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Going Up or Going Down?
The History and Future for CO_2 and Nuclear Power

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Abstract

Nuclear energy use is projected to *decrease* in the United States, Canada and Europe, and increase in Asia and the Pacific-Rim countries, as well as other economically growing countries while global total energy use grows. Net carbon dioxide and other energy production related emissions are projected to *increase*.

This dilemma is of growing CO_2 emissions and a declining reliance on non-carbon energy sources in developed countries, who are meant to show leadership to others. Despite Herculean international efforts to adopt alternate energy and emissions reduction strategies without damaging the national or global economies or energy-intensive industries, the economic and industrial development of the last 200 years has been carbon-fuelled and is projected to remain so. The impact of human activity on the Earth and increased CO_2 and other emissions into the atmosphere is now clear with resulting debates on global warming and climate change. I give the primary sources for the actual technical data, including key accessible and clickable websites that I have found useful, correlate trends which are currently known and provide the broad spectrum of future energy and emission projections and uncertainties.

I adopt a model for observed atmospheric GHG concentrations based on the correlation of historic and projected carbon energy use patterns. I estimate the *direct* impact of various alternate non-carbon energy portfolios on atmospheric CO_2 concentration for the 21st Century. To stabilize CO_2 concentrations at about today's levels requires introducing a portfolio of about 30-40% of our energy requirements from *all* the non-carbon energy sources, plus about 10% sequestration. This means weaning the world from about 90% reliance on carbon sources to about 60% over the next century.

Unconstrained or even planned growth in world population and energy use suggests we will need to use in combination *all* the non-carbon energy sources available to us in the 21st Century, to successfully manage and preserve the global environment. We establish the needed non-carbon portfolios for a significant fraction of future energy use without onerous or expensive restrictions on carbon fuels.

Nuclear has been unfairly described as unsafe and uneconomic, compared to other alternates, and hence not an acceptable non-energy carbon source. I argue that nuclear, renewable and hydrogen energy sources *together* are uniquely synergistic, reducing costs, extending energy resources, providing additional electricity generation capacity, and reducing transportation emissions. These benefits provide economic advantage and export potential, increase the lifetime of oil and gas resources, and encourage technical innovation in transportation.

Nuclear reactors, along with other energy sources, have a vital role in the potential for energy supply. Like all competitive energy technologies, nuclear reactors must have a long-term

commitment to technical innovation, combined with significant design enhancements. To manage global emissions, the key role of nuclear energy and advanced nuclear plants is clear, in both power generation, hydrogen manufacture and co-generation, whether or not the current worldwide value (~7-10%) or a growing share of the world energy market is assumed.

1. The World Environment and the Economy: Going up

Nuclear energy use is projected to *decrease* in the United States, Canada and Europe, and increase in Asia and the Pacific-Rim countries, as well as other economically growing countries. Meanwhile global total energy use grows based on using carbon fuels, and consequently, environmental CO_2 and other energy emissions are projected to *increase*. Thus, the world is on a fateful course, hoping that reduced energy demand, efficiency measures, carbon sequestration, wind and solar energy sources, lifestyle changes, technological advances, non-binding international Treaties, emissions trading, and national government taxes and policies will have sufficient impact to reduce carbon emissions.

This dilemma is of growing CO_2 emissions and a declining reliance on non-carbon energy sources in developed countries, who are meant to show leadership to others. Despite Herculean international efforts on Protocols to adopt alternate energy and emissions reduction strategies without damaging the national or global economies or energy-intensive industries, the economic and industrial development of the last 200 years has been carbon-fuelled and is projected to remain so. The impact of human activity on the Earth and increased CO_2 and other emissions into the atmosphere is now clear, measurement show an increase in anthropogenic CO_2 with resulting debates on global warming and climate change (Royal Society and the Engineering Academy, 1999).

I adopt a model for observed atmospheric GHG concentrations based on the correlation of historic and projected carbon energy use patterns. I estimate the *direct* impact of various alternate non-carbon energy portfolios on atmospheric CO_2 concentration for the 21st Century. To stabilize CO_2 concentrations at about today's levels requires introducing a portfolio of about 30-40% of *all* the non-carbon energy sources, plus about 10% sequestration. This means weaning the world from about 90% reliance on carbon sources to about 60% over the next century.

Unconstrained or even planned growth in world population and energy use suggests we will need to use in combination all the energy sources available to us in the 21st Century, to successfully manage and preserve the global environment. I establish the needed non-carbon portfolios for a significant fraction of future energy use without onerous or expensive restrictions on carbon fuels.

I examine the vast literature and debate on Climate Change and Greenhouse gases, linked as it is to energy use and economic and social growth issues for us all. I have studied this subject from the perspective of an informed and inquisitive scientist, who wants to make a personal and professional judgment on what is happening now and expected in the future, to understand the science, and to learn or decide what might be sensibly done. In this text, I give the primary sources for the technical data and the trends which are currently known and the broad spectrum of future energy projections and uncertainties. Thus, I hope that any interested reader can check for themselves the actual information, data and analyses and convince themselves (or not) of the global trends and directions, and decide what we might responsibly do.

There is just too much material and data openly available now with the Web to digest or summarize effectively. An informed reader with much available time can consult for example, the World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/pubs) and (http://www.ngdc.noaa.gov/paleo/data.html); the DOE ORNL Carbon Dioxide Information Center (http://www.cdiac.esd.ornl.gov/home.html); the US EPA's Global Warming site (http://www.epa.gov/globalwarming/emissions/index.html); and Environment Canada's Global Climate Change website (http://www.ec.gc.ca/climate/fact/science.html); and NRCan's Global Change Resource Center (http://www.climatechange.gc.ca/english/html/resource.html); and the World Bank Climate Change Home Page (http://www-esd.worldbank.org/cc/). Also of interest are well collated media sites (e.g. (http://www.pbs.org/wgbh/warming)). Much of the data, results, studies, predictions and positions are given here, including many technical references and sources once one is past the Front Page of the site.

The global energy issue is a coupled problem, linking energy use, economics, politics, world environment and global trade policies, not to mention the vested and varied interests of the human race, both now and in the future. It raises the whole question of sustainable development and how we have and will use energy. No wonder it is difficult to agree, expert or not, and for local, national and parochial concerns to be seconded to the more global ones in this socio-techno-geo-politico-environmental topic.

My view is we need to *manage* the environment of our Planet so we may continue to live and prosper on it. National policies and politics, economic realties and agendas may all differ; but Man's impact on the environment, or the Global Commons as it is called, is now measurable, and often worrisome (see the key data at IPCC, 1995 (http://www.shell.com); Royal Society, 1999 (http://www.royalsoc.ac.uk/policy/index.html); and the extensive EPA site (http://www.epa.gov/globalwarming/emissions/index.html)).

2. Historical Trends: World CO_2, Temperature and Trade Going Up

The trends and magnitudes of the stresses being imposed on the planet are becoming clear, by whatever measure is used, be it population rise (http://www.worldbank.org/); temperature change (http://www.epa.gov/globalwarming/emissions/index.html) and (http://www.statcan.ca); species count or extinction (http://www.wri.org); deforestation acreage, energy use (http://www.fe.doe.gov/) and (http://www.bpamoco.com); atmospheric gas concentrations (http://cdiac.esd.ornl.gov/home.html); sea level rise (IPPC, 1998 (http://www.epa.gov/globalwarming/emissions/index.html)); ice melting (http://www.worldwatch.org) or fresh water sources, (see also (http://www.climatechange.gc.ca/english/html/index.html)).
Obviously, the trends are subject to uncertainty: no one can be certain of what will happen. Nevertheless, you and I can establish the vector (direction) we are heading in, based on the available data, and then make judgments about what to do. The direction is either up or down, increasing or decreasing.

One of the most important of these directions is global climate change and/or global warming, and to give a recent quote:

> *"Reconstructions of annual global surface temperature patterns over several centuries are now possible, based on the multivariate calibration of widely distributed high-resolution proxy climate indicators. These reconstructions provide insight into both the spatial and temporal nature of climatic variations during the past six centuries. Time-dependent correlations of these temperature reconstructions with time series representing greenhouse gases, solar irradiance, and volcanic aerosols, suggest that each of these forcings has played a role in the climatic variability of the past several centuries, with greenhouse gases appearing to emerge as the dominant forcing during the 20th century. Northern hemisphere mean annual temperatures for three of the past eight years are warmer than any other year since (at least) 1400 AD, at a greater than 99.5% level of confidence."*
>
> Source: Mann, Michael E., Raymond S. Bradley, and Malcolm K. Hughes, 1998, Nature, 392, pp.779-787 (http://www.ngdc.noaa.gov/paleo/pubs/mann1998/frames.htm).

Richardson (2000) recently supplied me with this partial and compelling listing as evidence of the global changes being observed:

1. Ice core data shows present CO_2 is at highest concentration for 420,000 years at Vostok. In Antartica (Nature, 3 June 1999, p. 429).
2. Arctic ice melting: 40% volume lost in 3 decades, ice thinning from 1858-76 from 3.1m to 1.8m (15% per decade), data from US Navy submarines and research vessels (Sci, 3 December 1999, p. 1828).
3. Global temp risen 0.6^{o}C since mid-19th Century, however Alaska/Canadian arctic and east coast of Canada temperatures rising at highest rates in the world, 4^{o}C/100year (http://www.statcan.ca) and (BMJ, 19 June 1999, p. 1682/5).
4. Churchill polar bears starving due to hotter summers causing loss of ice cover, cannot fish through holes for seals (Nature Canada, Summer 1999, p. 33-35).
5. El Nino pre-1976 "return period" 3.5 years: pre-1976, 6 years for 125,000 years (http://www.noaa.gov) and (New Scientist, 9th October, 1999, p. 38).
6. Other indicators: BC ice man found due to retreating glacier; pacific salmon crashed over last 2y, oceans 5-6^{o}C higher; less salmon causing grizzlies to starve; coral bleaching first observed in 1979, with the most extensive damage ever recorded.

This is recorded and not anecdotal information. How much of this is the result of man is the real question. After all, large global climate variations have occurred before, and it all may be a natural cycle. However, the large scale use of carbon fuels is unique to Man and to the industrial society, and we have simply added this man-made carbon dioxide and other GHG's on top of the natural global temperature cycle and gaseous inventory. The Antarctic data from deep drilling to 100,000 to 400,000 years ago also provides a stunning correlation of CO_2 ppm (and methane) with temperature change. In Figure 1 is plotted the last 150,000 years of data corresponding to a full cycle of temperature change and is in fact indicating the impact of a delayed and expected decrease in global temperatures in the Halocene (recent) geologic era.

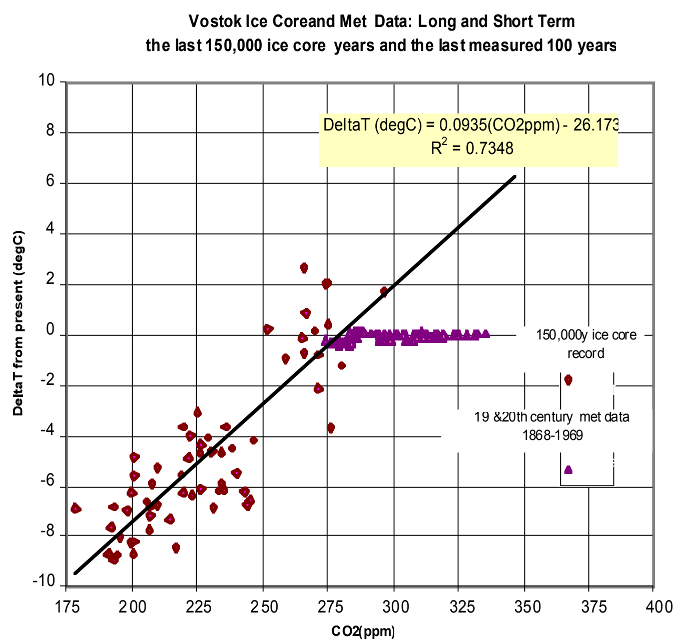


Figure 1 **The Correlation of Temperature Change with CO_2 for the Last 100 and 150,000 Years**

Antarctic Data: (http://ingrid.ldgo.columbia.edu/SOURCES/.ICE/.CORE/):
World meteorological data, ORNL CDIAC and StatsCan, 1999

In Figure 1, it also shows the recent 100 years of reliable surface temperature data from over 1000 stations. The increase is about 0.5 - 1°C over the last century, as a global average but is much (~5-10 times) slower than the Vostok polar data. We may observe that changes are larger in polar regions and that the trend is up.

The best fit line for the Antarctic polar regions (see Figure 2) is that the temperature change, ΔT, from the present is:

$$\Delta T(°C) = 0.09*(CO_2\ (ppm)) - 25 \qquad (1)$$

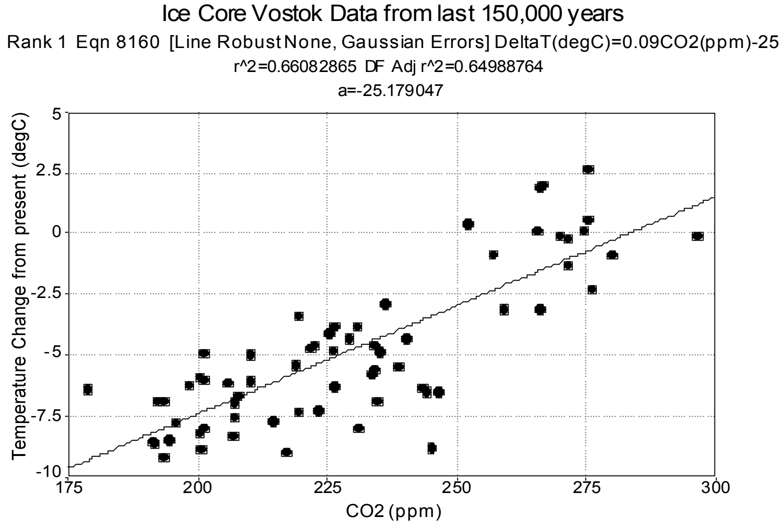


Figure 2 The Best Fit Line for 150,000 Years of Vostok Data

Some of the apparently slower global temperature change over the last hundred years could be due to a built in delay or phase lag, but no one is sure yet of that delay. The recent exponential rise in the Arctic Ice Core CO_2 data is one of the most convincing pieces of evidence since it correlates exactly with the onset of the industrial revolution (see Figure 3) and shows a 77-year e-folding or time constant. Thus the presumed doubling of the CO_2 every 100 years is an *underestimate.*

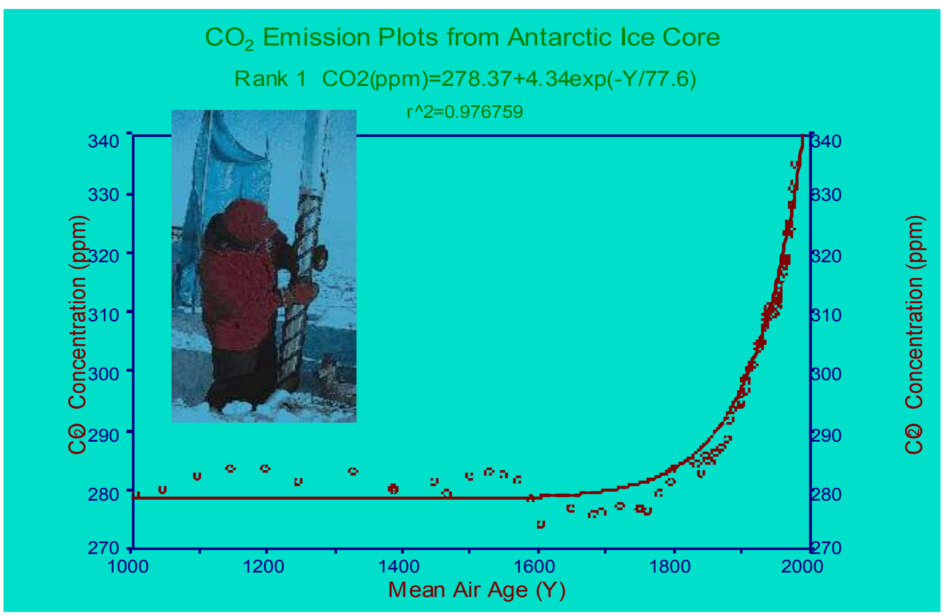


Figure 3 The Recent Exponential Rise in CO2 Levels

Picture courtesy of Taylor, K.C., Desert Research Institute, 2000 (Arctic Lawdome data (http://www.ngdc.noaa.gov/paleo/icecore/greenland/summit/index.html))

Such large temperature changes at the poles have the potential to dramatically "switch" the global ocean currents, by the influx of melting ice at the Poles (Taylor, K.C., 1999), such changes in the past being interred by the sediment record etc. The changes at the poles are much larger than the global average: and in Canada, the average temperature change is about twice the global average change (http://www.ec.gc.ca). Thus, the rate of ice thinning in the polar regions and glacial retreat are at an all time recent high (http://www.worldwatch.org).

3. The World Economy and Costing Carbon and CO_2 Emissions: Going Up

How can we as a society or a global community value GHG emissions is a key question, and has spawned a huge amount of international activity. One example is these extracts from the recent G8 (March 2000) Ministers' statement:

> *"Using the opportunities and advantages of the market and sending the right signals to the market are important for effectively addressing climate change. G-8 countries are introducing measures which may include market mechanisms and which will promote the reduction of greenhouse gas emissions. Significant business opportunities are emerging in a broad range of economic sectors as the need for new climate-friendly products and services grows.*
>
> *We must break with the unsustainable development patterns seen in the 20th century, to decouple economic development from increasing pressures on the environment, and to ensure that development occurs sustainably, incorporating a wise use of natural resources."*

To achieve these goals, there seem to be a spectrum of views and options, depending on the degree and variability of government and market incentives. Governments can set an effective value or limit on emissions using policy measures via energy or carbon taxes, credits, rebates, non-carbon and renewable portfolios and the like, usually within some quota or cap that regulates overall amounts. Commercial markets can determine a value via a trading scheme of credits, shares, offsets, etc. that allow emissons "rights" to be bought and sold, either nationally or internationally, within some overall framework.

It is self-evident that the cost of carbon will increase with limits on emissions, trading schemes, sequestration technology and increased use of non-carbon energy sources. The cost to the energy customer (us) of such measures (e.g. of subsidized carbon sequestration technologies or renewable credits or portfolios) are naturally included as a hidden subsidy or open market price for energy and hence for carbon emissions. Thus, for example, a ~1c/kWh credit for using wind power, as was recently adopted in the USA, effectively implies and values CO_2 as ~$12/t$CO_2$ when compared to the alternate of using high efficiency carbon-based derived power.

In fact, the world has already established a "market" value for CO_2 emissions via existing global trade. The growth in the world economy and energy are clearly highly correlated to the growth of gaseous concentrations in the atmosphere, as measured in CO_2 ppm over Hawaii (Figure 4). The world economic growth in the 20th Century has been based about 90% on carbon fuels: for Canada, the same trends hold, as the country heavily depends on world trade. Thus restrictions on emissions will lead to adverse and unacceptable economic impact unless business and incentives are included (Imperial Oil, 1998). There exists a second key correlation between world carbon energy use and CO_2, as shown in Figure 4, which is, for 1958 to 1994 and measured in US$ for 1986,

$$CO_2\ (\text{ppm}) = 2.5 * (\text{GWP}\ (\text{T\$})) + 293 \qquad (2)$$

where GWP is the gross world product measure. This implies, rather neatly, that if there were or had been no world trade activity (GWP=0$) we would indeed nearly be at the pre-industrial CO_2

level of 293ppm CO_2, close to the value shown in Figure 3. This leads to the conclusion that world economic growth is very good for the people but potentially very bad for the planet's CO_2 level.

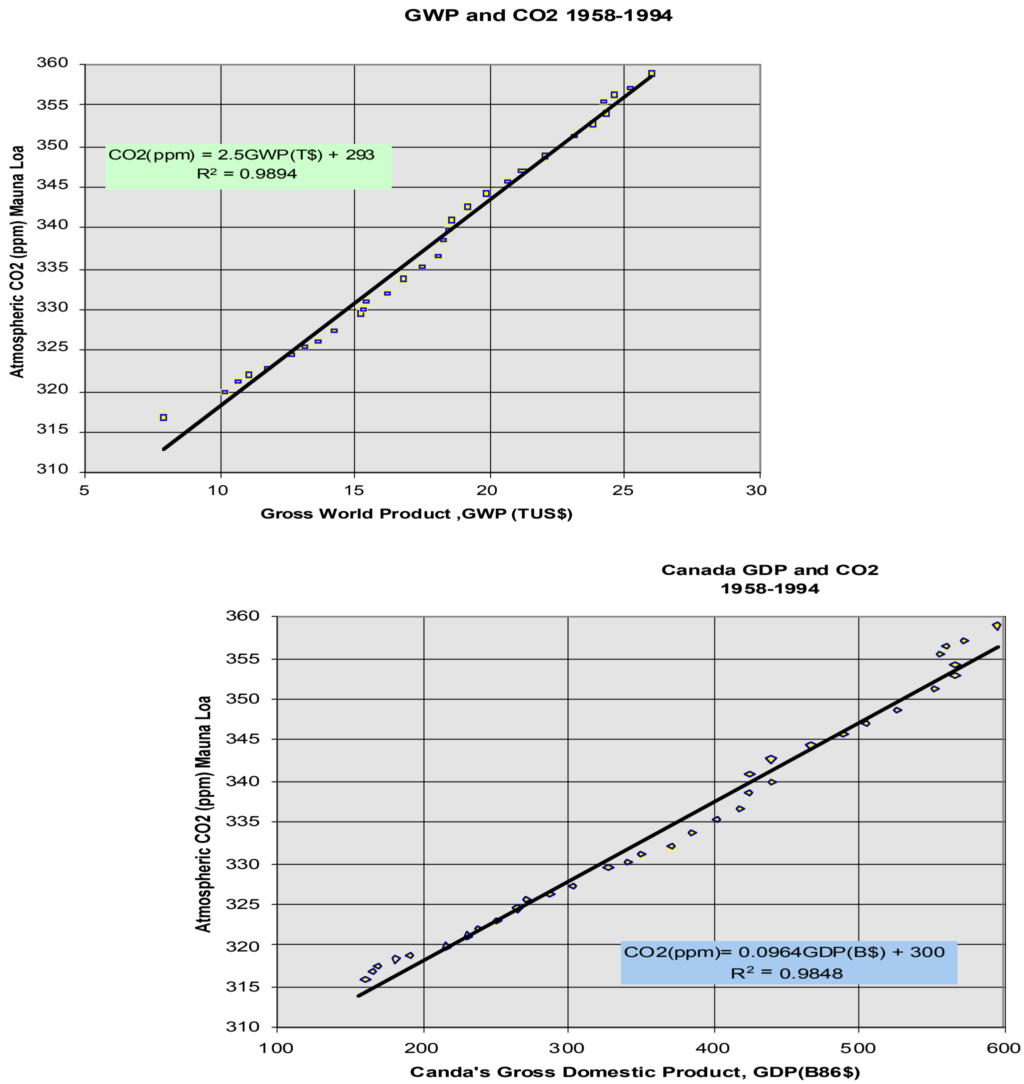


Figure 4 Global atmospheric CO_2 concentration trends with World and Canadian Trade

(Data Sources: World Bank (http://www.worldbank.org/); Statistics Canada, 1998, and US DOE CDIAC (http://cdiac.esd.ornl.gov/home.html)

We may value CO_2 on a global basis by converting CO_2 ppm concentration to $MtCO_2$ in the atmosphere, which from Equation (2), implies the identity:

1 tCO_2 ~ $60 US (1986).

Thus it took about 1 tCO_2 emitted into the atmosphere to grow the world economy by about $60. Alternatively, the cost of carbon energy is valued at about $60/t.

The EU has recently issued a key so-called Green Paper on emissions trading examining the policies and measures needed in detail (European Commission 2000 (http://europa.eu.int/comm/environment/docum/0087 en.htm)). Cost studies in the Appendix to this report showed an economic impact of ~ few B$/y with carbon valued around 100-300 $/tC. On a global scale the World Bank now has a prototype Carbon Fund (see (http://www.prototypecarbonfund.org/)) to which Canada is now contributing and initial trading already exists (see (http://www.wci-coal.com)).

Recent projections for the world economy to 2020 show an increasing rate of growth in the GWP (DOE International Energy Outlook 2000), so the world can expect corresponding increases in emissions also. The recent USA study (US DOE, 1998) showed a linear correlation for the US economy between the emissions reduction achieved and the "carbon price" rise. For the years 2008-20012 with changes of between -7% and +24% of 1990 emissions levels, I find their relation is given by:

Cost/tC (1996$/tC)= 0.61 * (Carbon Emissions Reduction per Year, MtC/y)

Therefore, depending on the CO_2 reduction assumptions made, the carbon price ranged from ~$70/tC to ~$300/tC over the interval, similar to the range of values determined by other economic modelling studies. These are several times the actual "world value", presumably because the measures are being forced on the economy over a short timescale, and are equivalent to a large non-carbon energy credit.

Note that the total economic cost of the reductions for the USA range between from ~$13B/y for +24% up to -$200B/y for -7% Carbon reductions compared to 1990. In round numbers, this is sufficient value to invest in between 10 and 150 600MW(e) nuclear plants per year, which since one such nuclear plant avoids ~ 2Mt/yC, avoids about 20-300MtC/y for the entire plant lifetimes.

4. Energy and Carbon Fuel Use: Going Up

Beginning about 1800, mankind lit a global bonfire of carbon fuels to successfully create the Industrial Revolution. Carbon-based energy has fired, enabled and driven today's technological and economic world.

I do not repeat all the past useful global analyses and energy, economic and technological projections, but instead make full use of them. The useful sources are WEC (http://www.worldenergy.org/wec-geis/); IEA (http://www.iea.org); the Energy Outlooks from DOE (http://www.eia.doe.gov); and from NRCan (http://www.nrcan.gc.ca); the gas picture from GRI (http://www.gri.org); electricity from EPRI (http://www.epri.com); coal from the World Coal Institute (http://www.wci-coal.com) and (http://www.worldcoal.com); oil and total energy from BP Amoco (http://www.bpamoco.com). Historically, world energy use has been based on carbon sources and the record is clear: energy use is growing, and carbon energy is the easy and predominant choice.

To correlate that carbon energy use with atmospheric CO_2 I used two nominally independent historical data sets, from the BP Amoco Statistical World Energy Digest and US DOE IEA. Since the carbon emissions from fossil fuel use and the total energy use were also given we have the following relations (plotted in Figure 5):

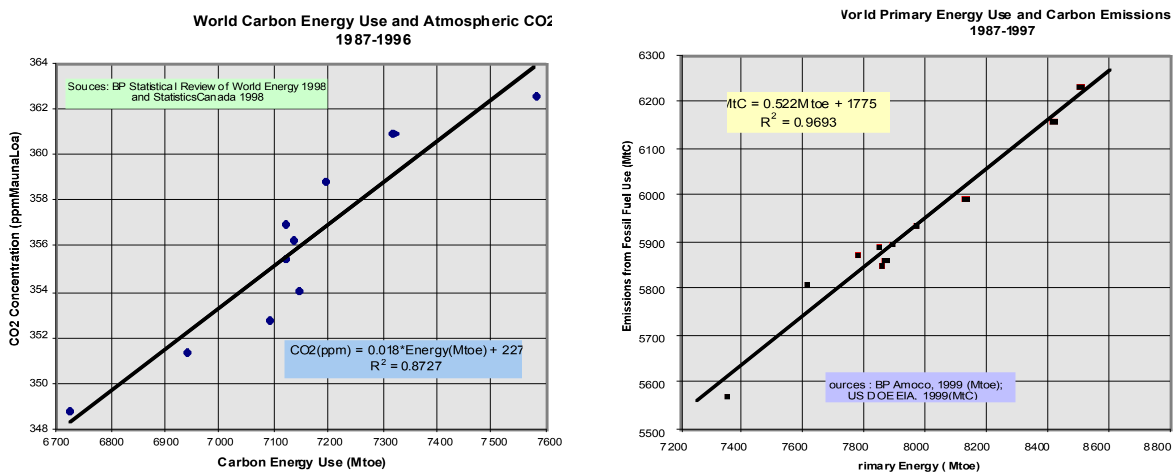


Figure 5 World Carbon Energy Use and CO_2 Concentration

(Data Sources: BP Amoco, Statistics Canada, and US DOE EIA, 1999)

From carbon emission from carbon fuels the concentration increase is:

$$CO_2\ (ppm) = 0.0164 * (Mt(C)) + 258.8 \qquad (3a)$$

For emissions from the use of carbon-based energy the concentration increase is:

$$CO_2\ (ppm) = 0.018 * (Mtoe) + 227 \qquad (3b)$$

For how much carbon (about 50%) which is emitted per unit carbon energy use:

$$Mt(C) = 0.522 * (Mtoe) \qquad (3c)$$

where Mtoe is the usual unit adopted by the world for carbon energy sources, in Megatonnes of Oil Equivalent energy.

So for a given global use of energy, carbon fuel or carbon emission, we can estimate the impact on CO_2 atmospheric concentration**.** To my knowledge these obvious interrelation formulae have not been stated before.

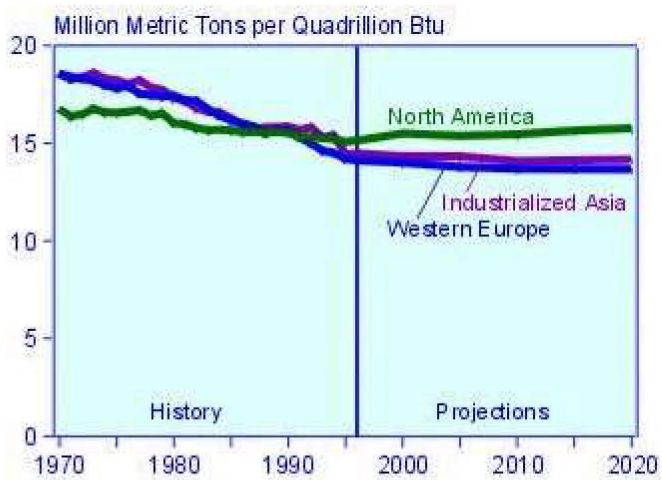


Figure 6 Carbon Energy Intensity

(Source: (http//www.doe.eia.gov), 2000)

Although carbon intensity has gone down from about 1980, (partly as a result of a switch to nuclear and natural gas use), it is now flattened out (Figure 6). Attempts to argue that per capita variations between countries are significant and specious, as the planet cares only about the total quantity. Nevertheless, global population is increasing as shown by the World Bank and the UN (see (http://www.undp.org/popin/)) and the references therein.

J.D. Durand, 1974. *Historical Estimates of World Population: An Evaluation* (University of Pennsylvania, Population Studies Center, Philadelphia), mimeo.

United Nations, 1973. *The Determinants and Consequences of Population Trends*, Vol.1 (United Nations, New York).

United Nations, 1966. *World Population Prospects as Assessed in 1963* (United Nations, New York).

United Nations, (forthcoming). *World Population Prospects: The 1998 Revision* (United Nations, New York).

World population is expected to grow to several billion. The best correlation between CO_2 and world population in billions, B, from the data for the last 2000 years is:

$$CO_2 \text{ (ppm)} = 14.6 \text{ (B)} + 272.4 \qquad (4)$$

Again it can be implied that if there were no-one on the planet emitting GHG's then the CO_2 would be at ~273 ppm, precisely the pre-industrial level.

Arguments and suppositions abound about ways of breaking the relationship between world growth and energy use: I simply take it as an historical fact, and ask what can be done to support the need for *sustainable* growth (i.e. defined here as growth with the minimum adverse global impact). From the above Equations (1) and (3a), we can roughly predict the Antarctic temperature change from the present based on future carbon energy use expressed in Mtoe as follows:

$$\Delta T \text{ (degC)} = 0.09*(0.018 * \text{(Mtoe)} + 227) - 25 \qquad (5)$$

The implication of this for the future is taken up in the next section but even if the estimates are uncertain to a factor of 3-5, the trend is not very satisfying for those living there.

5. Predicting 21st Century World Energy Use and Global CO_2: Going Up

World energy use is necessary to maintain the global economy we have established, and is projected to grow at about 1-2% per annum as shown in Figure 7 to the time frame to 2020. Projections to the end of the century can be made, based on world population and economic growth estimates (see for example the World Energy Council, International Institute for Applied Systems Analysis (IIASA) and International Energy Agency sites (http://www.worldenergy.org/) and (http://www.iiasa.ac.at) and (http://www.iea.org/stat.htm)).

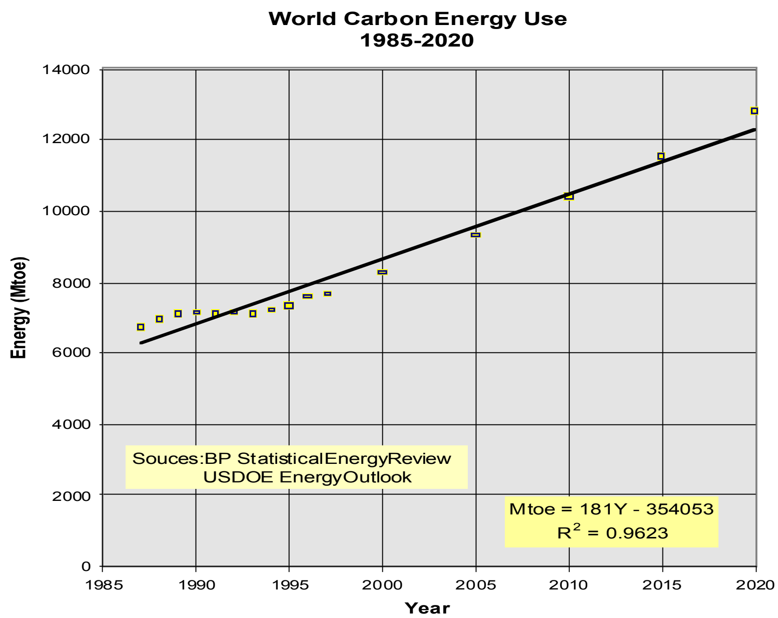


Figure 7 Projected World Carbon Energy Use to 2020

(Sources: History BP Amoco Energy Review, 1999; Projection US DOE International Energy Outlook, 1998)

The pattern of historical energy use is well documented by The BP Amoco Statistical Review of World Energy (available at (http://www.bpamoco.com/worldenergy/)) which can then be coupled and splined-fitted to the future projections by the US DOE Energy Information Agency (see Figure 7) in the International Energy Outlooks (http://www.eia.doe.gov/oiaf/ieo/index.html). A simple fit to these projections and history is that world carbon energy use will be given to a good approximation by:

Mtoe = 181 (year AD) -354000

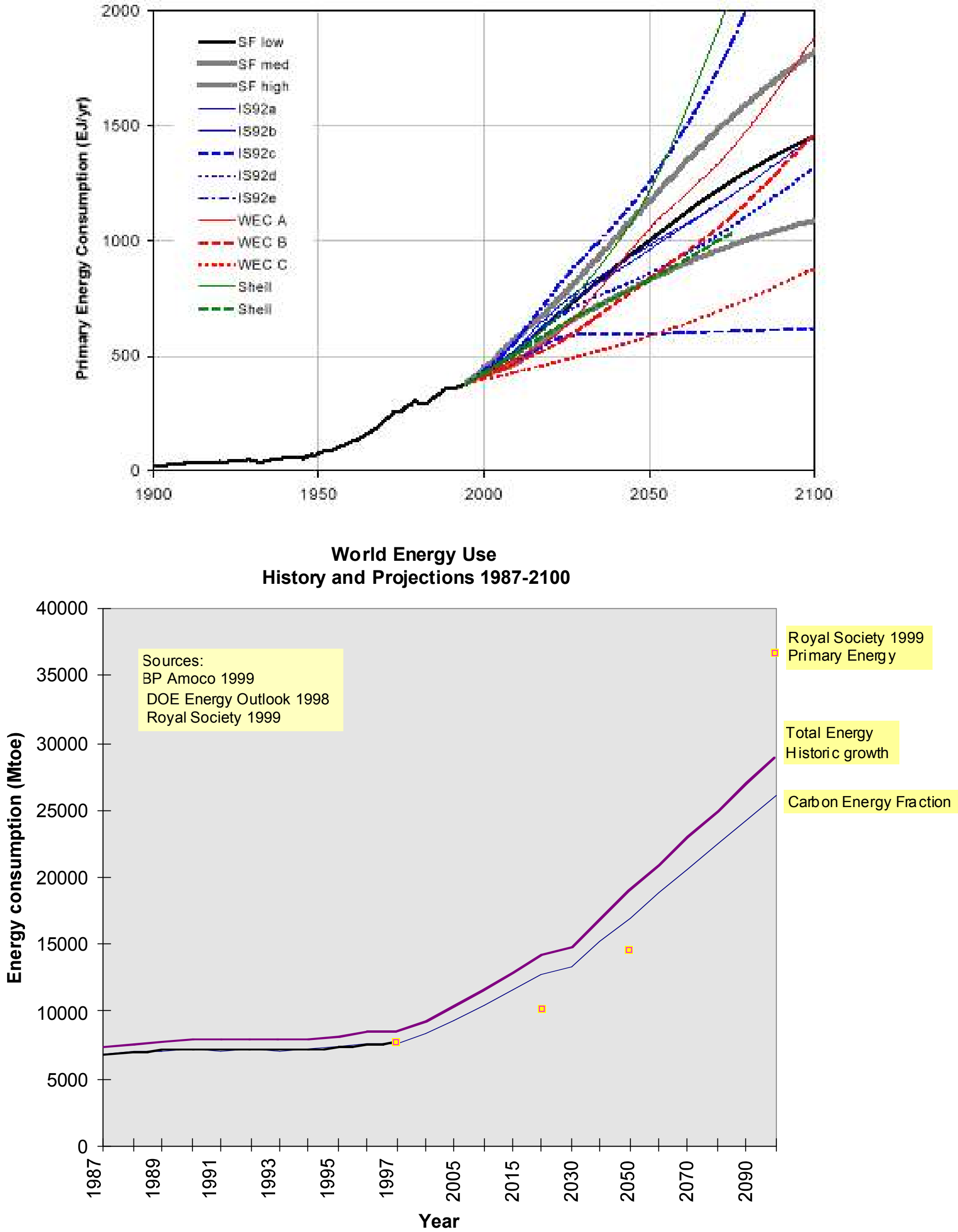


Figure 8 (a) and (b) Estimates of 21st Century World Energy Growth

(Sources: 1987-1997 BP Amoco; 2000-2020 US DOE EIA; 1997-2100 Royal Society; Fetter, 1998 (http://www.puaf.umd.edu/papers/fetter/publications-climate.htm))

If we know or can estimate the future *carbon* energy use, then the CO_2 ppm can be anticipated. Growths in future energy need and use are widely accepted: when uncertain about the future, economists and energy analysts make many predictions, and Fetter, 1998 (http://www.puaf.umd.edu/papers/fetter/publications-climate.htm), ably summarizes many of the projections. In consequence of energy growth, global climate change is predicted for the 21st

Century (IPCC, 1995 (http://www.whitehouse.gov); Royal Society, 1999). There are many projections for energy growth to 2020, and some to 2050 and even beyond (Fetter, 1998(a); IPCC, 1995; Krakowski, 1999) which show a spread of about a factor of 2-3, depending on the assumptions made (Figure 8).

As a best estimate, I have taken the historical 1-2% total energy use growth rate, which is in reasonable accord with history. This growth rate lies at about the mean of all the many projections, even knowing that in developing countries this is too low (i.e. where it is nearer to 5-10% per annum). With this model 1-2% rate for beyond 2020, and fitting to the DOE 2020 prediction (which is why there is a slight kink in the curve), we have the prediction shown in Figure 8(b) to 2100, where the historic growth is based on a 1-2 % rate before 2020. Using this approach, I have also calculated the "energy-as-usual" case with a ~ 90% carbon fraction, or can assume any other reasonable value.

As an eminent independent authority, the Royal Society and Engineering Academy, 1999, based their future values (for four points in future time) on thoughtful review of the many estimates, and is their view of a *prudent* projection for planning purposes. With these projections, or indeed any other, and using solely Equation (3b) with an assumed carbon energy fraction, we may estimate the CO_2 concentration *directly*. The result of this calculation is shown in Figure 9 for the historic 90% carbon fraction.

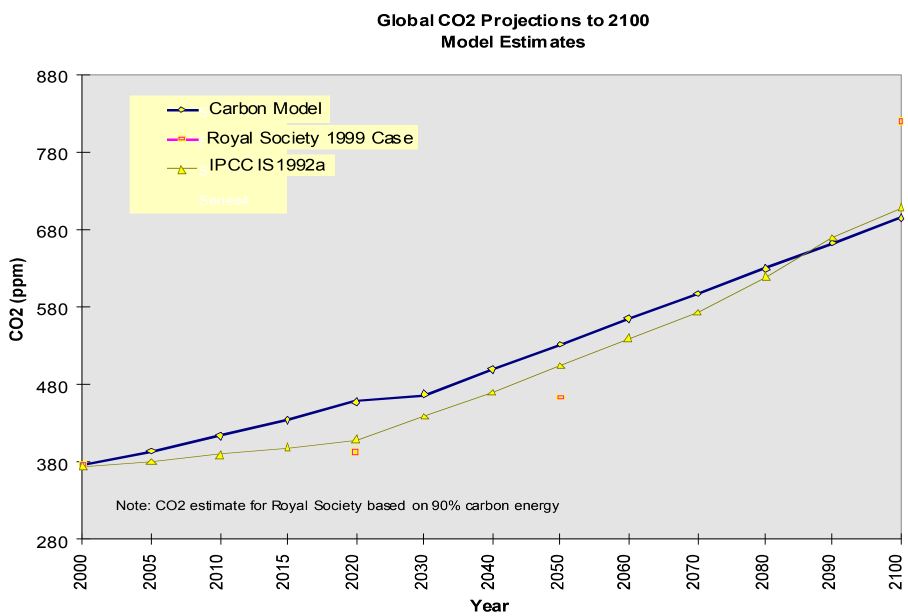


Figure 9 The Prediction of Global CO2 Based on 90% Carbon Energy-as-Usual Using (Equation (3b))

Basically the Energy-as-Usual (EAU) case gives the classic doubling of CO_2 ppm by 2100, which according to global climate change (GCM) analyses also gives significant potential local and regional climate changes (see e.g. (http://www.whitehouse.gov), 1999) and a global average temperature increase of between 1 to 4.5°C as given by the EPA, (http://www.epa.gov/globalwarming/emissions/index.html).

I observe that the "carbon model" prediction (Equation (3b)) is in reasonable accord with the IPCC IS92a scenario derived using GCM calculations, with a slightly greater earlier rise. This

IS92a case is the base case for many recent GCM calculations. Using the Royal Society latest 1999 energy estimate gives even higher values by 2100 (~800ppm) at a 90% carbon fraction.

I consider this graph as validating the "carbon model" against the IPCC IS92a, at least to the point that sensitivity studies can be made of the effect and trend of varying energy scenarios and technology impacts and needs on CO_2 ppm, with the advantage of not now having to use a more complex energy or GCM.

Note that Canada utilizes just 3% of world energy use, and produces only 2% of the global CO_2 emissions, so at first blush a pragmatic or naïve view is that whatever Canada does by itself would have little global impact. However, Canada's actions have extreme value as a world leader in the supply and use of a multitude of both carbon and non-carbon based energy resources and technology.

The estimate of the eventual Antarctic temperature change from the present to 2100 is then, from Equation (5), and using ~30000 Mtoe from Figures 7 and 8 as the potential "energy-as-usual" carbon energy usage:

$$\Delta T\ (^{\circ}C) = 0.09*(\ 0.018 * (30000\text{Mtoe}) + 227) - 25 = 44^{\circ}C \qquad (6)$$

Clearly unrealistically attainable since all will melt, this increase is then at least 10 times the global average value of 4.5°C given above. This large change at the polar regions is predicted to have drastic effects on global ocean currents, even perhaps reversing as the influx of melted water occurs at the poles (Taylor, K.C., 1999) long before this maximum value is reached. There is significant discussion and uncertainty (of a few 1000 years) as to whether CO_2 leads or lags the ΔT: the current rate of change at current CO_2 levels does not give us much time to resolve that question. The very large global variations in the impact are one more reason for dissenting and sometimes parochial views.

6. Potential Use of Nuclear, Hydrogen and Renewable Energy: Going Up

Can we reduce the GHG's, CO_2 and potential climate effects by reducing carbon energy use? What can be used instead? The reply to this question depends on who you are. From (a) renewable advocates, the answer is to turn to large scale solar and wind power; (b) national and regional economists and policy advocate legislation for energy and/or carbon taxes and emissions credits and trading; (c) others would rely on increased efficiency and reduced energy use; (d) nuclear energy advocates suggest large scale nuclear power additions; (e) carbon fuel suppliers' emphasis is on sequestration of carbon, reduction of emissions; and (f) energy suppliers and auto manufacturers emphasize fuel switching to natural gas and free market forces. So who is right? What are the practical solutions?

The Royal Society eloquently argues we will need all sources and means at our disposal. To try to answer that question, I tried to consider the merits and the **numerical** contributions that *all* reasonable energy technologies and economically and environmentally acceptable policy actions could attain. I found that nuclear, renewable and hydrogen energy sources are *uniquely* synergistic and complementary in reducing costs, electricity generation emissions and end use transportation emissions. This partnership is despite past historical use patterns and the competing self-interests and disputes amongst the various proponents.

Nuclear energy providing some 17% in 1995 of the entire world's energy consumption from electricity generation, and some 7% of the total energy consumption; and has had to face and jump the hurdles of competition, waste disposal, anti-nuclear weapons sentiment, and numerous technological teething troubles. Present *near-term* global and Canadian projections (NRcan, 1998; DOE, 1998; Feiveson, 1999) do not include significant new non-carbon nuclear energy in the future energy scenarios or emissions reduction measures. This is simply because short-term power generation needs are assumed to be met by burning another carbon-based world energy resource, namely natural gas and "energy-as-usual" prevails. Nuclear has been unfairly described as unsafe and uneconomic, compared to future alternates, and hence not an acceptable non-energy carbon source. I note this is mainly the philosophy of the industrially rich and energy endowed, implying somehow that there is or must be a "better" non-nuclear way. The historical nuclear generating costs are low (http://www.nei.org/) running in the US and Canada on average in the range of about 2-2.5 c/kWh in 1998$. This compares well with windpower at ~4- 4.5 c/kWh (http://www.wind.enron.com/energy/index.html/). Of course, some nuclear plants have closed, so have uneconomic coal, oil and gas plants, not to mention some wind farms and solar facilities. It is the market place at work.

Estimates for future generating costs can be made from many alternate non-carbon sources (Meneley et al, 1999), derived directly from The European Renewables Energy Study (TERES), and from current actual and projected values for future cost declines. The expected CANDU nuclear cost decline is ~35% or more, consistent with the market forces (Torgerson, D.F., 1999 and 2000). Irrespective of the absolute magnitudes, the point is that the estimates clearly show that 20-30 years are needed for renewable energy costs to significantly decline. Unfortunately, we have to make decisions and take actions on time scales shorter than that, but nevertheless relative energy costs are going down even as demand increases (see (http://www.eia.doe.gov)). Relative costs between different energy sources (oil, gas, nuclear, etc.) depend heavily on national and regional availability and politics as *local* market forces predominate as we grapple with *global* energy use.

There is one very clean fuel. Hydrogen derived from water electrolysis is limitless, and a non-carbon emissions free energy source (see the National Hydrogen Association site (http://www.ttcorp.com/nha/)). However, today it is mainly produced by the use of methane reforming that consumes energy and emits CO_2. The total cycle does not produce significant emissions reductions; and H_2 is sensitive to the cost of energy or electricity. In addition, for historical reasons, the societal and industrial infrastructure is based on liquid carbon fuels. The principal use of hydrogen in Transportation end use is then delayed further, because it must compete with gasoline and natural gas fuel costs. As to hydrogen cost from electrolysis, it is directly dependent on the input energy (power) cost. Feiveson, 1999 has stated that at 5 c/kWh, the cost of hydrogen was 2 to 3 times the cost compared to competitive reforming from natural gas or coal (with no carbon taxes). But we have already shown (Duffey et al, 1999) that by synergistically producing and selling heavy water (D_2O) for reactors, the cost of hydrogen from modern electrolysis plants is competitive with other sources for ~2.5 c/kWh. This price is half of Feiveson's estimate, is a price *already achieved* by current CANDU reactors, and indeed corresponds to the average of the competitive open market price of electricity in California (EPRI, 1999).

Similarly, it is clear that it will take many decades for renewables to penetrate the market significantly viz. the large additions made in the last 10 years at favorable windpower sites (BWEA, 1996 (http://www.bwea.com/) and (http://www.cranfield.ac.uk/sme/ppa/wind/turbtabl.html)). I have visited windfarms and solar installations in the US and UK: the shear scale of the enterprise and large area siting requirements, plus the low capacity factor and intermittent generation, means they need a grid "bank" (reverse metering), and hydrogen or batteries for peak energy storage.

Many mechanisms are being introduced to encourage the introduction of such alternate non-carbon power sources: "green" quotas, or Renewable Portfolios, or Capacity Credits are being legislated as a fraction of the electricity market, as well energy taxes with renewable refunds, all as an encouragement to reduce energy use and to help mask or defray the cost (see for example (http://www.energy.state.or.us/climate/climhme.htm)).

7. Nuclear Power and GHG Levels: Going Up or Going Down?

Looking at the recent projections for nuclear on a world-wide basis I found a slight discrepancy between the OECD (http://www.nea.fr/) upper projections and estimates and the upper estimates of the DOE, 1998 studies for the interval between 2000 and 2020, as shown in Figure 10.

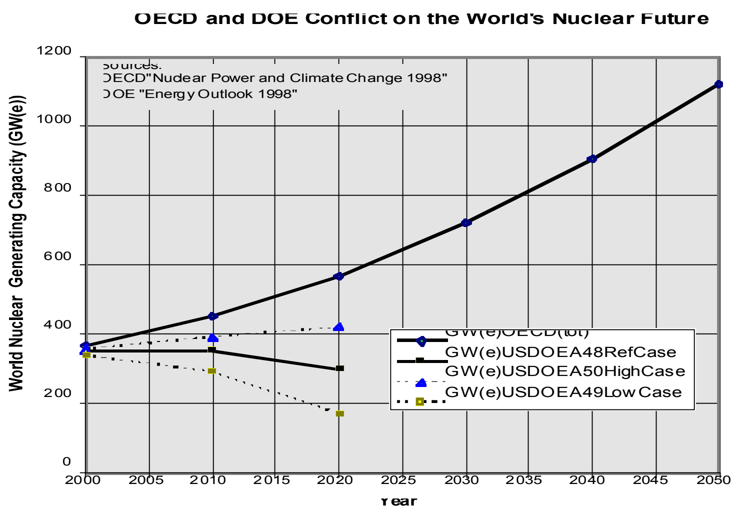


Figure 10 Recent OECD DOE Predictions of Future Global Nuclear Use
(Source: DOE Energy Outlook, 1998; OECD, 1998 (http://www.nea.fr/html/ndd/climate/climate.html))

The recent DOE International Energy Outlook 2000 repeats this same decline (http://www.eia.doe.gov/oiaf/ieo/index.html). These differences illustrate clearly the consequences of adopting extreme scenarios: of assuming nuclear introduction in developing countries yet allowing it to phase out on the developed world (the basis for the DOE estimate); or allowing nuclear to meet a substantial part of future energy growth as GHG effects and emissions restrictions take hold (the basis of the OECD estimate). The latest US estimates highlight the issue: global per capita CO_2 emissions are not falling, and CO_2 is rising, especially from North America (see Figures 11 and 12). Since major energy growth will occur in developing countries, what can they do and what do they want? The answer is cheap energy at any cost.

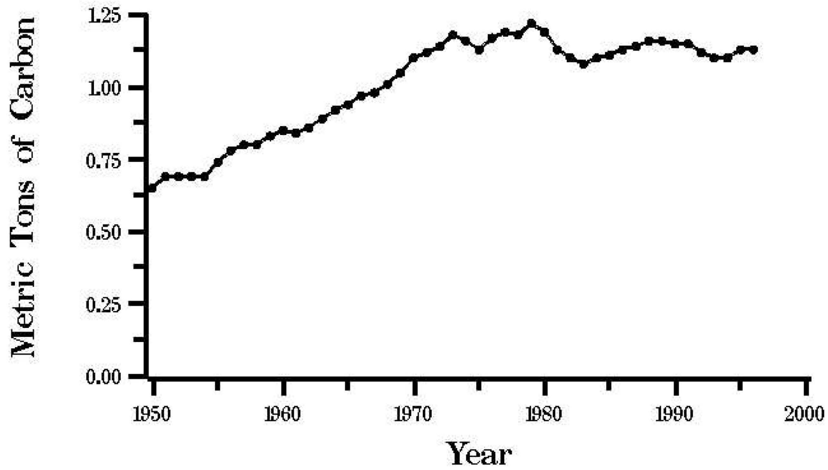


Figure 11 **Global Carbon Intensity in t/capita**

(Source: US CDIAC, 1999)

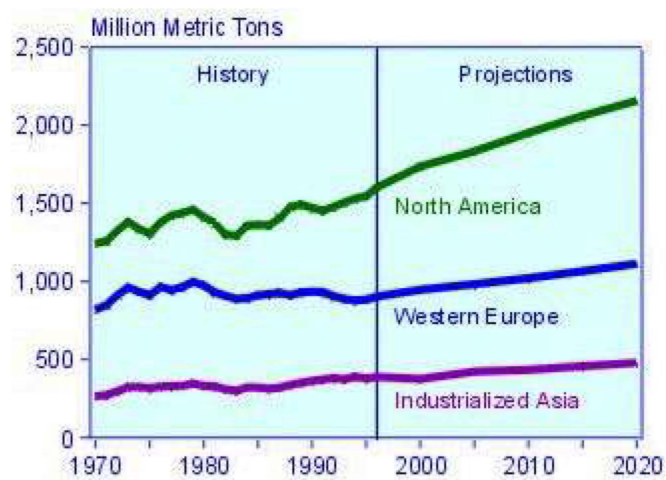


Figure 12 **Projected CO2 Emissions by Region**

(Source: US DOE EIA, 2000)

The full-cycle of carbon energy use is also now being examined. R&D on promising key sequestration technology for CO_2 removal and/or storage is under active demonstration, including saline aquifer injection (http://www.ieagreen.org.uk) in the SACS project, and similar "closed cycles" are being studied for emissions - free coal use.

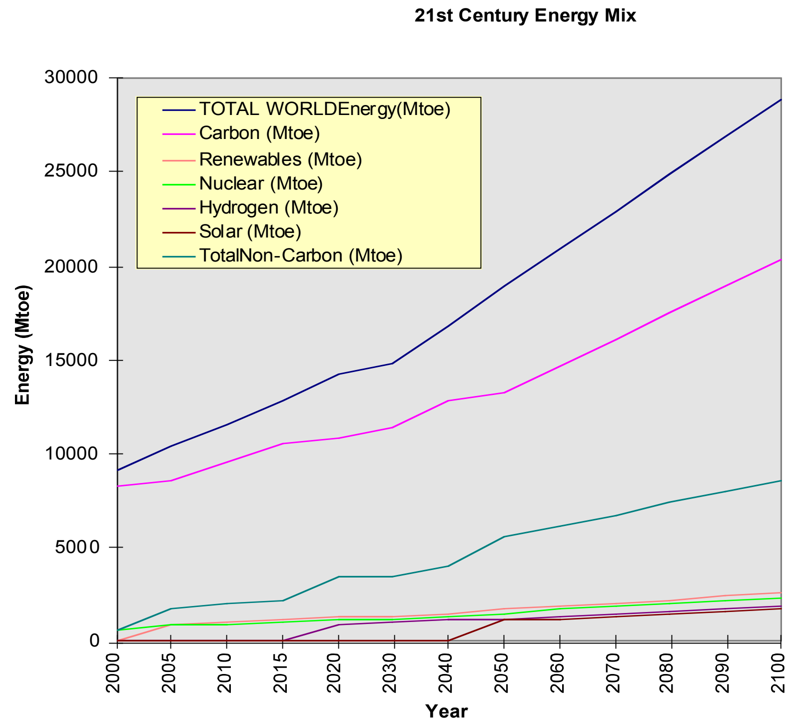
8. Quantifying Needed Non-carbon Energy Future Portfolios: Going Up

To stabilize CO_2 levels in the atmosphere, I conclude that in the 21st Century we will need all the non-carbon "green" energy and power we can find at economic rates, and combine that with central nuclear and hydro-generation to supplement the *needed* carbon sources. The required sources can be quantified as needed portfolios or market share. Such an exercise illustrates what can be achieved by reasonable technology introduced in reasonable ways.

If I could really predict the future without uncertainty, indeed I would not be human. We humans can make educated guesses, based on the science and predictions of the uncertainty of what we know. Using the historical Equation (3a), we can now estimate the impact and sensitivity of meeting the world energy needs for the 21st Century with assumed levels of non-carbon penetration, technological development time frames, cost reductions and competitiveness.

Previous work has defined the target or range of non-carbon amounts needed to stabilize CO_2 levels (e.g. IPCC, 1995; Hoffert et al, 1998) but *not* the means (Koike et al, 1999). Hoffert et al call for "massive investments in innovative energy research" and a non-carbon fraction of ~30% by 2020 to stabilize CO_2 levels at today's levels, or at least by 2050 even assuming a further 1% per annum improvement in postulated but unproved energy efficiency gains.

To quantify further specific numerical example of the means, I consider the introduction over realistic times of non-carbon energy, defining nominal ~ 10% penetration "portfolios" of nuclear, advanced nuclear, hydrogen, renewable and sequestration technologies to meet the needed energy demand. A target efficiency gain of ~10% was also examined. The energy demand was based on the nominal 1-2% growth case of Figure 13: obviously any other cases can be analyzed too. What is evident is that, despite *massive* non-carbon energy use, only utilizing a combination of sources can the inexorable CO_2 growth be halted and near-stabilization achieved. It is clear: the world cannot wait until 2100 to introduce non-carbon technology. It is also evident that carbon energy use still grows considerably, and nuclear energy remains a relatively small but key part of the total energy mix, which as a result is shown in Figure 14:



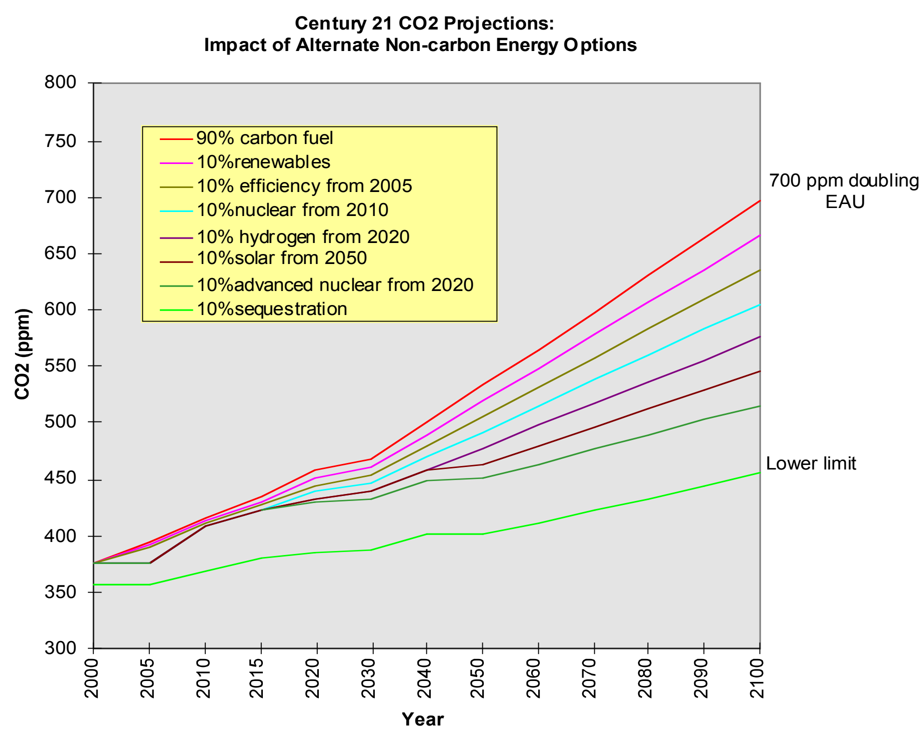


Figure 13 **Non-carbon Global Energy Portfolios and Impact on CO_2**

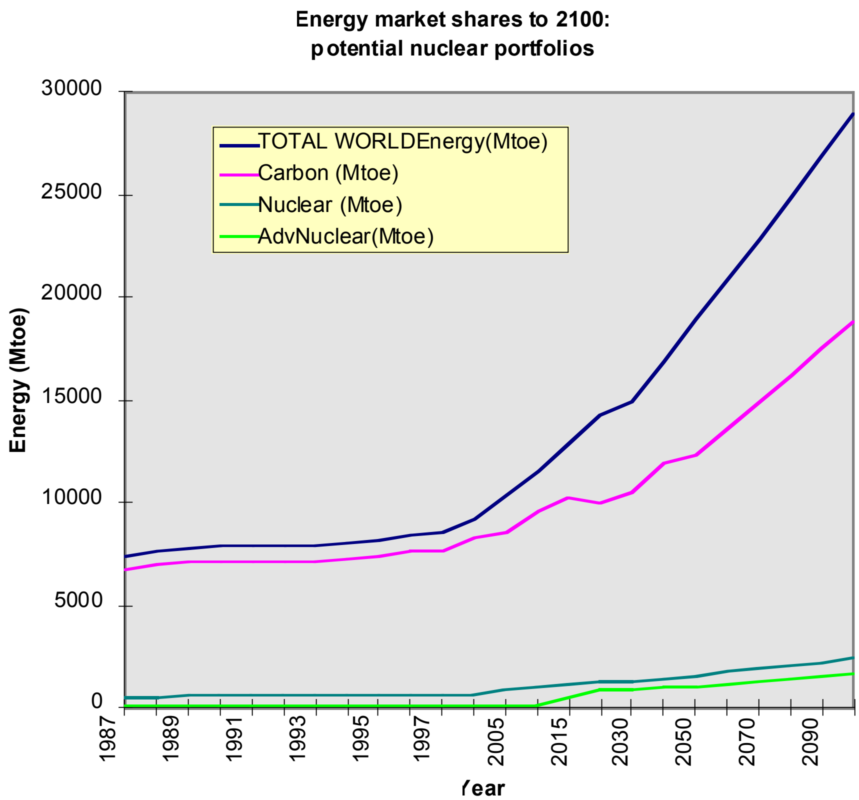


Figure 14 World Energy Mix to 2100 Based on 10% Non-carbon Portfolios

These deceptively simple graphs somewhat hide the startling facts that by 2100:

a) carbon energy sources are ~3 X their present value, and are still growing;
b) total potential nuclear energy component is ~3000 GW(e) capacity (about 3000 plants);
c) wind farms comprised of about 200,000 5MW horizontal axis turbines would be distributed around as ~50,000 wind farms;
d) transportation by 2100 absorbs around the same energy use as all of today's carbon energy;
e) assumed at 10%, sequestration must dispose of ~1 GtC /y; and
f) assumed 10% efficiency gains, even if achieved, also require nuclear, hydrogen and renewable contributions to stabilize emissions.

The nuclear portfolio estimate of ~3000 nuclear plants by 2100 is in very close agreement with the estimates of ~3000 GW(e) given by the totally independent IAEA E^3 analysis (Krakowski, 1999) and Japan's recent study (Koike et al, 1999). It is also very close to the EPRI Road Map results (http://www.epri.com).

The non-carbon bridge to the future I propose, as we have proposed before, *is a balance of hydrogen, renewables and nuclear non-carbon energy sources*, coupled with a *management of emissions.* The portfolio of electric and energy sources is robust, and includes a steady but more slowly *increasing diet of carbon fuels.*

9. The Nuclear Source of Hydrogen in Transportation: Going Up

In industrialized countries (like Canada and the USA) about 20-30% of total energy use is for transportation (cars, trucks, planes and trains) and is growing and is projected to be similar in the whole world soon (see International Energy Outlook 2000 (http://www.eia.doe.gov/oiaf/ieo/index.html)). From Equation (3a), we might expect this to be an equivalently and potentially big impact item on 20-30% of the CO_2, even if fuel economy is increased and/or emissions reduced, because the total transportation use grows. This fraction is precisely confirmed by the official Canadian and USA data and projections, just because transportation uses carbon based fuels. Indeed, if the whole world eventually adopts or uses the same mode to the same degree, *then up to ~30% of the global CO_2 will be from transportation* (the gasoline automobile).

We have shown elsewhere that hydrogen and nuclear energy can provide a unique impact in Canadian transportation (Duffey et al, 1999). As Feiveson, 1999 also remarks, “nuclear could have a role beyond the electricity sector *only if* (emphasis added) it is used to produce hydrogen”.

Transportation in Canada alone represents some 15% of the GDP, causing emissions of about 150MtCO_2/y rising to about 200MtCO_2/y by 2020. If we could switch fuel to hydrogen we could reduce these numbers (Berry, 1995). Sources of hydrogen usually considered are reforming, decomposition or electrolysis.

To minimize CO_2 emissions from the H_2 manufacturing and for the synergism to operate world-wide, there is therefore available a source of non-carbon electricity generation (namely a CANDU reactor). I call this the “nH_2 plant”, and is part of the self-sustaining energy cycle.
The nH_2 plant uses heavy water (D_2O) for its moderator to be efficient in energy production, and is hence unique in using a by-product of electrolysis to offset hydrogen production cost and to produce D_2O for future needs. Hydrogen can be produced with essentially zero emissions, by the preferred and simplest process of electrolysis of water in advanced electrolytic equipment. Thus the basic and simple concept is that the reactor is used to generate electricity for the grid, for local or distributed hydrogen production, and to make the by-products of heavy water, oxygen and process heat. The heavy water produced enables more nH_2 plants to be built.

As a worked numerical example, projections (Duffey et al, 1999) showed that 22 CANDUs installed by circa 2020 would meet, with hydropower, all Canada’s estimated needs for electricity, and could reduce CO_2 emissions by a further ~50Mt/y. There is no negative economic impact, as this power generation addition is needed to grow the economy anyway and to underwrite potential shortfalls in capacity.

One 700MW(e) nH_2 plant operating at 80% load factor can supply ~650,000 V/d with H_2 fuel with no net increase in CO_2 emissions. Fuel cell technology has reached this point now (http://www.ballard.com/). So we have:

One nH_2 plant @ 700MW(e)=>95t/yD_2 O+ 650,000 H_2V/d + 0 CO_2 (ppm)

with enough D_2O supply for filling up another nH_2 plant every 4-5 years, plants with an excess by-product after about 14 years. Therefore, a program of 20 reactors would supply ~13M hydrogen vehicles, and would be self-sufficient in D_2O production, and supply excess D_2O for export. The avoided CO_2 emissions reductions in electricity generation and transportation are ~ 120Mt/y. No restrictions on the oil and gas industries, or any others are needed, since these continue to fuel the base industrial and residential, and the transition electricity and transportation needs until at least 2020-2030.

Canadian emissions have been recently revised up, both as a result of economic growth and increases in oil sands emissions from natural gas use in upgrading (NRcan, 1999 (http://www.syncrude.ca/)). This trend is illustrated in Figure 15.

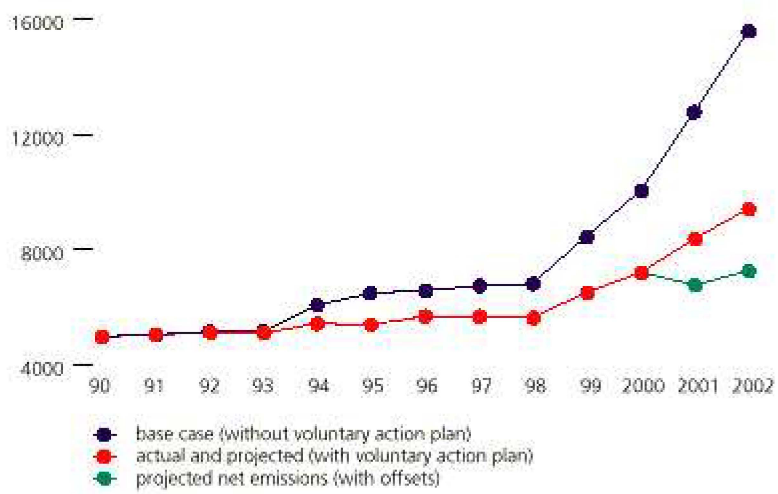


Figure 15 Estimated Increased CO_2 Emissions from Oil Sands in 1000s of Tonnes CO_2 Equivalent

(Source: Suncor, 2000 (http://www.suncor.com/we_care/wecare_globalclimate.html), (http://www.suncor.com/we_care/gclimpos.html#cogge))

A similar analysis can be conducted for the use of hydrogen from electrolysis for oil sands upgrading. This analysis results in the similar identity that, assuming a barrel of syncrude uses ~5kg of H_2 in upgrading:

One nH_2 plant @ 700 MW(e) = 24 M bbl/y (65 000 bbl/d) syncrude
+95* t/y D_2O + 980 k t/y O_2

It is evident that the potential industrial uses of low cost hydrogen are extremely significant, essentially eliminating emissions from transportation and hydrogen use. The analysis in this paper can be simply extended from Canada to the global energy projections. Assuming that transportation needs will be ~20% of world energy demand, and electricity ~20-30% of this same global energy demand, then meeting _ of these needs with non-carbon sources means a non-carbon portfolio of ~20-25 % in total. This fraction is not inconsistent with the analysis shown in Figure 8, and implies that the non-carbon portfolio can make greatest impact and should be focused on the electricity *and* transportation sectors (via hydrogen and electrification).

10. Conclusions and Directions: Where Are We Going?

I have examined and given the available sources and major pointers which lead to current estimates of potential climate change and the key role of rising greenhouse gases. Unless we switch to about a 30-50% reliance on non-carbon sources of energy, over the next few years (by 2020- 2050) we will have significant and potentially negative global impacts. The compelling evidence from technical observations, and a set of correlations between energy use, economic growth and CO_2 concentration, enables estimates of the impact of a range of future energy scenarios.

Uniquely synergistic opportunity between hydrogen, nuclear and renewable non-carbon sources of energy which can reduce CO_2 emission without harming the economy and industry. A carbon-based analysis of global CO_2 is developed and validated to predict CO_2 concentration sensitivities to various carbon to non-carbon energy mixes.

The analysis of global energy demand in the 21st Century is extended to include the impact on CO_2 concentration of portfolios of nuclear, advanced nuclear, windmills, hydrogen, solar and hydro sources, plus target efficiency gains and sequestration. All these must be used *in combination* to stabilize global CO_2 levels.

To quantify further specific numerical example of the means, I consider the introduction over realistic times of non-carbon energy, defining nominal ~ 10% penetration "portfolios" of nuclear, advanced nuclear, hydrogen, renewable and sequestration technologies to meet the needed energy demand. A target efficiency gain of ~10% was also examined. The energy demand was based on the nominal 1-2% growth case: obviously any other cases can be analyzed too. What is evident is that, despite *massive* non-carbon energy use, only utilizing a combination of sources can the inexorable CO_2 growth be halted and near-stabilization achieved. It is clear: the world cannot wait until 2100 to introduce non-carbon technology. It is also evident that carbon energy use still grows considerably, and nuclear energy remains a relatively small but key part of the energy mix.

For Canada, with its rich resources of CANDU technology and large oil and gas reserves, the opportunity exists to establish a balanced portfolio of hydrogen, nuclear, carbon and renewable energy sources as a contribution to global emissions management. The future market and need for non-carbon energy sources is huge: for nuclear in particular, the need for significant additional plants in both developing and developed countries is clear. The ability to synergistically create a market for hydrogen, fuel cells, reactors, and renewables is presented. It is shown that the focus should be on electrification and hydrogen fuels derived from non-carbon sources.

The global market for competitive low-cost nuclear reactors to 2100 is estimated at a minimum of 3000 reactors, even on a limited portfolio analysis basis. The use of competitive nH_2 plants will only increase this number.

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