The Contributions to Energy and Environmental Sustainability of Nuclear Energy, Windpower and Hydrogen

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Abstract: - The energy sources to meet the World's demand are well known, and recent increases, fluctuations and speculation in oil and gas prices show how dependent the world is on marginally adequate energy resources and reserves. A major switch in fuel and energy sources will undoubtedly impact both our urban and rural landscapes considerably. Yet the need for alternate energy sources, even if just to provide diversity of supply as well as displacement, is clear. The era of relatively cheap energy and stable prices is over.

We have examined deploying increased non-carbon energy sources, including distributed hydrogen production. In our studies of the Intergovernmental Panel on Climate Change's (IPCC) energy-use scenarios, we have assumed that an additional deployment is needed of nuclear and other non-carbon-based electricity by 2040. Because this is end-use energy switching, around 2.5 times as much of carbon-based input would be displaced. Using the IPCC-based global energy scenario analysis tools, we have shown how existing technology can lead to substantially reduced CO_2 emissions and declining carbon energy demand. Using non-carbon based (from nuclear and wind) hydrogen for up to some 80% of the world's automobile usage by 2040, and also supplying some 80% of the projected electric energy growth worldwide by 2030 from non-carbon sources would substantially dampen potential climate change. For most energy demand scenarios, this non-carbon substitution stops the acceleration of CO_2 build-up or even slows the rate of build-up and greatly improves the likelihood of limiting CO_2 to double the pre-industrial level.

Hydrogen is the accepted front-runner for a transportation fuel, producing minimal greenhouse gas (GHG) emissions. We have shown that electrolysis can be an attractive small-scale production process close to the point of fuel distribution and that large-scale, centralized production can meet the US DOE's target cost of $2000/tonne. This remains true when wind-generated electricity is added to a nuclear base.

We have examined the effect of low-cost storage on costs of centralized hydrogen production with and without wind-generated electricity added to a nuclear base, using real hourly data for purchase prices for electricity. The economics of co-producing electricity and hydrogen is shown to be enhanced and that co-production is more profitable than selling electricity alone. As a recent study by the Irish grid operator shows, intermittency and variability of wind-generated electricity limit its deployment to a small fraction of a grid's total electricity supply. Similarly, wind's low availability makes it uneconomic to dedicate an electrolysis installation to produce hydrogen by electrolysis. However, with a hydrogen production system able to accept extra current when the wind blows and with low-cost underground storage, high-quality wind sources are shown to be capable of adding hydrogen production to an electrolysis installation primarily supplied by nuclear electricity.

Real hourly data for wind-turbine output for a mid-latitude location has been included in our NuWind© model. The favourable economics for electrolytic hydrogen production apply to central generation at a location where a nuclear reactor, a good wind site, and hydrogen storage can be co-located. Because the production is large scale, hydrogen transmission by pipeline to market should be feasible and impacts the distribution systems that would be planned and installed in both urban and rural settings in the model society.

Key-Words: - Contributions, Energy, Environmental, Sustainability, Windpower, Hydrogen

1 Introduction: The Changing Energy Landscape

We do not have to enter the debate over whether climate change is real, whether it is worsening, or whether combustion of carbon fuels and CO_2 emissions are the cause. The fact is the human impacts of energy use on the environment has now reached global political notice, and the difficult and far-reaching requirements to curb emissions are now becoming more focused and urgent. The potential global and local urban and rural impact on energy use, production, fuel substitution, electricity requirements, and transportation means all require diligent study and thought.

The time for real technical, social and political action is now. Recognition of the seriously adverse effects of CO_2 accumulation in the Planet's atmosphere and oceans must lead to a major reduction and eventual phase-out of carbon-based fuels for transportation. In the ongoing absence of electric battery with an acceptably low weight to energy ratio, hydrogen is widely projected to be the transportation fuel of the 21st Century – the so-called "Hydrogen Economy". Hydrogen, however, has to be produced in ways that do not release significant amounts of CO_2 in the process. This paper examines the role and competitiveness of intermittent, large-scale means of introducing and substituting low-cost hydrogen.

To set the scale, timelines and magnitudes, we have studied a range encompassing the major different scenarios for the World's energy demand. These scenarios have been analysed examined using the latest version of the climate-modelling MAGICC/SCENGEN software (Version 4.1). We have updated and predicted the impacts of compare scenarios with either the projected mixes of energy sources or with 80% substitution with CO_2-free sources (likely predominantly nuclear and wind power) for coal-fired electricity (by 2030) and for transportation fuel (by 2040). For transportation, hydrogen produced by CO_2-free sources would replace gasoline and diesel fuels. To bracket the range of social model futures, we can simply focus on two scenarios from the Intergovernmental Panel on Climate Change (IPCC), one (A1FI) that is energy-profligate and one (B2) that is energy-conserving.

The results show that, interestingly, projected average global temperatures for all scenarios are fairly similar until about 2030 (a further rise beyond the 1990 average temperature of +0.75 K ± 0.1) regardless of energy usage and its sources. However, by 2050, the different IPCC scenarios are diverging markedly. Understandably, A1FI is projected to have noticeably stronger effects than B2 on average global temperatures (about 0.4 K more in 2050) but the effect is much stronger over land at mid and high latitudes (up to almost 1 deg K more). What is most striking is that the substitution of CO_2-free sources gives projected average temperature rises in 2050 over key land areas (North America and China) that are very similar for the two energy-use scenarios – typically 1 to 1.5 K. In contrast, projected rises with the unaltered cases are markedly different being about 2.5 K for A1FI and 1.5 to 2 K for B2. The projected changes in rainfall distribution show similar patterns, especially for the expected increases in higher latitudes.

With the assumption of no additional policies for substitution of energy sources beyond 2040, temperature divergence between the two scenarios of relative energy profligacy or conservation grows in the latter half of the 21st Century, even with substitution. However, the proposed early substitution of nuclear energy, wind power and hydrogen appears to buy time and is not crucially dependent on severe, near-term curtailment of energy use. Near-term curtailment is too difficult to implement: it presents particular difficulty at a time of rapid industrialization of major emerging economies. Of course, proportionally larger deployments of CO_2-free energy sources are needed for more energy-intensive scenarios.

While electrolysis is a long-established process for the production of hydrogen, it has been almost totally eclipsed by Steam Methane Reforming (SMR) technology for large-scale production. This is largely attributable to the remarkably low price of natural gas that prevailed until the end of the 20th Century [1]. Even at the average price of 5 $[1]/GJ that existed in the first few years of this century, electricity had to be priced at 1.8 ¢/kW.h to give electrolysis comparable energy-input costs to SMRs. Strongly preferred by its low cost for energy, extensive experience with the SMR route to hydrogen drove its capital cost down to levels that are only now being matched by electrolysis.

However, at least in North America, the economic advantage of SMRs may soon come to an end for two major reasons: a rising natural gas price and the cost of CO_2 sequestration. With insufficient new sources of natural gas in North America, the delivered price of natural gas has continued to rise and will likely settle around the recent level of almost 9 $/GJ (American commercial customers paid an average of 8.8 $/GJ in 2004), a level at which imported liquid natural gas also becomes economic. All other factors being equal, the comparable cost of electricity input to electrolysis is about 3 ¢/kW.h since it takes ~50 kWh to make one kilogram of hydrogen. (Note that conversion efficiency is secondary to a low electricity price in the overall hydrogen manufacturing cost.)

If hydrogen is consumed in a fuel cell, the efficiency of conversion into motive power is likely to be at least one-third better than a hybrid internal combustion engine (ICE) vehicle. This will approximately offset the energy consumed by the SMR process. Hence there is no advantage to following the hydrogen-fuel cell route unless the CO_2 produced by SMRs is sequestered – recognizing, of course, that sequestration from a stationary SMR is technically feasible while there is no practicable way of sequestering CO_2 produced by a free-ranging vehicle. For hydrogen produced by an SMR, the need to include CO_2 sequestration is inescapable.

The prices quoted for permits in carbon trading in Europe in 2005 have been rising and approached 35 $/tonne CO_2 in early 2005 July. However, this is still considerably short of the cost of actual sequestration: pressure-swing absorption (PSA) SMR is estimated to have capture costs of around 70 $/tonne CO_2 [2]. (Arguably – at least in the near future – the potential benefit of injecting CO_2 to enhance oil production could cover the cost of CO_2 pipeline transportation.) The 70 $/tonne level is equivalent to adding 3.50 $/GJ to the price of natural gas[2].

Ideally though, electrolytic hydrogen should be better than the cheaper of two expensive routes to hydrogen production. As this paper shows, intermittent, large-scale electrolysis has the potential to lead to hydrogen at very affordable prices. As well as utilizing variable electricity prices, variable electricity supply can also be considered and we examine in detail the possibility of blending electricity from nuclear with electricity from wind turbines, as included in our NuWind© concept.

2 Changing Future Energy Markets and the Concept of Intermittent Hydrogen

Unlike hydrogen, electricity is not storable. As a consequence, where free markets operate, the price of electricity bought by electricity grids varies hugely. The two Canadian jurisdictions where free-market pricing of electricity supply operates are Ontario and Alberta. The grids' market buying prices are set hourly on the previous day and are openly available [3,4]. Fig.1 shows the distribution of typical buying prices for a typical year. For roughly half the hours in the year, producers can sell electricity

[1] All dollars are expressed as $U.S. (2005) currency

[2] Other carbon fuel sources can also be used to produce hydrogen. Coal, bitumen or petroleum coke can all be gasified but these co-produce around twice as much CO_2 per unit of hydrogen. So while the fuel costs would be lower, sequestration would double and capital costs would also be higher. Using pure oxygen rather than air would lower the cost of CO_2 sequestration but adds about 20 $/tonne CO_2.

at above the production cost, sometimes with very large profit. Provided the costs of electrolysis equipment and of hydrogen storage are low enough, a producer could produce electrolytic hydrogen at other times. Unlike SMRs, electrolysis equipment can rapidly be switched on and off. For a modest premium, the electrolysis equipment can be adapted to allow the rate of production of electrolytic hydrogen to be varied considerably by varying cell current density. There is a small voltage premium to higher current density but that can be easily offset by low electricity value.

In previous papers [5], we have shown that small-scale, distributed production of electrolytic hydrogen could be competitive with SMR technology in the emerging phase of a Hydrogen Economy. We have also examined the practicality of large-scale hydrogen production with short-term storage where the cost of hydrogen storage (at 400 000 \$/tonne of H_2 capacity, typical of above-ground storage) has been a major cost factor [6]. Below we consider the economics of locating electricity generation at a site suitable for cavern storage of hydrogen, similar to that used for natural gas. Forsberg [7] has already shown that cavern storage would typically cost 800 to 1600 \$/tonne H_2. (This is not a large component of the hydrogen cost and so we have assumed a more conservative 2000 \$/tonne to allow for situations of less-favourable geology.) To date, salt cavern storage of hydrogen – which is the most obvious approach to tight, non-contaminating storage – has been unusual, but ICI on Teeside, UK, has used it successfully for almost 30 years. It is a demonstrated technology [8].

The capacity factor of wind-generated electricity is usually strongly seasonal in character (often varying by a factor of three on a monthly basis between the best winter month and the worst summer month). So low-cost storage has a particular advantage to accommodating wind-generated electricity since it opens up the possibility of seasonal storage.

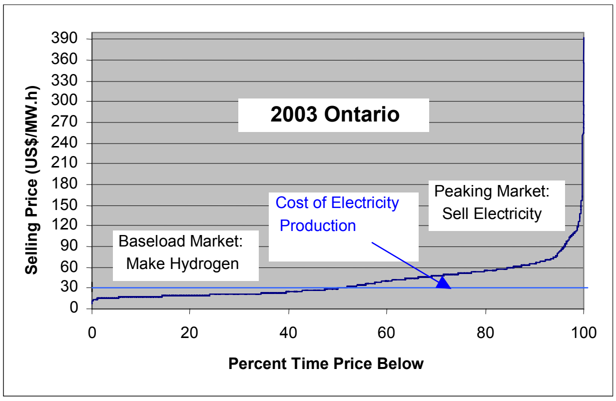

Fig.1: Distribution of Hourly Selling Price to Ontario Grid in 2003

3 The Excessive Cost of Hydrogen from Wind Alone

The high cost of hydrogen from electrolysis based on wind alone is evident from looking at an installation that relied only on wind (of the character considered here). If all of the electricity were converted to hydrogen, the electricity cost is unaltered at 1663 \$/t H_2. However, barely one-third of the hydrogen output is produced as a result of the low average availability of the wind so the cell cost rises from 379 \$/t H_2 to 1277 \$/t (including the 10% premium for variable-current cells). The storage requirement is calculated to be equivalent to 1160 h of full capacity and so that cost element rises to 53 \$/t H_2. The total is almost 3000 \$/t H_2.

This is an approximate estimate since it ignores the complexity of operating the cells over the full range range of available current. It is possible that there is some scope for avoiding periods of peak electricity prices but the cost of electrolysis equipment is higher with partial conversions to hydrogen and it seems unlikely that the benefit of lower electricity cost would offset the amplified electrolysis cost.

Wind alone has no prospect of a cost approaching the US DOE's 2000 \$/t H_2 target.

4 Synergistically Solving the Problems with Wind and Nuclear Together

Within the uncertainties over actual deployment of a technology, wind turbines and nuclear fission offer electrical energy at very similar costs – around 3 US¢.kW.h. And both technologies must address issues of timing. Nuclear, having a preponderance of fixed costs, is best operated at near 100% capacity. Wind, being at the mercy of the weather and climate, has to accommodate swings in availability on all times scales up to and including seasonal.

Wind power generation, by its very nature, is not easily characterized. As well as fluctuating, the energy available from it depends strongly on average wind speed at any location. In this study, we have used one year's hourly average wind data from an unidentified location in Wales [4] to quantify what a 1.5 MW GE wind turbine could deliver for locations with similar variability and wind speeds of either 8.37 (Type G) or 7.37 (Type H)[3] m/s. The assumed average wind speed has a strong influence on the total output of wind turbines and would be expected to yield 41.5 and 32.6% of nameplate capacity for those two speeds, respectively. As such, these two "types" can be considered to be "superior" and "typical" of wind's expected performance at mid to higher latitudes (UK House Of Lords (2004) [5]). Table 1 shows the estimated variation in electricity output for the wind data for the two average wind speeds.

A problem with seasonal variation in the potential supply is clearly evident in the Table 1 data. July contains only one-third of the energy output of December. This will not occur in all locations but it is likely to be fairly typical of mid-latitude locations, i.e. where much of the world's demand for energy is located.

Hydrogen production by water electrolysis (at either low or high temperatures) is one way that has been mooted to smooth fluctuations in both supply and demand. To assess the practicality of this conversion, we need to consider the economics of converting electricity to hydrogen by electrolysis in a model society.

5 Optimal Cost of Hydrogen with NuWind, Combining Nuclear Plus Wind

The most important factor in the economics of generating electricity from wind is the average output divided by the nameplate capacity. The proponents of wind usually claim capacity factors of 30 to 35% though actual large-scale deployments have almost always fallen far short of this target. However, as experience with wind grows and turbines become larger (operating in a stronger wind fields higher above the surface), better values should occur. Nonetheless, seasonality remains a major element influencing the capacity factor and of great importance in assessing whether wind can produce reliable and useful energy flows. For realism, a set of hourly wind data from the US Renewable Energy Agency's HOMER data base [9] was added to the NuWind© spreadsheets. By assuming an average wind speed of 7.37 m/s for this data set, an average capacity factor of 32.6% was derived.

The possibility of producing hydrogen from a mix of nuclear- and wind-generated electricity depends crucially on the ability of the electrolysis cells to accept additional current. This extended capacity of the cells must exceed the electrical production capacity of the nuclear component. As with nuclear without wind, hydrogen will be produced only when the value of electricity falls below a selected threshold but now at least some of the wind-produced electricity will also be converted into hydrogen. Figures 5 and 6 show costs of hydrogen production for nuclear only and the *incremental* costs of additional hydrogen produce by wind inputs averaging between 5 and 20% of the nuclear installation. (Because of wind's average capacity factor, the

[3] Types G and H designations are used to distinguish the results in the tables in the Appendix.

nameplate capacity of the wind installation will range beyond 60% of the nuclear installation.)

Because both the data for value of electricity and for wind generation are real and far from smooth functions, the calculated costs are also far from smooth. For Alberta in 2003, with its higher average electricity value, incremental production of hydrogen from wind would have been almost as attractively affordable as the base production from nuclear over the range of 30 to 90% conversion. For Ontario in 2004, where the average electricity value was lower, both the hydrogen produced from nuclear and the incremental hydrogen from wind tend to be more expensive than in Alberta. Still, the additional production of hydrogen from wind meets the DOE target for conversions above 50% and the incremental cost remains fairly close to that from nuclear alone.

6 Implications for Rural and Urban Planning in a Model Society

Undisputably, we need to dampen both new and existing energy demand by cutting waste and by use of more energy-efficient equipment. But we also need to substitute non-emitting technologies for existing energy generation – because we can only stop the rise in CO_2 atmospheric concentration if total emissions drop by 60% from current levels. It is how we meet the new energy expansion in the developing world that will largely determine the planet's future. The solution must also encompass moving transportation off oil. Currently, the most obvious way to address the carbon-free energy needs of transportation is by electrification, and by producing hydrogen as fuel (IPHE www.iphe.org), on top of any CAFÉ, hybrid vehicle and efficiency measures that are possible.

In our model society, the good news is that energy expansion in the developing countries is in any case needed – it is not an unexpected economic burden but a component of their climb to equitable living standards. Providing for developing countries' fair and adequate energy supply is not the issue. The issue is how humans generate this energy. Settling on non-CO_2-emitting technologies should be the most urgent issue for humanity and its governments. We have, immediately, to launch a technically realistic program of deploying CO_2-free technologies that are proven and cost-effective. The only proven technology currently able to provide a backbone for carbon replacement is nuclear fission. Alternatives (such as using carbon with effective methods for long-term CO_2 sequestration) may emerge and some renewable technologies can likely play a significant supporting role.

Despite large-scale wind deployment being envisaged in many future energy scenarios, primarily for electricity production, the Irish study shows that this may not be effective for emissions reduction because of the alternate sources required to "back up' for non-windy days. Areas of high wind capacity factor are also generally not where people wish to live, are in regions of natural beauty, or are off-shore, leading to multiple environmental debates, discussions and costs.

Our suggested approach, of a hybrid and synergistic energy system, which mixes base electricity generation and fluctuating wind sources, allows the making of hydrogen as a "fuel". This will impact the needed energy distribution system, and planning for an electric grid that allows for distributed production. In addition, both large and small reactors will be needed matched to the demand, and it can be estimated that the switching of 80% of transportation to hydrogen fuels more than doubles the nuclear requirement.

Conversion of the private vehicle fleet to hydrogen fuel is the largest challenge in deploying hydrogen in the transportation sector. However, even with this challenge, there are no major unresolved obstacles. Electricity allows hydrogen to be generated by electrolysis wherever it is required. On-board storage of the fuel can be as compressed gas at 70 MPa and fuel cells offer superior energy conversion efficiency. Even using typical retail prices for electricity, hydrogen fuel costs are reasonable. Increasing deployment of nuclear plants with high capacity factors (and of wind and solar power with their variable patterns of availability) will lead to power generation capacity that exceeds the instantaneous demand. So, as hydrogen's deployment as a fuel grows, the use of low-cost, off-peak electricity in centralized low-cost electrolysis cells should further reduce the cost of hydrogen generation.

7 The Advantages of Nuclear Fission

Intuitively, many people recoil from (any) dependency on nuclear fission, real or imagined, but it has major advantages beyond its widespread, existing use and negligible CO_2-emissions.

First, because it is a dense energy source containing one million times more energy than the same weight of carbon, management of the small amounts of waste is highly tractable. The land use and footprint is extremely small per unit of energy output.

Second, the resource base of uranium and thorium is so large as to be virtually inexhaustible, particularly if we move to sustainable optimized fuel cycles .The utilization of existing and known mining sites are extremely small compared to those utilized for coal and other mineral extraction, and the rural impact is already known.

Thirdly, the much-trumpeted "waste" issue is actually technically solved by geologic disposal, and can be properly handled again by proper urban and rural planning. Communities have actually volunteered to host such sites, and it may even assist the development of remote areas.

8 Local Gains and Global Trends: Implementation

For abatement of local pollution to negligible levels, fuel cells consuming H_2 are virtually equivalent to electric vehicles and with far less encumbrance in space and weight than batteries. Many proponents of fuel cells have assumed that their H_2 fuel can be produced on-board by reforming of fuels such as gasoline, natural gas, ethanol and methanol. However, while this would improve local air quality, this approach offers little reduction in overall GHG emissions. Indeed, if methanol were used as the fuel, overall CO_2 emissions could even be exacerbated by emissions associated with reforming of natural gas to produce methanol in the first place unless the CO_2 were sequestrated. While the overall fuel efficiency with on-board reforming is likely superior to that of a vehicle with a conventional ICE, the existing technology of vehicles powered by an ICE-battery hybrid offer comparable or lower GHG emissions. The conclusion of the earlier work is that GHG abatement requires H_2 as the on-board fuel as well as its production in ways that do not emit GHGs.

Some transport applications are easier to convert to H_2 than others. In an earlier paper, "The Case for Rail Conversion to Hydrogen-Powered Fuel Cells in the Context of CO_2 Emission Abatement", the attractions of converting rail transportation from diesel to fuel cells powered by liquid hydrogen (LH_2) were presented. This indirect approach to electrification appears to be far cheaper than direct electrification with its huge initial capital requirement unless the traffic density is very high. Installation is also disruptive to existing traffic. Marine and air transport showed almost as favourable characteristics. On the other hand, road commercial traffic (trucks and buses) was judged to have less favourable characteristics and private vehicles were far the least favoured. However, road transport is the predominant transportation mode and it must be substantially converted to non-carbon fuel for any effective CO_2-reduction strategy. Commercial vehicles would be most easily converted but, within the road sector, private vehicles are a large enough component that they must also be a part of the conversion to attain sufficient substitution with H_2 in the transportation sector.

A typical (Canadian) car powered by an ICE covers 21 000 km in a year with a fuel efficiency of 11.3 L/km (20.8 mile/gal (US). At recent fuel costs of ~80 c/L, the annual fuel cost is about $1900. Of course, a large component of this fuel cost is taxes. However, the gasoline-based norm provides a benchmark for car owners' current level of fuel costs. On the assumption that the ICE's efficiency is 15%, 3185 kW.h is actually expended as propulsive energy. So a fuel cell with 50% efficiency will require 6370 kW.h of hydrogen fuel or 161 kg of H_2. Since 1 kg H_2 requires about 50 kW.h of electricity to produce, and this electricity typically costs about 4 c/kW.h, the fuel costs (without taxes!) are only near C$320. For any nation, even adjusting for gas taxation at 200%, there are large fuelling cost savings of order 100 to 300 %.

There is a perceived issue for fuelling autos because it must pre-suppose a way of getting H_2 to the vehicle's tank, usually raising the spectre of a "new" H_2-distributing infrastructure. Within the constraints of using off-peak power and plugging into standard North American 117-volt power outlets, home fuelling could, in theory at least, supply most of the H_2 needs for the average (Canadian) vehicle. Those driving consistently greater distances could easily install multiple fuelling systems without constraint from the typical household's 200-amp capacity with the same fuel economics. For occasions with peaks of usage or extended trips remote from the home fuelling base, the same technology can be just as easily set up at service stations. After the demand for H_2 has grown enough to justify a fuelling network, any acceptable, cheaper ways to produce and distribute H_2 can easily be grafted on. The beauty of this approach – which is unique to H_2 among alternative fuels – is that infrastructure can largely grow with fuel usage rather than requiring a large initial investment in fuel distribution before vehicles can be deployed. Although hydrogen was widely distributed as around a 50% component of town gas until about 50 years ago, public caution toward H_2 could, at least initially, constrain the adoption of home fuel production.

9 Energy Demand and Use: Globally and Locally

Comparing the American pattern with data for the entire World, usage patterns appear broadly similar other than the American generation of electricity relies slightly more on carbon-based fuels for electricity generation (70% vs 63% for the World). The USA consumes 25% of the World's energy today. Hence one can get a reasonable first approximation for the World by multiplying American figures by a factor of four to maintain the status quo of energy usage. Applied worldwide to a static level of end-use energy, this pattern would lead to a reduction in carbon-based fuels of about 190 EJ/a. This would be delivered by about 2700 GW of non-carbon-based electrical generating capacity producing 76 EJ/a of electrical power.

Approximately, the pattern of energy substitution discussed for North America would cut carbon-based fuel use worldwide by 4×10^9 tonnes per annum and CO_2 emissions by 12×10^9 tonnes per annum. Given that the atmosphere's total mass is 5.2×10^{15} tonnes and that about 50% of the CO_2 emitted to the atmosphere remains there – the balance being absorbed largely in the oceans – the rate of increase of CO_2 in the global atmosphere would be reduced by about 0.75 ppm/a (volume basis).

This maintenance of the status quo in World energy consumption would deploy the expanded deployment of nuclear power in the IPCC's B1 scenario. However, total World energy usage is only expected to remain constant in the developed world. In the IPCC's B1 Scenario, a large rise in energy use in the developing countries raises total World energy consumption from 368 to ~800 EJ/a in 2040. As the IPCC scenario recognizes, it is not legitimate simply to project the existing World pattern forward to the middle of the 21st Century.

10 Conclusions

Massive deployment of CO_2-free technology is certainly within global society's reach but the program needs to be technically and economically coherent. Future substitution of hydrogen for carbon fuels also seems feasible, and most probably essential. This would require massive non-carbon production of hydrogen.

This paper looks at ways in which wind – currently the most promising of the renewable technologies – could be blended effectively with nuclear fission in a very complementary way. This would offer the opportunity to rethink our future energy use, electricity production and transportation fuels as they relate to sustainable development, and hence impact our rural and urban societies.

This present study and model refutes common misconceptions concerning the production of hydrogen by electrolysis and renewable sources alone:

- low-cost electricity is not a prerequisite for electrolytic hydrogen production; quite the contrary:
- the economics of hydrogen production are *improved* with a higher average value for electricity;
- the concept of smoothing the fluctuations of wind-generated electricity by converting it alone into hydrogen by electrolysis is economically very weak.

Three expected trends of future energy supplies appear to combine auspiciously:

(1) the demand for hydrogen for CO_2-free transportation will expand to justify large-scale hydrogen production in a model society;

(2) low-cost Generation III+ nuclear power can profitably supply peak demands of grids for electricity and convert off-peak power into hydrogen for less than the US DOE's target production cost of 2000 \$/t H_2; and

(3) a substantial component of electricity by wind generation – assuming the generating cost for wind to be comparable to that for nuclear – can be added to the nuclear base and the effects of wind's variability can largely be absorbed.

Note that expansion of the proportion of base-loaded nuclear power in electricity grids will tend to widen the spread between the value of electricity for peak and off-peak periods. This will tend to reinforce the economic attractiveness of this approach to hydrogen production, and enhance the concept's global competitiveness..

No technical obstacles are evident that would impede implementation of the strategy outlined in this paper.

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