospheric CO_2 concentrations in the atmosphere over Mauna Laua between 1958 and 1994 correlate almost perfectly with the World Bank's figures for Gross World Product (GWP). In other words, as world wealth has increased, using carbon-based energy, the CO_2 emissions have also increased. For the timeframe from 1960 to1996, the relation between energy use and GWP is simply derived using the data from the World Bank Indicators 2000 [6]. For industrial CO_2 emissions and GWP in current US dollars, with a correlation coefficient of about 91%:

$$\text{Emissions}\left(10^9\ tCO_2\right) = 0.54\left(\frac{tCO_2}{US\$}\right) \times GWP\left(10^9\ US\$\right) + 8\left(10^9\ tCO_2\right)$$

This formula says, rather neatly, that one tonne of CO_2 has a "natural value" of ~\$540 in terms of wealth of products added to the world. However, through natural processes approximately half of the CO_2 added to the atmosphere is removed – most readily understood in terms of equilibrium between the surface waters of the oceans (estimated to contain 800 x 10^9 tC) and the atmosphere. Thus, one tonne of carbon remaining in the atmosphere has been "naturally" valued over the last 35 years or so years at:

$$V_N \sim \$1000 / tCO_2$$

As we shall see next, this value gives an upper bound to the range of values available from completely independent national economic analyses.

The driving force behind energy consumption is well illustrated in Figure 1. The growth of wealth in the world is coupled to electricity use, and the link between electricity use and wealth is as strong as ever today, as it was when analysed by Nathwani *et al.* [7]. The latest data from the World Bank Indicators shows that in 1997 the Gross Domestic Product (GDP), per capita, for 97 countries, is given by:

$$\text{Wealth}\left(\frac{\text{US\$}^{1998}}{\text{capita}}\right) = 1.9\left(\frac{\text{US\$}^{1998}}{\text{kWh}}\right)\times \text{Electricity Use}\left(\frac{\text{kWh}}{\text{capita}}\right) + 1000\left(\frac{\text{US\$}^{1998}}{\text{capita}}\right)$$

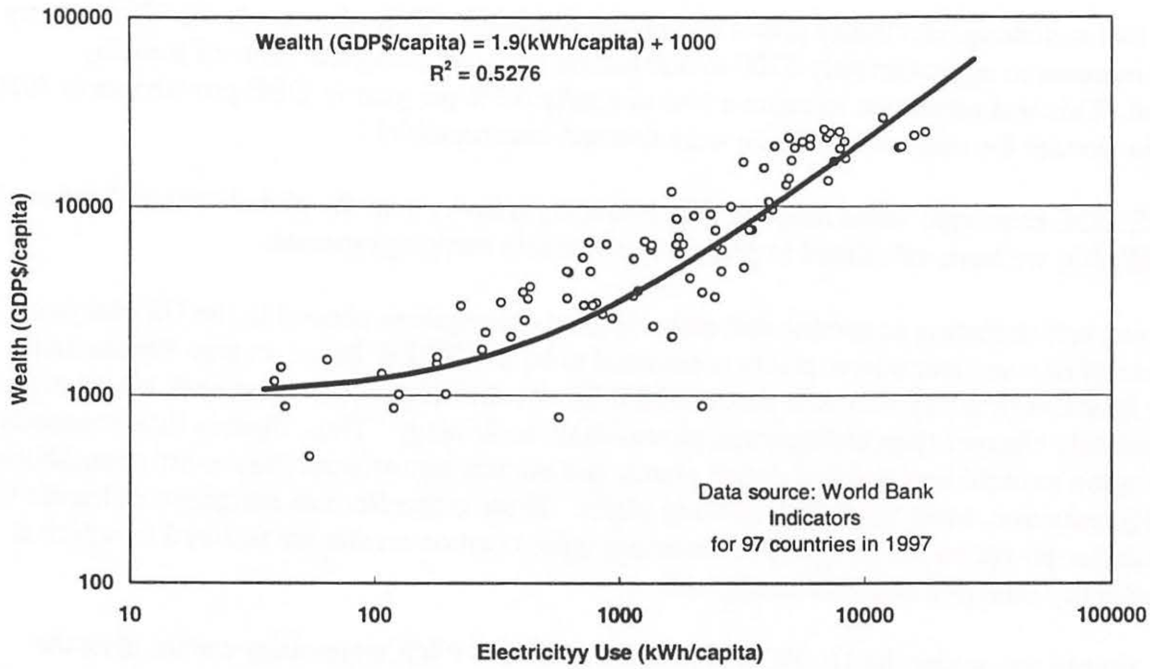

Figure 1 The Relation between Electricity Use and Wealth

So without electricity one is constrained to have an individual wealth of ~ \$1000 /y. Since everyone would like to have more wealth, national GDPs and, therefore, the GWP will grow as more energy is used. All nations and peoples wish to climb up this curve, or at least maintain their position high up on it so their economies grow. This means using electricity and hence the need to generate more of it. But as GWP grows using carbon fuels, so do the GHG (CO_2 equivalent) emissions. We must obviously turn to non-carbon sources to avoid negative impacts on the global atmosphere.

The embedded economic value placed by the world on the use of each kilowatt of electricity used to produce wealth is given from the above equation as:

$$1\,\text{kWh} = \frac{1}{1.9\left(\text{US\$}^{1998}/\text{kWh}\right)} \sim 53¢$$

Thus the *added economic value of electricity* sold on today's electric markets at ~\$40 /MWh is about ten times its cost. (Because the conversion of primary energy to electricity adds cost and value, the ratio is smaller than for primary energy.)

2.3 The US Estimate of the Avoided Carbon Cost

The US emits about 2.2 x 10^9 tCO_2/y from power [8]. To reduce emissions, the US DOE showed carbon values or "prices" in the range $250 – 350 /tC (approximately $67-95 /$tCO_2$) were needed to meet the Kyoto-agreed 7% reductions from 1990 emissions levels [9].

Using fuel switching, electricity prices would nearly double. Thus, the cost to the US economy would increase to approximately $200 to 300 billion per year, being the value of the CO_2 avoided. This was estimated to cause a loss of nearly 0.5% per year in GDP growth rate in 2010 [9]. No wonder the costs of reduction were deemed unacceptable!

The US DOE economic value range of $60-100/$tCO_2$ is lower than the global "natural" value of ~$1000/$tCO_2$ we have calculated to give us a reasonable working estimate.

However, self-defeating economic and technological assumptions abound in the US analyses. The cost of new nuclear power plants is assumed to be $1550 /kW based on new Pressurized Water Reactors (PWRs), which is about $300 /kW, or more, higher than new coal, oil, wind and gas, and only cheaper than biomass and photovoltaic technology. Thus, there is little economic justification to build new nuclear power plants, and nuclear power would make little contribution to GHG reduction, other than from existing plants. There is therefore an insignificant impact of new nuclear power on reducing GHG emissions unless carbon credits are factored in, which is economically (and politically) unacceptable.

Thus, simply put, under the US DOE assumptions *current* PWR technology cannot meet the market needs or an acceptable carbon price. Cheaper *new technology* has also been prematurely excluded and/or dismissed in a self-defeating assumption.

2.4 World Projections for the Avoided Carbon Cost

The UN IPCC [10] has recently published a large range of future energy and emissions scenarios that show a large growth in energy use and resulting potential adverse climatic impacts. Since the future is uncertain, the IPCC carefully avoids endorsing any given set of assumptions or scenarios. One thing is clear: to reduce GHG emissions, and consequently the threat of adverse climate change, a large switch (>60%) to non-carbon energy sources is required. The use of nuclear energy and renewables are both assumed to increase in an effort to avoid adverse climate change as the 21st century unfolds.

The UN IPCC does not value carbon, *per se,* but estimated emissions and climate change based on carbon fuel use. Just as all the national models do, the Special Report on Emissions Scenarios (SRES) makes assumptions regarding economic growth rates, energy sources, energy efficiency, electrical generation sources, population growth and other key indicators. The spectrum of IPCC analysis is broad enough to include analyses of different economic pathways [10]. These analyses accept that a decrease in productivity by the developed world is not a practical option.

The IPCC case that we determined to be the most realistic, Marker Scenario B2, follows the historic link between global energy use and GWP. This scenario also preserves and continues the same relationship between world economic growth and electricity use in the 21st century, as we have previously shown. Figure 2 compares the current prediction, based on the current correlation of wealth and electricity use, with the predictions-based outcome of economic analysis as assumed to 2100 using the values embedded in the typical IPCC scenario B2. The average use of electricity per capita rises from 2000 kWh to 10 000 kWh each year, implying almost exactly the factor of five increase of the IPCC projection.

Thus, the implied economic value of emissions assumed in the future is the same as the historical "natural" values.

But the IPCC scenarios are largely projections forward of the technical status quo. Because they do not allow for the introduction of any radical new technologies, they are flawed and their projections of GHG emissions are likely to be less valid with time as new low-GHG-emitting technologies take hold. The omission of one assumption, to us is obvious: the application of a new technology, that is, the potential for use of nuclear energy and hydrogen (H_2) fuel switching. The IPCC SRES assumed a fixed and high cost of electricity from new nuclear technology throughout the 21st century, with no cost advantage over most alternative technologies. It did not consider any reduction or reduced nuclear technology costs. The IPCC nuclear Levelized Unit Energy Cost (LUEC) estimate (largely based on Light Water Reactor (LWR) technology) is $72-97 /MWh (SRES Table 4-13b) [10]. When compared to Integrated Gas Combined Cycle (IGCC) and coal technology this is a > $10 /MWh cost *disadvantage*, which hence severely limits increased penetration by nuclear.

Thus, as shown in Figure 3 for the UN IPCC Marker Scenarios, electricity use grows as needed by the economic analysis. But the electricity market share of nuclear energy never exceeds 20% which is basically the same as today's value of 17%, and typically is 5-10% of total energy use, close to today's 7%. While the IPCC scenarios assume wind and solar power to be about the same cost as new nuclear technology, these renewable sources of electricity must be *assumed* to grow to 20 to 60% of world energy, compared to today's 10% (most of which is actually hydro-electric power).

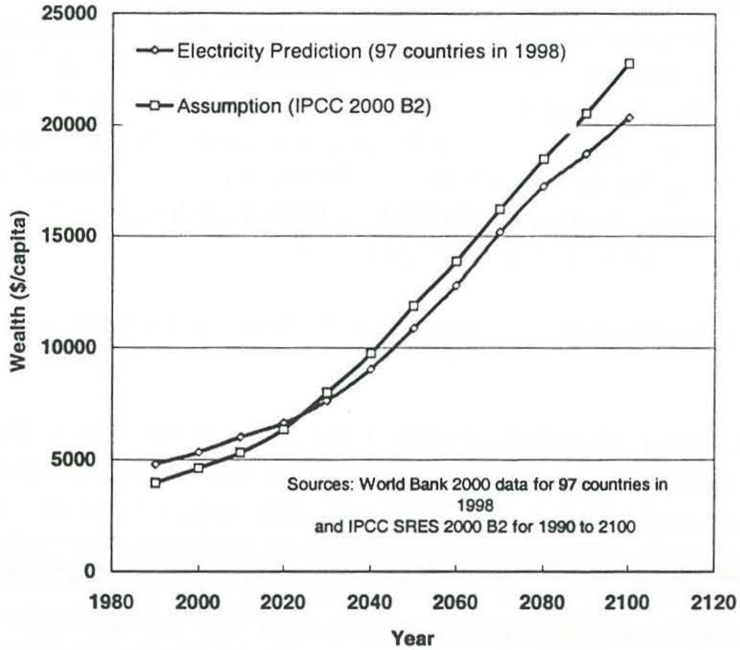

Figure 2 Wealth and Electricity Use in the World as Predicted from the Past and Assumed for the Future

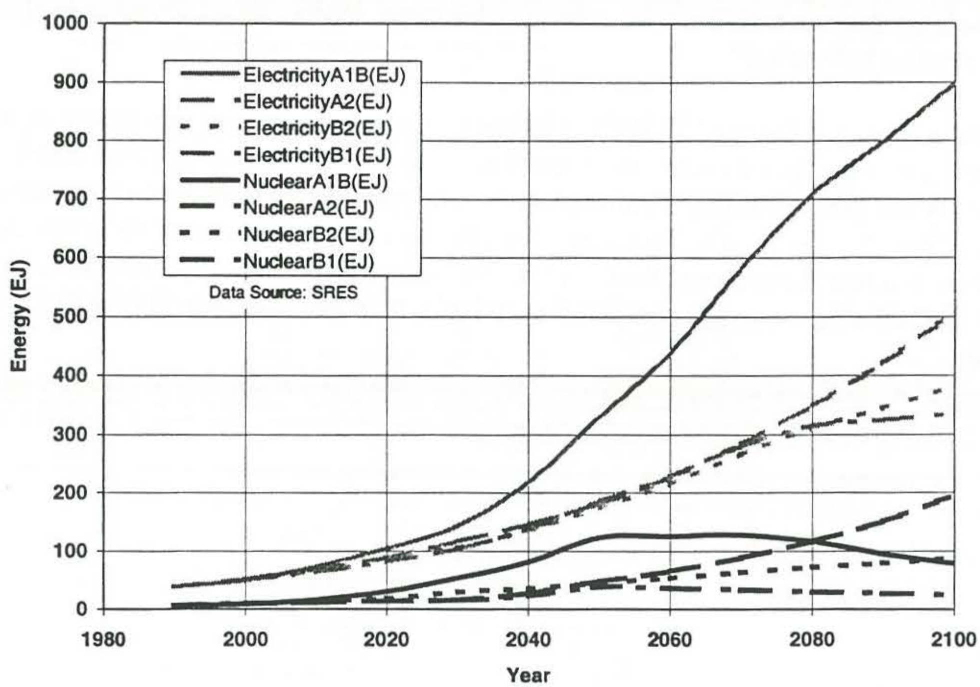

Figure 3 IPCC Electric Market Projection and Nuclear Market Share to 2100: Using Existing Technology

A linear relation was found not to hold true for all GHG emissions and energy use (e.g., methane

(CH_4), sulphur oxides (SO_X) and nitrogen oxides (NO_X)). But the relationship for the CO_2 emissions from carbon fuels for the whole set of IPCC Marker Scenarios is simply proportional to the carbon energy use:

$$CO_2\left(\frac{\text{GtC}}{\text{annum}}\right) = 0.02 \times \text{Carbon Energy}\left(\frac{\text{EJ}}{\text{annum}}\right)$$

This average relationship depends on the exact mix of carbon sources: if mostly coal, 0.03 is appropriate; oil about 0.02; natural gas 0.015 (cf. Table 2). If we assume that the carbon energy is used to make electricity at 50% efficiency, 1EJ ~ 139 kWh and converting to CO_2 we have: 7 GJ/tCO_2 or 1900 kWh/tCO_2. Therefore, as an illustration, valuing CO_2 at a "natural value" of ~ \$1000 /tCO_2 eq., gives the electricity a "natural" value of:

$$1\,\text{kWh} = \frac{\text{Natural Value of } CO_2}{\text{Emission Rate}} = \frac{\$1000/tCO_{2eq}}{1900\,\text{kWh}/tCO_2} \approx \$0.53/\text{kWh} = \$530/\text{MWh}$$

This value is entirely consistent with the derivation in Section 2.2, and is approximately ten times the current market value of electricity, which is what we would expect assuming if the average global electricity cost is indeed related to the GWP.

2.5 The Avoidance Cost and the Credit Price in the UK and the EU

The value of the marginal "carbon credit" is estimated by knowing the relationship between the Generating Cost Differential and the Emission Reduction of a given electrical energy. The Generating Cost Differential, ΔC, is the estimated difference in the electric generating or energy cost of the alternate compared to the nominal cheapest cost of a carbon source (e.g., combined cycle gas turbine (CCGT) versus a CHP plant). The Emission Reduction, ΔE, is defined as the amount of CO_2 eq. emissions that are avoided by a given alternate non-emitting source. The carbon credit is then:

$$\text{Carbon Credit}\left(\frac{US\$}{tCO_2}\right) = \frac{\Delta C}{\Delta E} = \frac{\text{Generating Cost Differential}\left(US\$/\text{MWh}\right)}{\text{Emission Reduction}\left(tCO_2/\text{MWh}\right)}$$

The "carbon credit" or "price" obtained for the UK-based assessment (i.e., in the DTI paper [11]) for a current PWR technology baseline capital cost of nearly \$2000/kW, using interest rates of 11%, was ~ \$100 /tCO_2 [12]. This "price" was judged as not politically acceptable to make the nuclear costs comparable to that from CCGTs.

Similarly the Department of Trade and Industry (DTI) in the UK has recently estimated that, using today's renewables technology, the costs of avoidance would be in the range –\$22 to 75 /tCO_2, and –\$10 to 39/tCO_2 using existing nuclear technology [11]. Embedded in the DTI numbers are a myriad of subsidies and supporting schemes for renewables. There is a "Renewable Obligation" of 10% electrical generation by renewable energies, subsidies from the Climate Change Levy, exemption of renewables from the Levy, a Non-Fossil-Fuel Obligation, funds from the National Lottery "New Opportunities Fund", funds from a World Wildlife Fund, plus R&D support, all totalling today approximately \$1000 M/y. This support is for an avoidance of ~4 MtCO_2/y from 8 TWh currently, rising to perhaps 80 TWh (or 40 MtCO_2/y) by

2010. The implied subsidy of the avoided CO_2 is therefore ~\$25/tCO_2.

It is not obvious how the subsidy amounts were originally derived, but again it is clearly at the low end of the technological avoidance cost estimates and therefore may not be sufficient to achieve a significant effect in GHG reductions.

The European Union (EU) emits about 2.2 x 10^9 tCO_2/y, and has used the Kyoto Treaty as a socio-political exercise. Even the IPCC estimates that the proposed global GHG reductions are so small and so late that even full adherence to the Kyoto Treaty by 2012 would not significantly impact global emissions and reduce climate change [10].

The EU estimate for the marginal cost for emission reduction of 8% by 2012 was found to be between €.99 20-42 tCO_2 eq. (weighted EU average), according to how the individual and collective EU States reached the target [13]. The compliance costs for the EU would be €.99 3.7 billion/y for the period 2008-2012. Thus, the total cost of all EU Member States would range from €.99 3.7 billion to €.99 7.5 billion/y or about 1% of the EU GDP in 2010. The marginal abatement cost in each Member State would range from €.99 1 /tCO_2 eq. to over €.99 100 /tCO_2 eq.

As in the US, the EU developed a curve for the cost of the total carbon emissions reduction amount in $\Sigma MtCO_2$ versus the cost per $MtCO_{2eq}$, V_A. The estimated costs are systematically lower than in the US, but combining the two sets of results for the US and the EU studies, and taking 1€ in 1999 as then about US\$1, we arrive at a compelling empirical relation which is shown in the Figure 4:

$$V_A\left(\frac{US\$}{MtCO_{2eq}}\right) \approx 39\exp(0.0015\times \text{Total Carbon Emissions Reduction } (\Sigma MtCO_{2eq}))$$

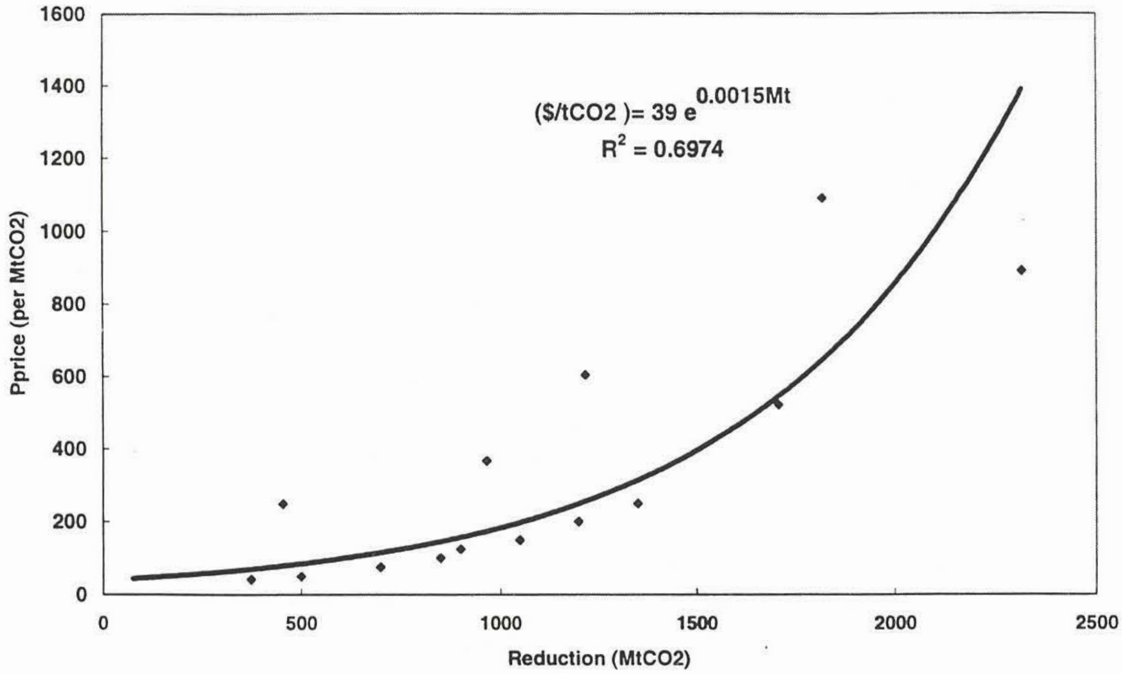

Figure 4 The Approximate Cost Curve for CO_2 Reduction with the Combined Data from the US [9] and the EU [13] Economic Studies

Therefore, the base cost of reduction, V_o (at ~ \$39 /tCO_2) is much lower (~ 10%) than the "natural capital" cost (at V_N ~ \$540 /tCO_2) for any avoidance or reduction, and therefore implies an economic (as a reduced GDP contribution to the GWP) disadvantage for any significant increase, as it gets harder to achieve. The cost of avoidance is soon larger than 10% and is therefore unacceptable. This curve of increased cost with increasing reductions, but with more of a sharp rise or cliff edge increase at some large reduction amount, was also confirmed in the analysis of technologies for reducing upstream emissions in the oil and gas industry [14].

Therefore, we can postulate the existence of a generalized form the above equation of:

$$V_A\left(\frac{\text{US\$}}{\text{MtCO}_{2eq}}\right) = k \times V_N \exp\left(\text{K} \times \text{Total Carbon Emissions Reduction } \left(\Sigma\text{MtCO}_{2eq}\right)\right)$$

where k is the "fractional natural cost factor" of order 0.1. This explains why sequestering carbon in forests or subsidizing windmills for about ~ \$5-10 /tCO_2 superficially looks so attractive in comparison to other options. This is less than the actual economic value or the cost of a real technological solution.

Now the US did offer a subsidy (in FY 2000 ~ \$10 /MWh) for wind power, which, if windmills displace coal generation, avoids about 0.4-1 tCO_2/MWh depending on the load factor. Therefore, this subsidy represents an implicit or hidden carbon "value" of ~ \$10-20 /tCO_2, not comparable to the "natural" value but enough to help increase the use of wind installations where they make sense.

2.6 Excluding New Technology

Unfortunately, self-defeating assumptions are also embedded in the EU energy analyses originating from the Commission of the European Communities (CEC), also known as the "Green Paper" [15]; the cost of power is not given in this study. However, in the latest Green Paper, the EU cost is given using year-2000 estimates, while recognizing an increased reliance on imported energy is risky as a long-term strategy. Again, using current LWR nuclear technology it was stated:

> "The generation costs of nuclear power are, however, about 40% higher than the cheapest alternative, gas." [15]

With year-2001 values given as about $45.1/MWh for nuclear power versus $31.8/MWh for a CCGT, this is a cost disadvantage of $13.3/MWh. Hence new nuclear and renewables would BOTH have to rely on carbon "value" credits to be built, which is unacceptable politically as it would cost too much.

The EU Green Paper report also states (our italics):

> "Nuclear energy and solid fuels are the *undesirables* among energy products although their contribution within the global energy balance, which is restricted almost exclusively to the generation of electricity, is enormous. *These two sources of energy account for 35 and 26% respectively of the electricity produced (in the EU).* As can be seen, the cost of electricity generation is the lowest for CCGTs followed closely by energy generated from imported coal. Given the *current subsidies* to wind energy in many Member States, their generation costs are already fairly competitive". [15]

Now we already know that, subsidized or not (which is a hidden carbon cost), the cost of electric power will vary across the EU, as it does elsewhere, and in the future. Hence, the estimates made are not in accord with the future situation in France (Table 4), which was projected forward 50 years. With various scenarios, and rising energy prices, the estimates show the following:

Table 4
Projected Average Cost of Electricity in France to 2050 [16]

Hypothèse « tension »	**CCGT** (centimes/kWh)		**Nucléaire** (centimes/kWh)	
	2000-2050	2020-2050	2000-2050	2020-2050
H2	22.4	20.4	14.1	16.1
H3	25.4	19.9	14.7	16.6
B2	22.6	22.4	14.5	16.6
B3	25.4	25.3	14.5	16.8

This illustration shows a maximum cost advantage for nuclear energy of ~ 4-8 centime/kWh or about $6-11 /MWh in the future, which is almost the exact opposite of the current disadvantage of $13.3 /MWh in the EU study based on current costs.

Further self-defeating remarks in the Green Paper follow, which dismiss the use of new technology using old arguments:

> "At the moment, it seems *unlikely* that nuclear energy will see renewed growth. In the long-term, its contribution is linked to the pursuit of policies to combat climate change, its competitive position vis-à-vis other energy sources, public acceptance and a possible solution to the problem of nuclear waste. Concerns about global warming have changed the perception of energy supply constraints. *The question is particularly pertinent for nuclear energy which will make it possible to avoid 312 Mt of emissions of CO_2 in the EU in 2010 (7% of all the GHG emitted in the Union), the equivalent of the CO_2 emissions produced by some 100 million cars.*" [15]

Waste disposal has been examined and shown by Pena-Torres [12] and others to be an insignificant cost, and hence purely a political issue as shown to be in the US National Energy Policy [17]. Basically, such social problems and rejections of new technology always exist until resolved by market forces and/or direct political action.

In the last sentence, the quote alludes to transportation; the EU was so close to having the answer to their problems, but so far away from actually seeing it. The technological solution *was* recognized by the US National Energy Policy Report [17] which "recommends the President support the expansion of nuclear energy ... as a major component of our energy policy"... and further states, in its support of H_2 use in transportation and elsewhere, "in the long run, energy technologies such as H_2 show great promise ... and could be derived from renewable energy sources, such as solar, nuclear and fossil."

Fuel switching in transportation to zero *full cycle* emissions fuels (like H_2 from non-carbon sources) allows for massive reductions in GHG emissions. Such emission reductions we can now actually estimate.

3. ENABLING ECONOMIC GROWTH AND EMISSIONS TO BE DECOUPLED: THE ECONOMIC AND SUSTAINABLE PORTFOLIO

How can we sensibly value carbon, reduce GHG emissions and still not hurt the economies of the industrial nations and the growth aspirations of the rest of the world?

Projected energy prices and energy-use policies must consider the realities of finite energy resources and the effect of these both on global growth and GHG emissions in the 21^{st} century. There is a fair degree of consensus on the need for sustainable, substantial and continuing growth in the world's developing economies. The world's economies, however, are going to have to bear both the costs of adapting present methods of energy production in order to reduce GHG emissions for the long-term, and any interim costs to offset the cumulative effects of the ever-increasing GHG emissions. The obvious - but so far unimplemented - path forward is to deploy technology that decouples energy production from GHG emissions. Such a path would see the intelligent use of technology and the implementation of sensible voluntary measures on curbing emissions while still making acceptable economic sense and impact.

3.1 The Value of Energy

We have to find ways to decouple the historic correlation between GWP and CO_2 accumulation in the atmosphere, caused by the underlying global reliance on carbon energy to fuel economic and social growth. To make that switch, we must know the costs of the alternate approaches. This was explicitly examined in the IPCC scenarios, and resulted in a series of trajectories for world energy use and GDP growth out to 2100. These postulated wealth-energy trajectories are shown in Figure 5. The dashed line is the historic projection of energy use based on the last ten years of published data [3], which includes biomass, and is given by:

$$\text{World Energy Use (EJ)} = 4.24\left(\frac{\text{EJ}}{10^9\,\text{US\$}}\right)\times \text{GWP}\left(10^9\,\text{US\$}\right) + 240\,(\text{EJ})$$

Thus, one EJ is historically and largely in the future valued at ~ \$4.2 trillion, which if all the energy were from electricity (which it cannot be), implies a value of \$15 000/MWh, an economic leverage of several hundred times of outputs versus inputs.

If energy use is fixed or capped at some amount, then the impact on GWP is nearly proportionate, which is unacceptable. The IPCC analysis clearly shows the best that can be hoped for is about a factor of two reductions in energy use for the same GWP, and that IPCC Marker Scenario B2 is the closest to the historical energy-wealth curve for the world.

If it were not for the concerns about increased GHG emissions, the link between GWP and CO_2 could well be maintained by switching toward coal as a fuel source. However, since coal produces 50 to 100% more CO_2 per unit of energy than oil or natural gas, switching in that direction would be unwelcome unless linked to an effective means of CO_2 sequestration or other means of reducing the amount of CO_2. Although still at an early conceptual stage, developing and costing *truly* "zero GHG emissions coal" technology is of major value to the environment and of great potential value to the world.

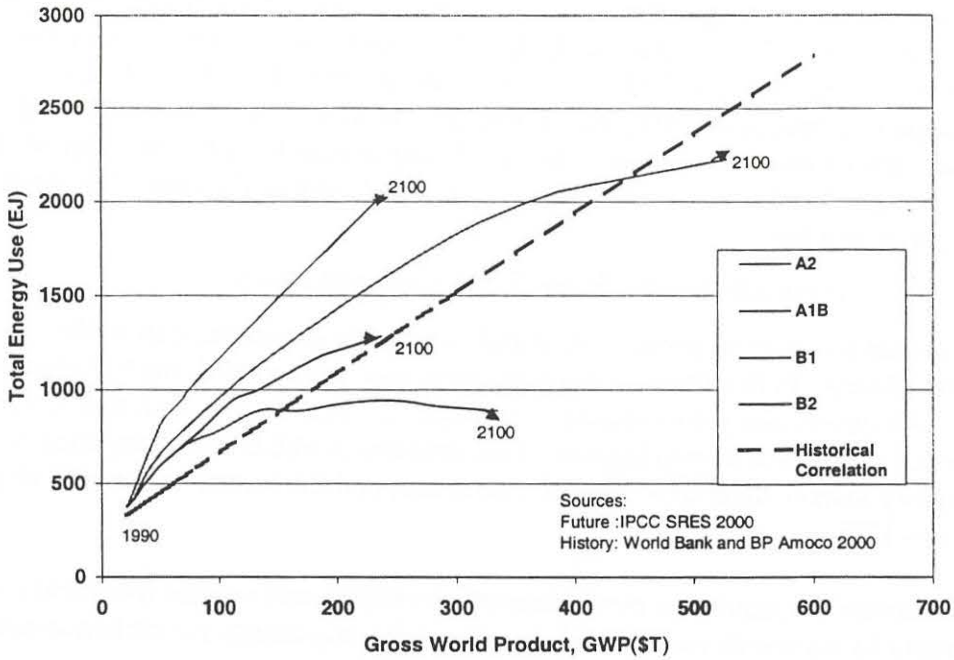

Figure 5 The Global Wealth-Energy Growth Trajectories Assumed by the IPCC Marker Scenarios Compared to the Historic Pattern

3.2 The Market Share

To significantly penetrate the energy market the product must be competitive (cheaper) when compared to alternative sources. By assuming a new technology in an existing market to be more expensive means, it will not be used as much. The national or local market share for any given fuel or energy source is governed by the competitive price of that particular energy source. That is why subsidies in the form of "trading credits" (sometimes known as "flexibility mechanisms" for those unable to reach their avoidance targets) were highly sought after in the Kyoto Treaty. The trading schemes (called the Joint Implementation and the Clean Development Mechanisms) allow countries to trade emissions rights across borders in return for cash.

Thus, historically inexpensive carbon fuels have led to a high global reliance on carbon fuels (~ 80 to 90%) simply because they are cheaper. However, it has been clearly demonstrated in 2001 (and before) that there is a large and dramatic surge in natural gas and oil spot and forward prices for small shifts in marginal supply and demand and vast increases in electricity prices in Alberta and California as demand exceeded supply. Thus, there is potentially a high volatility in price when the demand-price relationship (elasticity) is ultimately non-linear.

Whether we knew it or not, such economic factors have been and are at work in today's local and national electricity markets. The share or penetration of nuclear electricity in the electric energy market is non-linearly dependent on the price differential versus the local competition. The maximum share is ~ 80% penetration for a marginal $10-20 /MWh generating-cost advantage.

The relation is derived from the Organization for Economic Cooperation and Development (OECD) [18] and the Nuclear Energy Institute (NEI) [19] data for power generating costs and International Atomic Energy Agency (IAEA) market share in 1998 [20]. The data are for Canada, France, Japan, Korea, Spain, US, Brazil, Russia, and those countries with the highest fractions have the highest carbon fuel costs. The best fit expression for the percentage share of nuclear generation in the *local or national* electricity market, S, is based on the *local market cost advantage*, A, and is given by:

$$\text{Electricity Market Share, S}\left(\%\right) = 6\exp\left(0.12 \times \text{A}\right)$$

Note that a *cost advantage must be present*: to simply equal the generating cost of the competition is insufficient. In the absence of a cost advantage, only a small market share (not exceeding ~ 6%) will occur, likely attributable to strategic reasons, such as grid stability or power independence and source diversification. This explains *both* the IPCC projected nuclear technology electricity market share of ~ 10-20% maximum, and the historical share of world energy markets at ~ 17%.

In today's and tomorrow's competitive power markets we expect and assume the market share to be determined solely by economic factors, and do not assume any credits for carbon avoidance, trading or credits.

3.3 The Economic Value of Energy and Sequestration

CO_2 might be sequestered in various possible ways, including:

1. pumping into the deep ocean layers that will not mix with surface water for at least hundreds of years;
2. return to emptied gas or oil reservoirs (which is already practised as a method of stimulating oil and gas production); and
3. reaction with rocks to form carbonates.

Edmonds *et al.* [21] suggest use of \$15 /tCO_2 as an approximate estimate of the cost of permanent sequestration.

That technology would add \$46 /toe and would raise the energy cost per \$1000 of GWP to \$59, an increase of about 1.7%. As an inflationary effect that looks quite acceptable but a better way of framing it is as the required improvement in energy consumption per unit of GWP, a 40% improvement. To place this in context, this is almost exactly the change in average carbon-based energy costs that has occurred from 1973 to the present.

4. INTRODUCING NEW TECHNOLOGY FOR COMPETITIVE POWER AND HYDROGEN, TRANSPORTATION IN CANADA AND THE WORLD

We provide a method and quantify the impact of introducing new technology on global emissions. As noted above, the "Next Generation" advanced nuclear technology cost reduction targets (as taken from the US Department of Energy Generation IV Requirements [22]) gives nuclear a > \$40 /MWh advantage over current electricity cost. Similarly wind power has a > \$30 /MWh advantage. We decided to conduct precisely that plausible calculation for the case of added nuclear and renewable technology with competitive rates, and the fuel switching to H_2 from non-carbon distributed electrolysis.

4.1 Global Analysis

For the global analysis for 2000 to 2100, we used the IPCC Marker Scenarios as a basis. We adopted 80% as the maximum nuclear and renewable electric penetration based on the target CANDU generating cost with an *advantage* exceeding $20 US/MWh [23] compared to the IGCC and coal plants at $78-86 US/MWh [10] (excluding fuel costs). This should be compared to the IPCC nuclear LUEC estimate (largely based on LWR) of $72-97 /MWh (SRES Table 4-13b [10] and [12]).

To estimate the maximum potential impact, specific and plausible assumptions were made for the overall global analysis:

1. 5% of transportation energy using H_2 fuel introduced by 2020,
2. 80% of transportation energy using H_2 fuel introduced by 2040,
3. 20% of carbon energy is used for transportation worldwide, and
4. 80% of global energy will be produced by either nuclear or renewables power by 2100.

This analysis of the *relative* impacts of differing nuclear and H_2 portfolios can be pursued using the climate change freeware MAGICC/SCENGEN Version 2.4 [24], which was developed for the express purposes of "vulnerability and adaptation assessments" by Wigley and co-workers. This software is a very useful and powerful scoping tool.

To determine the relative impacts of the changing economics on the energy portfolios, we ran all the major IPCC Marker scenarios (A1B, A2, B1 and B2) and two additional IPCC scenarios (A1FI and A1T) in MAGICC, and then adapted the energy inputs for the duo assumption of increased nuclear electricity and, separately, for H_2 fuel use. The penetration fractions for the energy markets and technology timescales were as assumed above, with 30% of renewable energy contributing to the electricity market throughout.

The next factor is derived from the IPCC SRES [10]. Use of additional nuclear energy proportionally reduces the use of all three of the carbon energy sources (coal, oil and natural gas), and no changes from the deforestation data given in the scenarios. There is no double accounting in a given scenario for either nuclear power or H_2 energy levels already being produced by nuclear power.

The MAGICC results show that the introduction of increased nuclear use and nuclear generated H_2 fuel will result in a decrease in overall GHG emissions, despite a net increase in GHG emissions over the next century. In several scenarios (especially the IPCC 2000 scenarios that focus on technology improvements and environmental issues), the use of nuclear technology and non-carbon generated H_2 fuel helped to stabilize the atmospheric concentrations of GHGs and reduced CH_4 concentrations. The impact of the increased nuclear usage and H_2 fuel resulted in a decrease of the atmospheric concentrations of CO_2 by up to ~ 100 ppm for the marker (A1B, A2, B1 and B2) scenarios (even more for the more extreme scenario A1FI) compared to the original scenarios, by 2100. *There is therefore no impact except the positive one of enabling the sustainable future global economic growth.*

The typical results for the four IPCC Marker scenarios, including B2, are shown in Figure 6. Also shown are the scenarios that projected an increased use of nuclear technology and H_2 transportation fuel, produced from non-carbon energy sources.

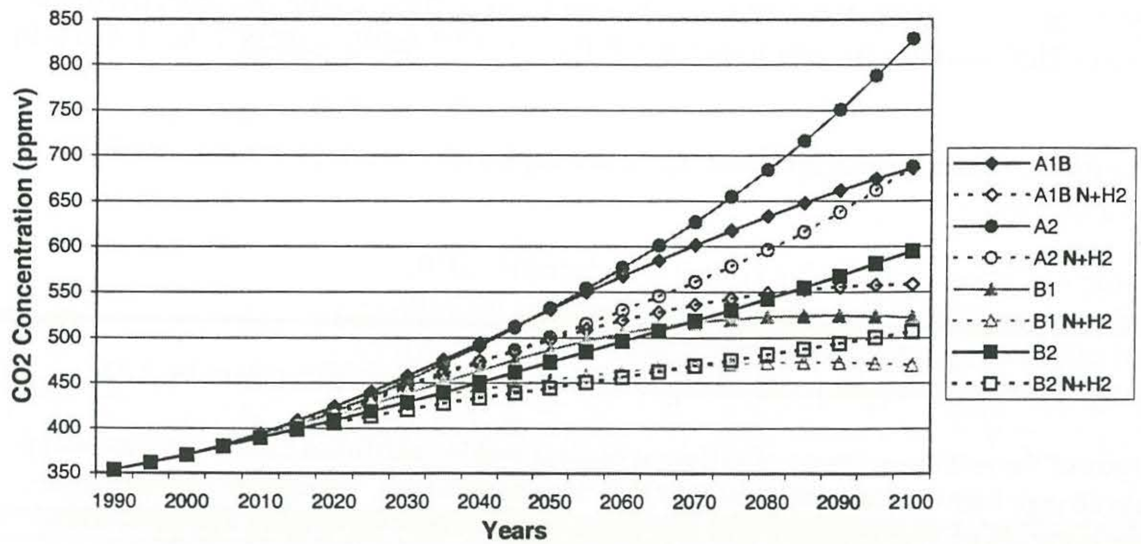

Figure 6 Estimated Atmospheric Concentration of CO_2 for the Original IPCC Marker Scenarios and the Differing Assumptions Scenarios (Shown by the "N+H2" Lines) [25].

We believe the potential impacts are too large and beneficial to be ignored. From the reduction of ~ 100 ppm in CO_2 we can now estimate a value based on the "natural value" relation with the GWP. Since 1 ppm CO_2 in the atmosphere is ~5 x10^9 tCO_2, then the reduction is worth, assuming CO_2 to have a final avoided price, cost or natural "value" in 2100 in terms of ΔC:

$$V_N\left(\frac{US\$}{tCO_2}\right) = 100\ \text{ppm}\ (CO_{2,\text{atmos}}) \times 5\left(\frac{10^9 tCO_2}{\text{ppm}\ (CO_{2,\text{atmos}})}\right) \times \Delta C\left(\frac{US\$}{tCO_2}\right) = \$500\left(10^9 \Delta C\right)$$

or, from the 100 years of investment, ~\$5 ΔC billion/y.

We have ascertained a range of values from the studies and literature of approximately \$20 for the lowest up to ~\$1000 /tCO_2 for the highest, so the avoided CO_2 global economic value is in the range of approximately \$100 billion/y to \$5 trillion/y.

For each year the GWP is about an average of ~ \$100 trillion. Thus the avoided emissions benefits are equivalent to between 0.1 % to a maximum of ~ 5% of the GWP in environmental or "natural value" terms, and fully justify the use of nuclear and hydrogen technology.

4.2 A National Analysis: The Canada Case

We use Canada here as an example of a short-term evaluation of the "value" of avoided emissions on a national and smaller scale. Canada is ~2% of the GWP and global energy use and we want to illustrate the impact of technology on a more local scale. Present projections of electric additions throughout Canada almost all use natural gas or coal, just like in the US, so emissions from the power-generating sector are slated to rise inexorably.

For Canada, the potential electric market penetration, S, was assumed to occur before 2020 using advanced (i.e., Next Generation CANDU) nuclear technologies with a cost advantage based on the projected forward costs of CCGTs [26]. There was still a significant contribution by hydropower and renewable sources of energy, and the addition of nuclear was premised on the cost advantage, the power market growth and allowing the future addition of new hydro and renewable technologies, as well.

The GHG emissions from nuclear technology are comparable to wind power, and only a few percent of the life-cycle assessments of alternative energy-producing technologies. The numerical results show clearly the significant contribution nuclear energy can make to both managing and avoiding potential adverse effects on global climate conditions. The analysis assumed only the economic cost advantage based on the target costs for new (next generation) nuclear technology.

The new technology was assumed not to be available before 2005, and the electricity demand was determined only by the Energy in Canada 2000 projections [26]. No significant fuel switching to H_2 was assumed to occur before 2020.

The results shown in Figure 7 clearly indicates a reduction of ~15 $MtCO_2$/y from adopting new nuclear technology. In addition, CO_2 emissions from the power-generating sector are stabilized without need of any other economic restrictions, emissions trading or fuel switching.

The value of the GHG reduction is easily estimated from our prior analyses, which, as before, indicates that globally CO_2 has a "value" of between ~$20 to 1000 US/$tCO_2$. Therefore, the avoided CO_2 has a "natural economic value" of from approximately $300 million/y to $15 billion/y by 2020.

The cost of implementing Kyoto restrictions on Canada is uncertain, but was loosely estimated at about $330–670 M/y to 2010 [27]. If true, this cost range is precisely the same as the benefit or "natural economic" value we have estimated here, except that *by using new technology there is actually no extra economic penalty to pay!*

The accumulated reduction from 2005–2020 is ~ 38 $MtCO_2$, and is worth a minimum of about $800 M at $20/$tCO_2$. This is derived from a total generation of ~ 260 TWh, or a reduction of ~ 150 tCO_2/kWh. The power is hence naturally valued at:

$$\text{Value of Power}\left(\frac{\text{US\$}}{\text{MWh}}\right) = \frac{\text{US\$ 0.8}}{\text{260 kWh}} \approx \frac{\text{US\$ 3}}{\text{MWh}}$$

This is a significant economic cost benefit on a per megawatt generated basis, and is equivalent to about 10% of the local generating cost from new technology of approximately $30 US/MWh.

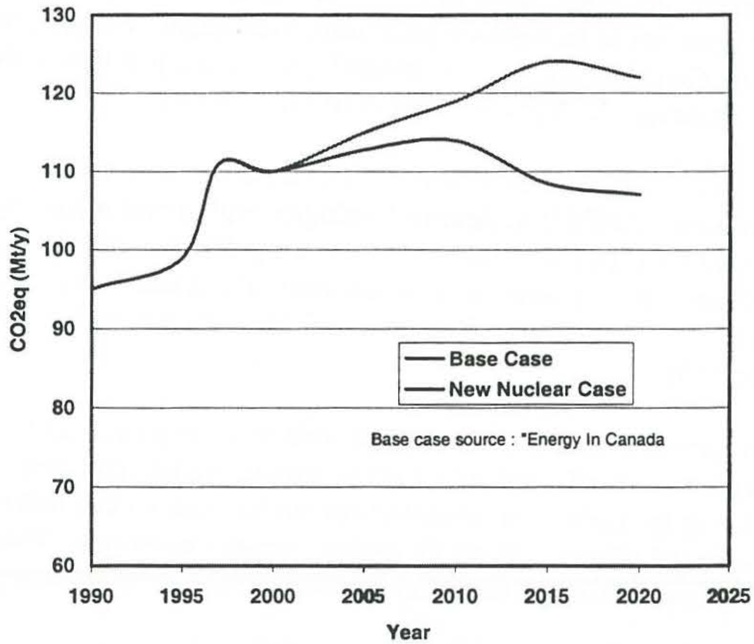

Figure 7 Reduction in GHG Emissions from Power Generation in Canada from Using New Technology

5. CONCLUSIONS: THE ECONOMIC AND GLOBAL VALUES OF NEW ENERGY TECHNOLOGY

The economic impact and environmental benefits of adopting new energy technologies are profound. We focus on economic implications of a primary Climate Change avoidance strategy, namely GHG reduction using technology. The global trends strongly suggest that, if we do nothing, the world will experience adverse climate changes, which will be extremely difficult to reverse and cause severe disruption (or worse) with significant impacts on the world economy.

If the world had to rely on existing technologies at existing prices, there would be severe problems with the cost of implementing reduction in GHG emissions. We have reviewed the evaluations by the US and the EU on the implied cost of carbon emissions reductions, and derived a correlation between the costs for reduction versus amount. We have also estimated the global "natural value" of CO_2 as part of the engine of world growth, which lies at about $540 /t$CO_2$ and a range of estimates based on varying models and assumptions.

Since electricity is essential to the growth of global economy, the economies of all nations are related to their increased use of electricity. We show this embedded relationship to hold true using the latest data for both now, and for the future projections by the IPCC.

We identified a series of technological self-defeating assumptions in the US, IPCC and EU predictions used for future emissions scenarios:

1. unreasonably high *relative* values are assumed for new technology generating costs that preclude significant market penetration by non-carbon energy sources; and

2. no consideration is consequentially made for the penetration of H_2 as a full-cycle, zero-emissions transportation fuel.

By limiting the options for introduction of new technology, the costs of carbon avoidance have not been properly estimated. Indeed, particularly when combined with intrinsic *a priori* anti-nuclear prejudices, the results of these carbon-avoidance analyses are profoundly flawed and pessimistic. On the other hand, by including new technology at realistic prices in our analysis, we show that global emissions can be reduced even further than the levels predicted by the IPCC scenarios with minor cost.

Rises in current electricity market prices, and future energy growth in energy demands in the US and the world, are causing a major re-appraisal of the need for additional electricity supply with reduced cost and emissions. The only available, coherent route that stands up to rigorous scrutiny is additional supply from switching to new nuclear and H_2 technologies. Hydrogen can be derived largely from new nuclear technology also, leading to fuel switching in transportation, coupled with contributions from other non-carbon sources (hydropower and wind). We conclude that nuclear's market share has been underestimated, and show a large economic contribution of new technology based solely on the technological cost advantage.

We have developed a general method to value the impact of a new technology on emissions reduction. We examine the impact of new technologies on both global and national projections made by the IPCC and in Canada, adopting the latest projections as the base cases. By using H_2 and nuclear technology wisely, our economic analyses show a quantified potential global impact that combined, is of some 100 ppm reduction in atmospheric CO_2. The economic benefit or "natural value" is shown to correspond to a minimum of 0.1% and up to 5% of the world's economy.

For the test case of Canada, by using new nuclear technology alone, emissions are stabilized in the power-generating sector. The economic benefit or 'natural value' is shown to correspond to about 10% of the local generating cost, and to be ~ \$300 M/year, or about 0.05% of the GDP, by 2020.

Excuses or attempts to limit new technologies from adoption or use for emissions reduction or trading in the Kyoto treaty negotiations are without merit. Any technology can be evaluated by any nation and the world based on of its economic impact, GHG reduction potential and technological readiness. The quantification is essential, and on this basis, we have shown as worked examples that the adoption of nuclear and H_2 technologies has significant economic benefits.

For the first time, we have provided a method to cost GHG reduction using simple and rational tools and techniques that are validated by and derived from the available data. The H_2 and advanced nuclear-based technologies outlined here are largely proven and capable of being deployed on the extremely large-scale needed. Above all, the economic use of available new technology has to be stressed.

We conclude that values and costs of CO_2 emissions in the range of $20 to $50/t$CO_2$ are both presently economically justified and will likely have negligible impact on world economic development. In addition, the attribution of this cost to CO_2 emissions will effectively promote the adoption of new technology.

6. ACKNOWLEDGMENTS

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