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From Option to Solution: The Nuclear Contribution to Global Sustainability Using the Newest Innovations

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Abstract

This paper describes our analyses of future energy scenarios that exploit the latest technological innovations in nuclear plant design concepts and in using hydrogen-based fuels.

There is a pressing world need to provide for growing global energy demand while reducing the adverse effects of anthropogenic emissions, by adopting energy sources that enable sustainable economic, social and environmental development. In the light of projected and actual energy needs and possible climate changes, many recent statements support the introduction of more non-carbon based energy sources. Electricity has a major role to play here, securing economic growth by using 'clean and green' fuels that afford environmental protection. To date, nuclear energy is not usually described explicitly as one of the 'solutions' for world energy needs, but is included as a possible 'option'. This is obfuscation. Using the innovative advances of the last few years, nuclear energy can now be shown to be a key player. From being a perhaps controversial and 'fall back' option, nuclear energy emerges as one of the major contributors to global sustainability.

This shift in stance is possible from two innovations that we describe that will occur in the time frame 2005-2010, coupled with the realization that real action is necessary on mitigating climate change.

- The emergence of low-cost nuclear design options which can meet market targets for competitiveness, capital cost, investor return, increased efficiency, energy security and operating performance;
- The potential future switch in transportation to hydrogen fuels in the same time frame – now recognized by major car manufacturers – which approximately doubles the potential and sustainable contribution for the nuclear market.

Nuclear energy can ensure a sustainable energy future for the world, enabling economic growth, renewables deployment and greenhouse gas (GHG) reductions. This is now being recognised in the industrial and political arenas, as illustrated,

for example, by the latest policy statements from many countries in North America, former FSU states, the EU, India and Asia.

We show, by actual analysis, how nuclear energy meets, into the indefinite future:

- the goals of Agenda 21;
- the three elements required for sustainability (economic, environmental and social);
- public transparency, enabling many industrialized countries to meet their emissions reductions within the Kyoto targets;
- the stabilisation of future climate change by enabling the hydrogen economy; and
- technical innovation, which stabilizes energy prices and ensures security and stability of supply.

The world of energy scenarios: climbing the ladder

The world is highly dependent on energy, and hence on electricity for its economic growth (*Figure 1*). In fact, the whole world wants to climb the ladder of increasing wealth, and to do so must proportionately increase their electricity and energy use. To allow the people of the world to grow, we must allow energy use to grow: as energy use grows, so do emissions if we rely solely on fossil fuels. It is as simple as that.

The industrial world depends and runs on 90% of its energy derived from fossil and nuclear fuels. Of course, we cannot and must not harm the key energy industry, or competitive trade and export positions. The obvious answer is to use non-carbon energy sources and fuels wherever we can, and so improve our living standards and expectations at the same time. Nuclear energy should feature large in that contribution, and there is a growing realization, at least in the technically informed community, that building a greater nuclear power capacity may be the only really sensible way to proceed over the next 10-30 years or so.

There are probably many more future energy scenarios than there are institutions that study and produce them. Gazing into the future is an attractive, inexact but necessary science, and large economic and energy models have been used to attempt to scope out the future. We simply note that past energy use has grown to feed economic growth and we expect that to continue, especially in the newly industrialized and economically developing nations. In fact, energy use drives every modern economy and increased national and personal wealth is derived from that energy use. Countries and people everywhere wish to and do climb (or, at the very least, strive not to descend) the ladder of energy and electricity use to increase or maintain their wealth. Shell's analysis [1] shows clearly the energy use ladder, with increasing GDP with energy use needs per capita spanning more than a range of x10 for nine selected countries and the EU. We show here the comparable electricity use ladder for 97 countries in Figure 1.

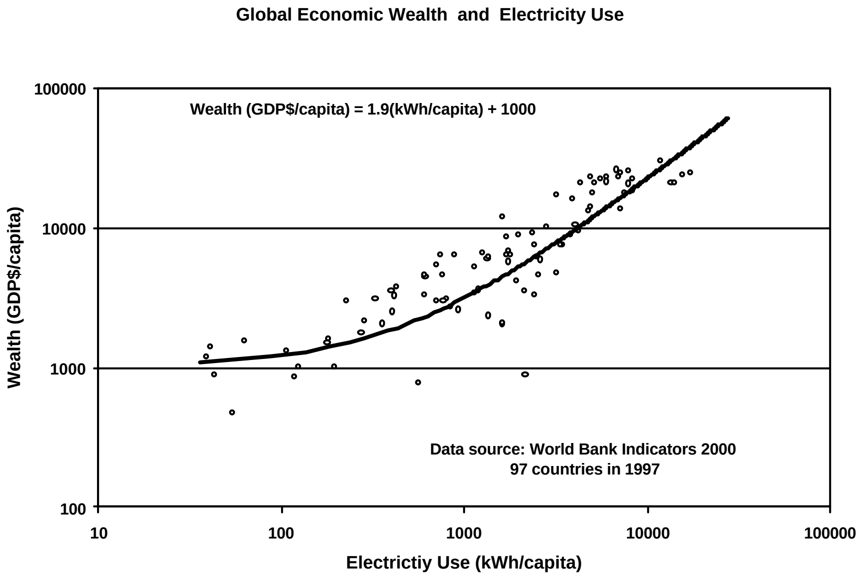

Figure 1: The global electricity and wealth ladder (Source: World Bank Indicators, 2000)

In fact, the latest scenarios of the United Nations Intergovernmental Panel on Climate Change (IPCC) [2] also have this same ladder embedded in their future projections, with electricity use growing as the world's economy grows. The global sustainability debate and argument is that this growth ('ladder climbing') is not sustainable, due to adverse pollution and GHGs, exhaustion of finite carbon-based energy supplies, and the need for resource conservation simply for the survival of future generations. The reality is that energy demand is driven by local needs and choices related to the current energy market, and fuel availability and price versus demand. In the absence of large scale government 'policy measures' (various energy or carbon taxes, subsidies, portfolios, obligations, credits, etc) the competitive market prevails, using what is cheapest and most plentiful. That is why there have been swings in the past from coal to oil to nuclear to gas for the fuel for new construction. What is attractive to build today depends on the price and availability today, and the degree to which assured and economic supplies can be contracted for in the future.

Without nuclear energy most industrialized nations have no hope of meeting any emissions reduction target at all. The EU Commissioner, Loyola de Palacio stated in 2002 that: 'Against the background of electoral campaigns, Europe needed a rational, objective and transparent debate because nuclear energy is a factor for stabilizing prices and guaranteeing supply. A new problem exists: the speeding-up of global warming. Nuclear energy would allow us to cut down on 300 million tons of carbon every year in Europe. If we abandon nuclear energy, we have to say how we will produce this electricity and tons of CO_2 will be produced with conventional forms of energy. It's a very serious problem'. Loyola de Palacio concluded that, given that renewable forms of energy were not able to replace nuclear energy, '…without nuclear power, Europe will be unable to meet the Kyoto objectives'.

The UK's Chief Science Adviser has said that a new nuclear programme is the only way Britain will meet its target of getting emissions to 23% of 1990 levels by the end of the decade. He did not believe renewable energy – such as wind farms – would be sufficient *on its own* to cut emissions that are blamed by many scientists for contributing to global warming.

The UK government, and others, has said any decision on whether to build new nuclear power stations would be a matter for the commercial sector. In other words, it must be competitive in the market and compete on its merits.

We therefore show the full and dramatic changes that occur in future projections when innovations from nuclear and hydrogen energy are properly included as a substantial part of a sustainable and acceptable solution. This can and will occur in competitive power and energy markets using as a start the new reactor concepts available today. Using accepted methods and the latest UN studies as a reference, we adopt proven methods, and show how global sustainability can be achieved. Global sustainability is assured using existing technology and the correct choices of fuel mix, with the nuclear market share increased in a sustainable manner worldwide.

Including innovation

But even if Kyoto were ratified, we would still need to switch to 40% or more non-emitting power sources by about 2040, if we are to have any chance of stabilizing atmospheric CO_2 concentrations. That is why we need to find energy alternatives, and to ensure energy security and stable energy prices.

Neither nuclear nor hydrogen innovations have been fully or effectively included in the latest IPCC, WEC, RCEP and IIASA scenarios, because:

- the nuclear component is largely based on existing designs with projected higher costs than gas plants, thus limiting their market penetration; and
- transportation is usually restricted to conventional fuel use, with fuel cell and other innovations not considered available before 2030.

New nuclear technology and hydrogen as a fuel have been mentioned but have not been fully included in the latest published future energy scenarios of the IEA/NEA, Shell and others. Nuclear energy is usually included as an option to evaluate the impact, but either in a largely technology-as-usual mode using existing reactor designs, or as a phase-out option, the latter being considered more politically opportune in the EU than elsewhere. Commonly, the chosen scenarios try to cover the whole range of social and economic options related to future global energy demand, from:

- so-called 'business-as-usual' (BAU), with continued high energy demand with reduced fossil fuel use, to
- so-called ecologically-driven (ED) limits requiring extreme energy conservation and a postulated large switch away from fossil fuels to renewables.

Therefore, all of the 'future options' studies to date try to cover their bets, and do not commit to any one, or claim any preferences.

With no sound technical bases and only economic assumptions, it is impossible to decide what the truth may be. For example, leaving aside politically inspired phase-out, the NEA model scenarios give a possible total energy share for nuclear of 15-20%, rising to 30-70% with the imposition of so-called ‘carbon taxes’ to restrain GHG emissions. The assumptions give a very wide range for potential projected nuclear energy deployment. For the ED-BO scenario, deployment by 2020 is 70±20 GW(e)/a; for the BAU-BO scenario, the figure is 25±10 GW(e)/a and the uncertainties grow thereafter. However, these NEA projections both lead to an increase by 2050 in deployed nuclear power by factors of four to eight over today’s fleet of 400 reactors [3, 4].

Hydrogen as fuel in the future from both nuclear energy and renewables from electrolysis is explicitly mentioned in the Shell Report [5], which also considers qualitatively a range of social and economic energy futures. Actual numbers are harder to find. Of the models used by the NEA, the LDNE21 model innovative technologies options include hydrogen production and use, particularly for methanol synthesis, which in the absence of sequestration would actually increase the full-cycle GHG emissions.

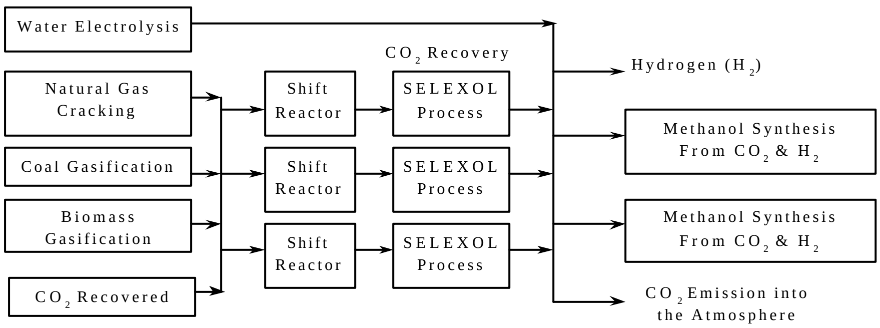

Figure 2: The hydrogen production model used in the LDNE21 model by the NEA (Source: OECD/NEA, 2002)

Only in scenario ED-BO do the global GHG emissions actually decrease, and then only from 8 $GtCO_2$/y to about 6 $GtCO_2$/y, which has the largest nuclear power increase.

The relative hydrogen production is not given, and no attention is apparently paid to fuel switching in transportation. Therefore, the full potential of future nuclear energy and its impact using hydrogen as an energy carrier has not been shown.

New estimates of global future emissions for the 21st Century have been recently published by the IPCC. In its new report [2], the IPCC predicts large increases in CO_2 and potentially adverse effects of climate change and global warming.

The 'emissions scenarios', from the IPCC [2], examine many alternate futures, including business-as-usual, and they allow for energy use growth consistent with the global economic and social growth patterns. Considerable energy use and economic growth occurs in developing nations. Four major scenarios (the 'marker scenarios') cover most of the range of assumptions. All scenarios envisage increases in energy use, as well as in energy efficiency, renewable and nuclear energy use.

The IPCC's scenarios all include expanding nuclear deployment, with nuclear growing in most scenarios by an order of magnitude above the current level by 2050. However, in its projections, the IPCC has assumed that nuclear will remain confined to supplying traditional electricity markets and modestly increasing its electricity share. Consequently, and despite also projecting substantial increases in energy supplies from other sustainable sources, none of the IPCC projections offerS a solution to the build-up of GHGs in the atmosphere.

We contend that only a much greater reliance on nuclear power can stabilize GHG levels and halt the expected rise in global temperatures. And to realize the full potential of nuclear, its role will have to expand into energy sectors not traditionally supplied by electricity.

Securing a sustainable energy future

There are several new concepts for nuclear plants on the drawing board, and some are now entering the market. There is international interest and investment, and Canada is involved with France, USA, Japan, UK, Korea and Argentina in the 'next generation' of nuclear reactor designs suitable for both near-term and longer-term market deployment. The nuclear innovation announced from Canada is the 'next generation' of CANDU®, which includes the new ACR 700 ™ (*Figure 3*). The ACR is an evolutionary design that does not involve any significant leap in technology, and builds seamlessly on present experience. That minimizes risk, maximizes confidence, and enables investment returns. By optimizing the whole plant design, including an increase in efficiency of ~10%, and adopting a more compact layout, the capital target costs are significantly reduced (by over 40%) over current designs and competitors.

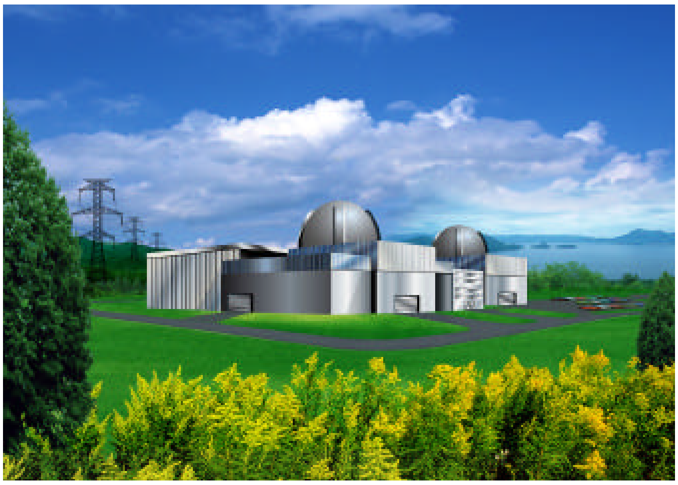

Figure 3: The new ACR700 concept (Source: AECL)

With the capital (overnight) cost of ~US$1000/kW installed, which competitive power markets demand, AECL is proceeding to design the low-cost ACR for deployment in 2005 and beyond in both Canada and large international (US, UK and China) markets. All essential CANDU features are preserved, and safety is enhanced. The ACR is recognized as economic and innovative, and scores highly for deployment in the International Generation IV Initiative, which includes the US, Japan, France, UK, Argentina and Korea. It scores highly against all the formal evaluation criteria used by the US DOE for assessing innovative and advanced concepts. Therefore, CANDU ACR can contribute significantly to future power needs and avoided emissions.

The unit energy cost is very competitive at ~3¢US/kWh versus conventional nuclear designs and with natural gas at expected market prices. Natural gas is a low-cost competitor in the power market, but is sensitive to fuel price. The need for energy security requires a fuel mix that retains price stability. Markets and investors require significant returns on investment also, and commercial funding of new plant construction is essential (with government guarantees only where necessary in the national interest). Commercial interest rates are likely to be in the range of 8-10% or more. Conventional or typical nuclear plants, with high capital costs, are only competitive for discount rates of less than 6%.

The competitive position for the ACR gives it access to a large market 'share' that, according to the data, depends only on the relative generating cost of the alternates. Thus, a large contribution from the ACR is expected in both the world and Canada's energy mix, with a potential to deploy the first units in and by 2009.

This low generating cost also makes electrolysis of water to produce hydrogen (perhaps during off-peak hours) economically attractive compared to conventional methods. 'Renewables and nuclear are highly complementary sources of carbon free electricity and so the siting of Ontario's first multi-turbine wind farm right next to our Bruce Power nuclear station is highly appropriate' said Robin Jeffrey, CEO of British Energy, recently. Thus, nuclear energy can enable the introduction of renewables, and provide synergism with an electricity grid that will also enable the introduction of hydrogen production for use as fuel for fuel cell automobiles, giving truly zero-emissions transport.

Nuclear energy can then stabilize our emissions. The numbers speak for themselves. We estimate that each 600-megawatt reactor invested in at market rates at US$1000/kW could *each and every day:*

- produce enough electricity for the direct and indirect consumption of 60 000 people; or
- provide enough hydrogen to power some 550 000 fuel cell vehicles every day; or
- produce 85 000 barrels of synthetic crude oil; while still
- avoiding emitting 5000 to 15 000 tons of CO_2; and
- avoid carbon sequestration costs of 1-3¢/kWh.

Reasonable assumptions for the future

To run these estimates into real impacts we have run calculations for previously published and reputable global energy scenarios. But we included the option and innovations of new nuclear builds and fuel switching to hydrogen in transportation as markets permit.

We have estimated the actual technical impact of reduced emissions using additional nuclear energy plants installed in a competitive market using the new generation of technology. Our estimates, which are reported in this technical paper, use the IPCC-derived estimates of future energy scenarios, and – since we believe that more nuclear capacity could be deployed than they have allowed – we undertook the actual calculations. We find that using nuclear energy for 80% of all new electricity from 2020 or so, and introducing hydrogen in transportation by 2040 or so, would not only stabilize emissions, but also actually *reduce* them for all the scenarios studied. (Of course, these scenarios incorporate great uncertainties and we do not claim the estimates to be exact values – they are simply indicative of the *relative* potential effects.)

Table 1 – The percentage distribution of primary energy for the IPCC marker scenarios

Year	A1B			A2			B1			B2		
	Carbon	Nuclear	Renew.	Carbon	Nuclear	Renew.	Carbon	Nuclear	Renew.	Carbon	Nuclear	Renew.
1990	82.4	1.6	16.0	94.9	2.6	2.6	80.4	2.2	17.4	82.6	2.0	15.4
2000	84.0	1.9	14.1	93.3	3.6	3.1	78.9	3.4	17.7	84.1	2.0	14.0
2010	87.7	2.9	9.5	92.2	3.1	4.7	79.5	4.3	16.1	83.5	2.3	14.2
2020	84.0	4.2	11.8	91.8	2.9	5.4	78.9	5.4	15.7	81.8	2.8	15.4
2030	80.1	5.9	14.0	87.4	4.4	8.2	76.9	6.9	16.2	79.3	3.4	17.2
2040	72.8	7.6	19.6	84.3	5.6	10.2	74.1	9.3	16.6	75.3	4.1	20.6
2050	64.2	9.1	26.7	82.0	6.4	11.6	69.8	12.9	17.3	70.1	5.5	24.4
2060	57.3	8.2	34.5	79.0	8.0	13.0	64.3	17.0	18.8	66.4	6.3	27.4
2070	49.6	7.1	43.3	76.7	9.3	14.0	59.1	21.1	19.7	60.9	7.7	31.3
2080	43.6	5.8	50.7	74.7	10.9	14.4	54.7	25.1	20.2	56.8	8.4	34.8
2090	39.5	4.5	56.0	73.2	12.4	14.4	51.0	28.8	20.2	53.5	9.3	37.1
2100	35.3	3.5	61.2	71.9	13.6	14.4	47.9	32.1	20.0	50.7	10.5	38.8

The reference timeline (N+H_2) was given in Duffey et al. [6], where the assumptions were explained. The timeline was paced by technology introduction and market penetration considerations, but represents the *maximum potential* nuclear contribution:

- 5% of transportation energy using hydrogen fuel is introduced by 2020, as a modest start, and increased each year as the vehicle fleet ages until,
- 80% of transportation energy using hydrogen fuel is introduced between 2025 and 2040;
- 20% of carbon energy is used for transportation worldwide, based on the IPCC estimates and not displacing all carbon fuel use in currently industrialized nations;
- 80% of new electricity will be produced by either nuclear or renewable energy sources by 2020, based on a synergistic balance between the maximum expectation for renewables portfolios (10-40%) and for competitive nuclear plants (70-40%).

It was assumed that the hydrogen fuel is produced through electrolysis, rather than from steam-methane reforming. In addition, the energy supply for the electrolysis was assumed to come from a non-GHG emitting source: nuclear power or other sustainables with few CO_2 emissions.

Care is required in understanding how energy consumption is expressed. The IPCC's tabulations use primary energy for the carbonaceous fuels (i.e. without allowance for conversion efficiency) and electrical energy for nuclear and other sustainable fuels[1]. One must allow for the substantial inefficiencies with which, for example, coal is converted to electricity or gasoline to propulsion energy when making substitutions. Fortunately, 40% is a good representation of both the relative efficiencies of internal combustion engines compared to a fuel cell's conversion of electricity to propulsive energy and of coal's conversion to electricity. Since these pathways are dominant in the electricity generation and transportation domains, electricity can reasonably be substituted for carbonaceous fuels using a 2.5 multiplier for the amount of carbonaceous fuel displaced.

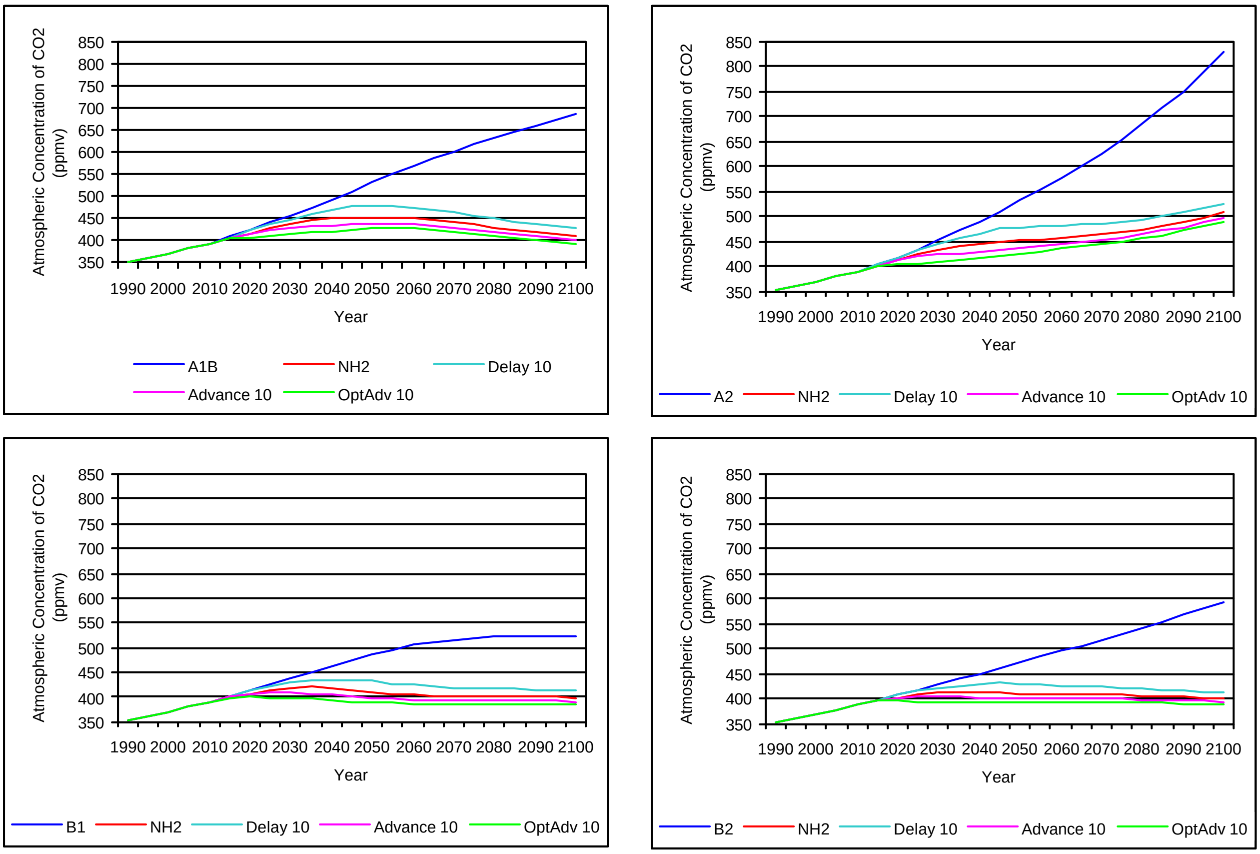

Figure 4: The carbon dioxide atmospheric concentrations: possible-bounding estimates of reduction in expected global CO_2 concentration due to introducing hydrogen fuel and nuclear energy

The results for the relative impacts on atmospheric CO_2 concentration are shown in *Figure 4*, where the effects of a delay or an advance of 10 years in technology introduction are also shown. There is no requirement here for any negative economic impact, or to force the deployment, or to tax carbon. We just have to innovate and use the technology that is at hand – nuclear energy, hydrogen fuel, and large-scale electrolysis.

[1] There is no single, good way of representing energy demand since conversion efficiencies from primary to secondary (electrical) to delivered vary with the technology used.

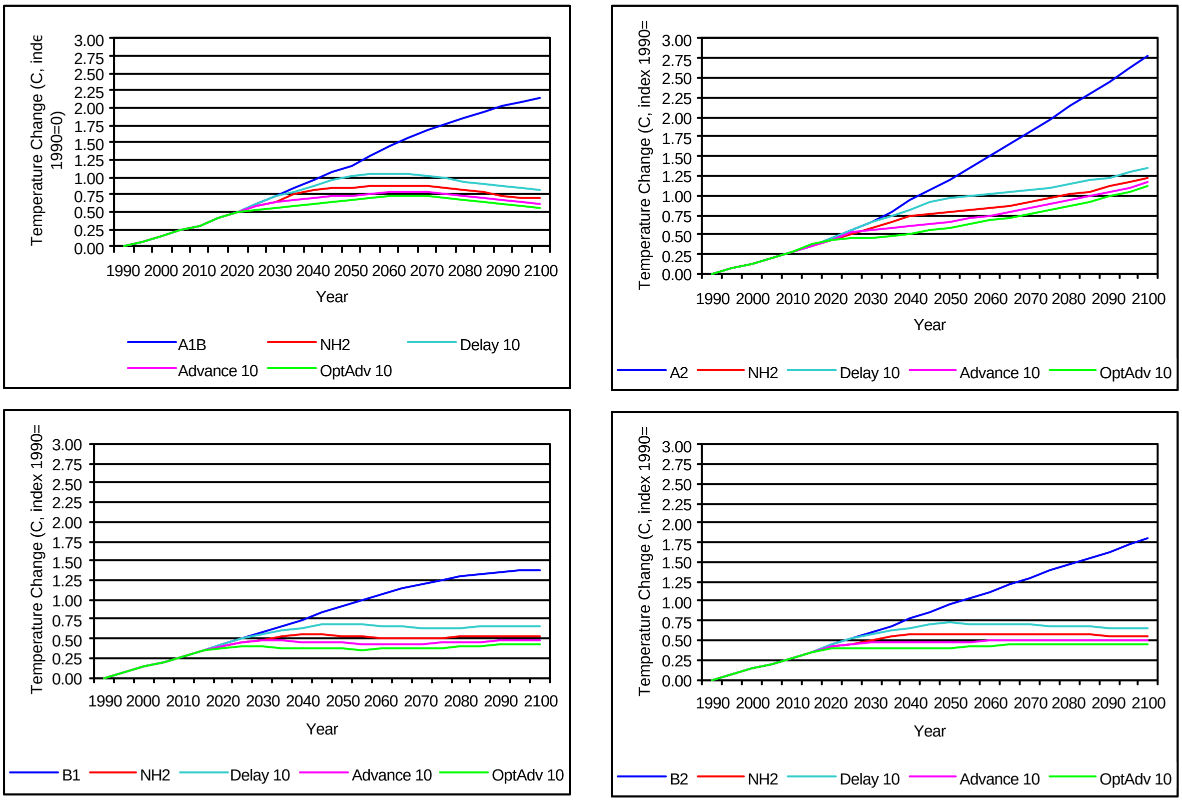

Figure 5: The relative projected temperature changes for the four IPCC marker scenarios and each of the four-modelled variations

With the additional nuclear deployment, scenario A1B has the atmospheric concentrations of CO_2 rise until close to 2050 when the concentrations start to drop till the end of the century. In scenario A2, the atmospheric concentrations of CO_2 continue to rise until the end of the century, though at a significantly lesser rate than the original IPCC scenario. The CO_2 concentrations in the B1 and B2 scenarios also follow a similar trend as the temperature trends (shown in *Figure* 5). Temperatures rise in the four variations of both scenarios until the middle of the century and then drop for approximately 20 years before levelling out at constant values till the end of the century.

Deep penetration of non-CO_2-emitting electricity into the growing transportation sector is the key difference in our reworkings of the IPCC scenarios. We have assumed that 80% of transportation will move from oil-based energy to fuel-cell/electric between 2025 and 2040. In *Figures 6* and *7*, we show the calculated effects on CO_2 concentrations and global temperatures for the IPCC's B1 scenario along with the NEA/IAEA's BAU-BO (LDNE21) scenario, two scenarios which are initially quite similar in their projected nuclear components, along with our modified 'N+H_2' version of the IPCC's B1 case [7].

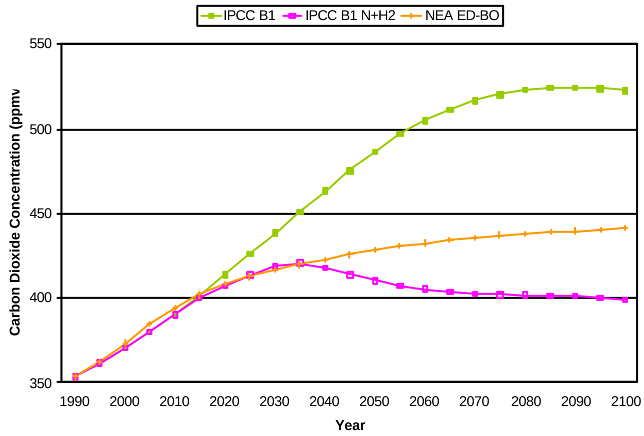

Figure 6: CO_2 concentrations for selected scenarios

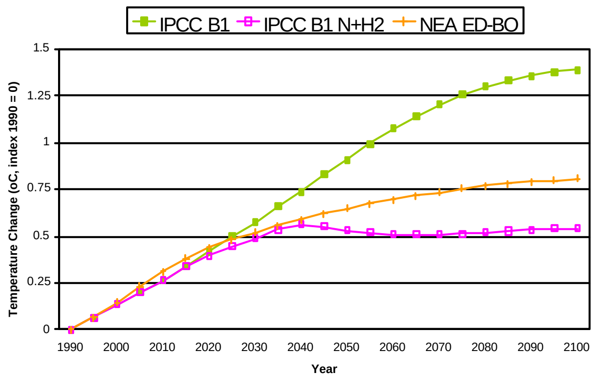

Figure 7: Projected rise in global temperature for selected scenarios

The IPCC's B1 projects a larger growth in total energy demand than the NEA's LDNE21, a difference that is offset in the first third of the 21st Century by larger nuclear substitution for electricity generation of AECL's N+H_2 modification to B1. The subsequent inclusion of the transport sector produces a further sharp deviation downward from the NEA/IAEA projection and a marked beneficial effect. Typically, in reactor numbers, we find that in industrialized nations, a nominal programme of ACRs would stabilize power sector emissions in a country, and a doubling or trebling of that deployment would stabilize and reduce transportation emissions. Worldwide, while meeting the growing energy usage of developing countries, total nuclear deployment would have to grow by an order of magnitude or slightly more.

We can estimate the investment needed in typical nuclear R&D and concept deployment as being less than 1% of potential yearly sales. This investment would be returned commercially, with more than 5000 plants also avoiding over 15 000 million tCO_2 each year. The value of the investment in CO_2 avoidance terms, as evaluated by 'carbon cost curves', values carbon at an equivalent price of <US$5/tC for discount rates of 7-10%. This is a much lower 'price' than *any other non-carbon alternate*, including sequestration, tax incentives for intermittent non-carbon power sources such as windmills, or as might be assessed for marginal efficiency improvements.

Naturally, there are hurdles to jump: international licensing and user requirements, waste disposal agreements, intervener objections, competitor pressures, and sheer manufacturing capacity. But we must face them, define them, solve them, and grow the business: no one said it would be easy to do. The results are worth it. The oil and gas industries will taper off slowly within a growing overall energy market, renewables will prosper, city air will be cleaner, power will be stable in price, waste will be reduced and world oil and gas reserves will be extended. Best of all, world energy use is sustainable, with transition to thorium fuel cycles over the next 10-50 years providing affordable and sustainable fuel for many centuries, with the possibility of fusion power coming forward in the latter half of the 21st century.

Equally important, by following this definite path, a goal, time and thinking space is made available for introducing even more innovations and new technologies – ones that we have not even thought of now.

Conclusions: assuring sustainability

We have considered and quantified the potential impact of new technology on global energy futures, environmental effects and in providing globally sustainable development. The introduction of new nuclear technology, and of switching to hydrogen fuel, has been analysed for a range of future projections made in and by the latest international studies, including those by the UN IPCC and the OECD NEA.

Our new analyses include competitive new nuclear plants (ACRs) and large-scale fuel switching in transportation. On the proposed scale, the use of non-GHG emitting sources can have a profound effect on the reduction of global GHG emissions and subsequently GHG atmospheric concentrations and global temperature rise. Also, the variations indicate that the world will need to make a significant shift away from GHG-emitting fuels just to stabilize the impact of climate change within the next 100 years, in accord with the projections of the UN IPCC. The full nuclear potential has been evaluated and shown to be vital in assuring a sustainable energy and environmental future.

While the relative temperature and GHG changes may – at first glance – look fairly insignificant, the impact of even small changes on a global scale can have profound effects. While some governments argue that the cost of addressing the climate change issue would be too great in the short term, in the long term the cost of delaying decisions to act on the climate change issue are likely to be much more significant. Therefore, nuclear energy, and its synergistic action in deploying other fuels, means that it is no longer an option but must be a vital and immediate contributor to the future.

Acknowledgement

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