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Towards A New World:
The convenient contributions of nuclear energy to a sustainable future

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Abstract

Over the last few years, there has been growing concern about the sustainability of the Planet as a result of increasing energy use. The major issues are: increased energy prices in the world markets; growing energy demand in emerging economies; security and stability of oil and gas supply; potentially adverse climate change due to carbon-based emissions; and the need to deploy economic, sustainable and reliable alternatives. Largely undefined “wedges” of alternate energy technologies are claimed to be needed.

In light of these major difficulties, there is renewed interest and need for a greater role for nuclear energy as a safe, sustainable and economic energy contributor. This shift in opinion is being viewed by some as politically “inconvenient”, while it is accepted by others and viewed as being absolutely essential. We have carefully considered, and analyzed what are actually very “convenient” contributions that nuclear energy can and should make to a globally sustainable energy future. These include restraining emissions, providing safe and secure power, operating synergistically with other sources, and being both socially and financially attractive. In this paper we attempt to *quantify* the major contributions:

a) The *reduction in climate change* potential and the global impact of future nuclear energy deployment through emissions reduction, using established analysis tools which permit varying the projected future penetration and scale of nuclear energy.
b) The *minimization of economic costs* and the maximization of global benefits, including investment requirements, carbon price implications, competitive market penetration, and effect of variable daily pricing.
c) The *introduction of fuel switching*, including base-load nuclear energy synergistically enabling both hydrogen production and the introduction of significant wind power.
d) The *management and reduction of waste streams,* utilizing intelligent designs and fuel cycles that optimize fuel resource use and minimize emissions, waste disposal requirements and concerns.
e) The *effectiveness of available technologies* to meet global needs, plus their future strategic development and deployment potential.

We present the steps being taken to realize this increased nuclear contribution, showing the beneficial impacts both in the short- and the long-term. The deployment of a large amount of nuclear energy is shown to be achievable, sensible and supportive of global sustainability, and energy security.

1. Wedging the Planet: fictional energy for the foreseeable Future

In every country of the world future economic growth is tied to energy and electricity use. Our global and individual prosperity, the alleviation of poverty, and the sustainability of the world, depend on having a supply of emissions-free and safely generated energy. Recent price increases in fossil fuels, and the occurrence of supply shortages and electricity blackouts, also emphasize our need for reliable, safe and economic power. In the developing world, notably China and India with their burgeoning energy needs, increased attention is now being paid to sustainable energy paths [1].

Over the last few years, there has been growing concern about the sustainability of the Planet as a result of increasing energy use. The major issues are: increased energy prices in the world markets; growing energy demand in emerging economies; security and stability of oil and gas supply; potentially adverse climate change due to carbon-based emissions; and the need to deploy economic, sustainable and reliable alternatives [2].

In projecting forward, the energy use and emissions reductions technologies that would be needed to restrain both energy demand and greenhouse gas (GHG) releases to atmosphere are largely undefined “wedges” of energy saving and alternate energy technologies. These are assumed to be needed, based on simplified linear introduction with totally unrealistic economic assumptions. Competitive market forces are either assumed to not be operating, or are not considered.

There is broad agreement in most analyses for the next 50-plus years between the current carbon-based energy scenarios and resulting emissions reduction needed. These are similar for the fifteen technology “wedges” examined by Pacala and Socolow [3], the 60% carbon emissions reduction predicted as required by the UK Royal Commission [4], and the estimated scenarios for global stabilization in the UN IPCC temperature and emissions calculations [5]. Over 50 years some 150 $GtCO_2$ have to be avoided somehow, even for modest assumptions of global economic, electricity, emissions and energy growth. These four “E’s” are simply correlated, in that needed Economic growth leads to growth in Energy use, which requires additional Electricity generation, which all then result in more Emissions. But there is also a common unstated shortfall, since the energy and emissions technology targets are fictional, and are actually known to be unattainable. In fact, most of the discussion even turns towards reducing energy use, rather than towards optimizing new sources.

The “inconvenient” and missing truth is the *data*, which are available, provided by world reality, and driven by worldly economics. Large increases in energy efficiency have already happened in the USA. However, this has meant that more energy is available for other uses, so there has been a reduced rate of increase but no decrease in energy usage [6]. The case of California is often sighted as using less “megawatts” [7]. However, in California manufacturing has actually been exported elsewhere, as a shift occurred to a service economy, and both energy supply and manufacturing now come largely from outside the state, particularly including energy and consumer goods from Mexico and Canada. Such simple shifting, also to offshore countries like China and India, of the emissions from energy generation and manufacturing is quaintly called “leakage” in the environmental literature (Kyoto) [8]. Perversely, Mexico must now import gas in order to supply the USA under NAFTA; and Canada pays Californian energy prices. Any energy use reduction or “conservation” by the developed nations simply makes it available on the world market to the developing nations: China and India will eagerly use all the energy that North America and Europe do not use, since what is made available by others just lowers the global demand and price [9, 10]. More hybrid vehicles that use electricity still use more energy, even if each uses less gasoline, as long as demand for vehicles continues to increase [9]. Our cities are ever more inefficient and over crowded, and would take centuries to re-plan or replace (Worldwatch Institute) [11]. There is therefore no global decrease of emissions, population and energy use at this stage of world development.

As to using renewable power, other than hydroelectric, some “inconvenient” data for windmills is now available. In Germany, the giant power company E.On reports that it requires installation of 50,000 MW of wind generation capacity to replace 2000 MW of conventional power, a factor of 25 more, at a price of about ten times conventional power prices [12]. Not surprisingly, they are now looking to invest in power plants outside Germany. In Ireland, careful study showed emissions were predicted to actually grow as more wind power was added [13]. The wind is so variable that more back-up power was needed from other sources, just as it is imported from the power-producing neighbors to massively wind-powered Denmark, whose total GHG emissions are not reduced [14].

For fossil based sources, capturing (sequestering) carbon is important to achieve, and is a real possibility for sources close to mines, caverns, or existing shafts, oil wells, gas fields and stable geology [10]. However, the amounts needed to be sequestered per year are huge (billions of tonnes) and the costs so large that a “magically created” world carbon market is needed with uniform rules, otherwise no one company, country or economy can afford to take the penalty alone [15]. The oxymoron of “clean coal” power generation is achievable at a price that is likely to reduce its competitive position, and hence will not be introduced without subsidies [16].

Which brings in the final “inconvenient” truth: market share for any form of generation is dependent on price advantage [17]. This is particularly true for energy that is globally and internationally traded, and for electricity that is locally competed based on price [18, 19, 20]. Since most of the “alternative” and “renewable” forms of energy are more expensive, their introduction will require government subsidies, taxes, global carbon emission quotas, or legislated or regulated generating portfolio requirements.

We can show this for relevant cases and examples. For solar power, the decrease in cost with learning and market competition is evident [17], but the specific capital cost for solar cells ($/kW installed) is inherently higher by a factor of about ten than for alternatives, despite massive reductions and government subsidies. Indeed the learning curve shows little sign of further reductions, and the minimum possible has likely been reached for conventional or known manufacturing and materials, as is also the case for windpower [17]. Hence, there is a trend to larger and larger installations (wind farms and solar towers) in an attempt to take advantage of economies of scale, thus increasing the environmental footprint and land usage [14]. This increases the local opposition to siting on aesthetic grounds, especially without subsidies [2], a social phenomenon known as “BANANA”, or of building absolutely nothing anywhere.

What all this real world data means is that there is an “inconvenient” and unmentionable “wedge shortfall” of at least 50% in needed energy supply (or about 30% in emissions reduction) in the projections of energy use and CO_2 emission reductions that can be achieved using the simplest possible technology “wedges”. Even the best efficiency efforts will not keep world energy use from increasing by about three times by 2050, and emissions causing atmospheric carbon dioxide from rising to beyond the projected threshold (of 550 ppm), despite deploying as many wedge portfolios of windmills, efficient automobiles, carbon taxes, insulated houses, and solar water heaters as we can. The assumed energy use and emissions reductions are fictional in this future world without considering economic forces.

However, the problems remain as “inconvenient” facts. The need to meet global energy growth is real: the need to make energy available to those who do not have it is an imperative; providing a sustainable rather than short-term solution is required; and the need to do all of the above with minimal environmental impact is also highly desirable.

2. The Nuclear Wedge Advantage

In light of these major difficulties, there is renewed interest in a greater role for nuclear energy as a safe, sustainable and economic energy contributor. Nuclear energy is viewed by some as politically “inconvenient”, by others as a missing and/or rather unattractive option, but by an increasing number of people as an acceptable and absolutely essential component of the global energy mix. The need to optimize energy use globally in an economically sensible manner is key.

We have carefully considered and analyzed the contributions that nuclear energy can and should make to a globally sustainable energy future. These include restraining emissions, providing safe and secure power, operating synergistically with other sources, and being both socially and financially attractive. The necessary economic factors are explicitly included. In what follows we *quantify* the major contributions:

a) The *reduction in climate change* potential (and global impact) of future nuclear energy deployment through emissions reduction, using established analysis tools, which permit variations in the projected penetration and scale of nuclear energy.
b) The *minimization of economic costs* and the maximization of global benefits, including investment requirements, carbon price implications, competitive market penetration, and effect of variable daily pricing.
c) The *introduction of fuel switching*, including base load nuclear energy synergistically enabling both hydrogen production and the introduction of significant wind power.

d) The *management and reduction of waste streams,* utilizing intelligent designs and fuel cycles that optimize fuel resource use and minimize emissions, waste disposal requirements and concerns.
e) The *utilization of available technologies* to implement these strategies, and their future development and deployment potential.

Nuclear energy has two advantages beyond its widespread, existing use and negligible CO_2-emissions that should be recognized. First, because it is a dense energy source containing one million times more energy than the same weight of carbon, management of the small amount of waste is highly tractable. 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.

Nuclear development is still proceeding apace. Advanced concepts for nuclear reactors are now being studied by the leading international nuclear countries, which address continuous improvement in the key areas of economics, safety, sustainability and non-proliferation [21]. These goals must be achieved whilst also meeting the market needs, minimizing investor risk, and satisfying all regulatory and environmental requirements. The continuing fear and old debate over the proliferation of nuclear weapons should not inhibit the design, development, and deployment of new reactors whose sole purpose, intent and fuel cycle are transparently linked to peaceful energy production.

The closure of the so-called waste issue concerning used nuclear fuel is being addressed by the development of safe and secure intermediate storage followed by long term geologic disposal, both with minimum environmental impact [22, 23].

There is a need for expanded use of renewable energy sources, notably windmills, to supplement other indigenous sources. There is a unique synergism between nuclear and wind energy, which enables wind power to achieve a threshold level where it is sustainable without cost subsidies, despite its low load factors and intermittency. Therefore, a particularly important role for nuclear power in the future will be its links to the hydrogen economy [24]. The future could well be the Hydrogen Age. We show that a major reduction in GHGs worldwide can be obtained by nuclear-electric production of hydrogen, thus alleviating the potential effects of GHGs on future generations.

Hydrogen is becoming the reference fuel for future transportation, and hydrogen may well provide the energy “currency” for electric-drive motor propulsion. A vision has been formulated for hydrogen production from advanced energy sources and nuclear reactors. Fulfillment of this vision will depend on the economics of hydrogen production in 2020 or later, and the fulfillment of the R&D underway internationally. Prior to 2020, hydrogen needs to gain a substantial foothold without incurring excessive costs for the establishment of the distribution network for the new fuel. Provided electricity is produced at costs expected for nuclear reactors of near-term design, electrolysis appears to offer superior economics when the SMR(Steam Methane Reforming)-related costs of distribution and sequestration (or an equivalent emission levy) are included. In the longer-term, high-temperature thermo-chemical processes hold the hope of further developments.

Finally, the full utilization of nuclear resources enables a smooth transition to the global energy future. More than sufficient uranium and thorium resources are available for the next few hundred years (the foreseeable future) if one includes switching from once-through uranium cycles to the reprocessing and reuse of used fuel.

Our global scenario analyses confirm that a considered and thoughtful expansion of carbon-free energy sources is not only needed to meet 50-60% of global energy demand by 2040, but is an achievable “wedge”. This strategy provides a pathway to stabilize atmospheric concentrations of GHGs by using co-production of electricity and process heat and hydrogen as a transportation fuel from wind and nuclear energy. The transition is thereby enabled to a safe, secure, sustainable and sensible energy future.

3. The potential for reduction in climate change

The World’s pattern of energy production today is unarguably not sustainable. Demand for oil, the most convenient and versatile resource, is showing the effects of supply limitations. The known reserves are stated as adequate for 100 years but only at current usage rates, and only at increasing cost. Gas costs have risen substantially with increased global demand and worldwide shipment of LNG will only occur at prices equivalent to those for oil. Demand pressure has already raised the threshold price for economic oil exploitation as, for example, in drilling in increasingly deep ocean waters and in oil sands development. But beyond our rapid consumption of finite resources, our collective emissions of CO_2 to the atmosphere and the oceans are now seen to be undermining the stability of climate and the productivity of our oceans [5]. The effects of CO_2 concentration on planetary climate change and ocean productivity cannot be defined precisely, but accumulating CO_2 is effectively irreversible in the immediate future and the only lever at the disposal of human society is the speed with which we desist and reduce CO_2 emissions. The urgency of switching to CO_2-free energy sources can hardly be exaggerated. While there is no definable threshold of CO_2 build-up beyond which we shall have committed our planetary systems to inexorable severe disruption, apart from the projections of climate models, observations of rising temperatures, melting ice, shifting seasons and falling pH of ocean waters provide ample direct evidence of the havoc already arising from our GHG emissions. Carbon mitigation is a global imperative [3, 4, 25].

The solution may be contained within the problem, which is driven more by new energy demand than replacement of old energy sources. Substitution is a fraction of the main problem, which is really the large inescapable expansion of total energy demand as developing economies climb out of their current energy deprivation.

Many authorative and independent estimates of future growth in energy demand have been made; and the selected timeframes range from the relatively near-term (the next 20 years), e.g., [6, 9, 26, 27], out to the end of the century, e.g., by [5, 28]. All show possible growth in energy demand of between two to seven times today’s use unless remarkable and unprecedented conservation and energy poverty occur. The resulting ecological impacts have been estimated by both governments and environmental organizations [4, 29, 30, 31, 32].

Over the last 40 years, world wealth (measured by GWP in T$) is correlated to energy use (measured in Mtoe). The future projections all assume continued global economic growth (circa 2% per annum global average), increased population, unlimited energy supply, and projected forward energy price estimates. The trends and impacts are clear:

a) future energy needs are *double to seven times* those of today by the middle to end of the 21st Century, largely driven by the developing countries catching up;
b) clear correlations exist between increasing wealth per capita (measured as the GDP or GWP) and increasing energy and electricity use per capita so *electricity use and economic growth are and continue to be coupled, as recently evidenced in China and India*;
c) because projected growth, of both the economies and energy demand, is projected to come largely from carbon-base fuels (oil, gas and coal) there are *large increases in emissions*, notably GHGs, which also increase the potential for future climate change;
d) unless a reduction of about 60% is made in the current level of emissions, the *global CO_2 concentration will continue its upward trajectory far above levels prevailing for at least the last million years and at unprecedented rates* with unknown consequences;
e) continuing the present trends leads to *dramatic potential for ecological changes*, such as low (is)land flooding, arctic ice loss, global precipitation shifts, storm pattern changes, ocean current reversals, species loss and forced migrations, forestation changes, and increased desertification; some of which are already underway
f) large-scale increases in energy demand *cause immense pressures for new energy sources* and for decarbonizing existing energy use;
g) *there is a potential for changes in geopolitical landscapes* caused by shifts in climate and energy needs, and the resulting economic shifts;
h) conventional energy *reserves of oil and gas will decline*, despite new exploration and better technologies for oil recovery, and the use of coal will be restricted by social and environmental forces, leading to new and more expensive discovery and recovery options;
i) insufficient land space and large variability in generating capacity factor *will limit the global extent of wind power* without economic subsidies and back-up power;
j) delaying the introduction of increased nuclear energy and of hydrogen as a fuel will result in potentially *unacceptable and perhaps irreversible consequences* in terms of emission increases and climate shifts.

The United Nations Intergovernmental Panel on Climate Change [5] has developed a series of scenarios on how the world's energy consumption may change over the next century. Of the four main scenarios, scenario B1 envisages the lowest energy requirement. This scenario arises from a rapid migration toward a relatively rich global society but with a lifestyle that broadly reduces demand on resources, including energy. The IPCC, like everyone else, makes no claim to knowing how world energy usage will actually unfold.

Scenarios like B1 offer relatively low energy requirements and relatively equitable distribution of wealth throughout the world. But reducing GHG emissions is a prodigious challenge in even the B1 scenario. Among the IPCC scenarios, B1 is the scenario envisaging the largest percentage dependence on nuclear power. Applied worldwide to an unchanged end-use energy pattern, this implies that a reduction in carbon-based fuels of about 190 EJ/a. could be delivered by about 2700 GW of non-carbon-based electrical generating capacity producing 76 EJ/a of electrical power.

However, total world energy usage is expected to remain constant only in the developed world while growing elsewhere. In the IPCC's scenarios, a large rise in energy use in the developing and newly-industrialized countries, like China, raises total world energy consumption from 368 to ~800 EJ/a in 2040. As the IPCC scenarios recognize, it is not legitimate simply to project the existing world pattern forward to the middle of the 21st Century. (After 2050, IPCC's B1 scenario projects/assumes a decline of energy use by almost 40% in 2100 from the peak). Developing Countries' usage of energy is projected to have increased by 430 EJ/a. While the IPCC's B1 also envisages an increase in the wind, solar, etc., category of 60 EJ/a worldwide by 2040, this is dwarfed by the overall growth and *leaves an overall gap of 370 EJ/a to be supplied from carbon-based sources.*

Clearly there is room for a greater substitution of non-carbon-based fuels in meeting the expansion of energy demand in the developing world. As it stands, the IPCC's scenarios imply that the developing world's expansion would add twice or more as much CO_2 to the atmosphere as is avoided by the aggressive substitution postulated largely for the developed world. This is neither sustainable nor realistic, as energy costs between the two will cause multinational manufacturing and industry to simply migrate to the regions with the lowest energy costs, adding to the problem.

We need to evaluate the impacts and "convenient" solutions offered by nuclear energy technology. For these analyses, which go beyond the IPCC's scenarios, we have assigned the proposed increase in nuclear deployment to three groupings and examined their cumulative effect. The large assumed contribution from renewables (largely wind power) is *unaltered* and not substituted.

The first component of the increase (designated "N") has been attributed to replacing carbon-based electricity generation within the current pattern of electricity production with nuclear, deployed between 2010 and 2025.

The second component of the increase (designated "H_2") requires deployment of new transport technology and so is assumed to be deployed later between 2025 and 2040, likely overlapping since off-peak capacity from "N" fits well with "H_2" demand as we show below.

The third component handles the continued increased demand for energy from the developing world (designated "E") and is introduced uniformly through the 2020 to 2040 period.

The first two components are assumed to be in proportion to the current distribution of North American usage. The third component represents a vigorous displacement of carbon-based energy sources needed in the developing world. Typical global patterns have been derived [33] to illustrate the significant impact on potential climate change for the IPCC scenarios, and one is illustrated in Figure 1 below. Whether or not these patterns are followed or correct in detail is not important; what are important are the large predicted changes in both amounts and patterns of global temperature increases.

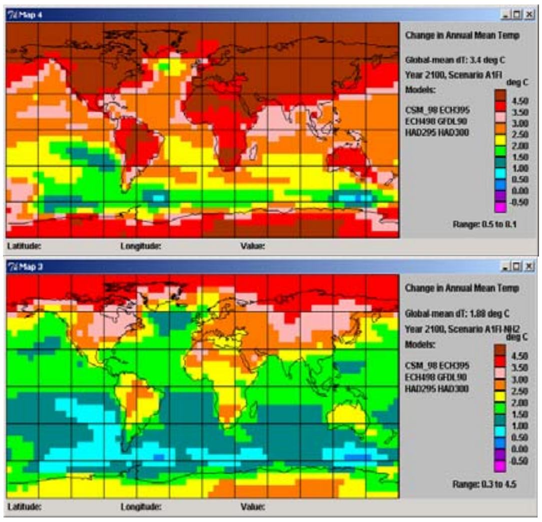

Figure 1: Projected Temperature Rises for Scenarios A1FI and A1FI+N+H2 for 2100

Obviously different amounts, dates and penetration/substitution fractions could be assumed. We take these numbers and dates as indicative of the maximum attainable substitution, thus setting the boundary of what are the total energy needs, and what could be achieved in emissions reduction.

We have also presented calculations [34] of the effects of nuclear and hydrogen substitutions on representative scenarios from the Intergovernmental Panel on Climate Change (IPCC). The expected atmospheric CO_2 concentrations and associated estimates of average temperature rises were presented using Version 2.4 of the MAGICC/SCENGEN software (2000). Whether this code is exact or precise in its climate change forecasts is not an issue here, as we examine the relative impacts of changing energy-use scenarios to determine the sensitivity to change. In the updated modelling presented here, we have used the newer Version 4.1 [35].

Today, electricity from nuclear reactors worldwide produces about 2300 TW.h/a (8 EJ/a) and other non-carbon-fuel sources (predominantly hydro) added 3.0 EJ/a. An expansion by a factor of at least fourteen (14) is required to meet global demand by the year 2100. Recognizing that the IPCC scenarios already require a large expansion of carbon-free energy from other than nuclear power, we assume, quite arbitrarily, that 80% of the needed growth would come from nuclear reactors. For example, this is 62% more than envisaged in the IPCC's B1 scenario. Energy delivery on this scale would require in excess of 4300 GW of power at 90% capacity. If the average reactor size is 1000 MW, that would require a *10-fold increase by 2100 in reactor numbers over the current ~460 reactors operating or under construction worldwide.*

In Figure 1 we show the IPCC projections (using MAGICC/SCENGEN V. 4.1) with our adaptation of the IPCC scenarios with the above substitutions of coal-fired electricity and transportation fuels. Recognizing the IPCC's existing projection of nuclear capacity, the total envisaged increase for non-carbon-based electricity generation, at 90% capacity factor, would require 5400 GW of non-carbon-based generation by 2040.

Thus, with these assumptions, using the IPCC-based global energy scenario analysis tools [35, 36] we have shown that the nuclear and hydrogen technology could together stabilize emissions, reduce projected carbon energy demand and manage climate change.

Using non-carbon based hydrogen (from nuclear and wind) for up to some 80% of the world's automobile usage by 2040, and also by supplying some 80% of the projected electric energy growth worldwide by 2020 from non-carbon sources would reduce potential climate change, and stabilize GHG levels, such as CO_2*, by 2100*.

This is entirely consistent with the well known conclusions [3, 4] that projected a 60 % reduction in carbon fuel usage would be needed to stabilize climate change.

4. The minimization of economic costs and the maximization of global benefits

Recent increases, fluctuations and speculation in oil and gas prices show how dependent the world is on limited energy resources and reserves. The need for alternate energy sources to provide both diversity of supply and displacement of carbon-based sources is clear.

Anti-nuclear dogma can often cause irrational technology choices based solely on flawed beliefs, rather than on facts and social needs. However, history clearly shows that scientific and technical progress ultimately will continue despite any efforts to suppress or ignore it, and no matter how inconvenient the pathway.

Any technology, including nuclear reactors for electricity, energy and hydrogen production, must be sold into competitive power markets where energy price, unit energy cost, capital cost, and project risk and return on investment are all key elements. The lowest *relative* cost competitor sets the benchmark, and this varies by geopolitical as well as geologic region. Thus, piped natural gas is the natural option in Europe, Russia, the Middle East and most of North America which are either producers and/or are close to supplies; coal is the option in China and in selected countries like Poland and Australia, and regions like Virginia and Alberta where soft and hard coal is cheaply available; liquefied natural gas from tanker imports is relevant to major energy importers like Japan, South and North Korea; and hydropower is the obvious alternate in water and river-rich regions, such as Brazil, Norway and Canada if resources are sustainable.

Therefore, for any energy technology, and importantly any new market penetration, the design, construction, and operation *in toto* must be competitive with the cheapest alternative, which will vary by region, country and customer. This is the essential feature that is missing in most analyses suggesting alternate energy sources. Analysis of generating cost data for the 1990s shows that a market price differential for electricity generating cost versus the locally most competitive alternate sets both the market share and the ultimate price [37].

Nuclear energy costs are therefore indirectly coupled to carbon fuel costs via the price at which electricity can be sold into the market. Competitive cost is the necessary condition: the build decision is then heavily based on price coupled with issues related to emissions avoidance and energy security [16, 38, 39]. The most competitive global economic benchmarks at this time may be those published by the OECD and are taken as a guide [1]. Today some 440 reactors are deployed, with an average capacity that contributes about 16% of the world's electricity usage.

The cost, safety and licensability of new plant offerings must all be attractive to the customer. As with any technology, nuclear reactors must emphasize safety in both design and operation. The major improvements in economics, safety characteristics and performance of new reactor designs, like the ACR, retain the proven benefits of the present families of Light Water Reactor (LWR) and Heavy Water Reactor (HWR) nuclear power plants.

Over the timescale from now until 2040, we might expect significant deployment of Generation III+ designs. This spurs a need for plants that are mass-produced with higher efficiency, even lower costs, and an even higher degree of local or national fabrication. Thus, increased modularity, flexible plant size and standardization will be the trends as new customers and operators come into the market. Such energy futures are given or can be implied by future scenarios, such as the [5, 27, 40] "footprint" studies. Compared to any other alternatives, nuclear energy offers the smallest footprint of all, and enables efficient land use without excessive ecological impacts, as shown in Figure 2.

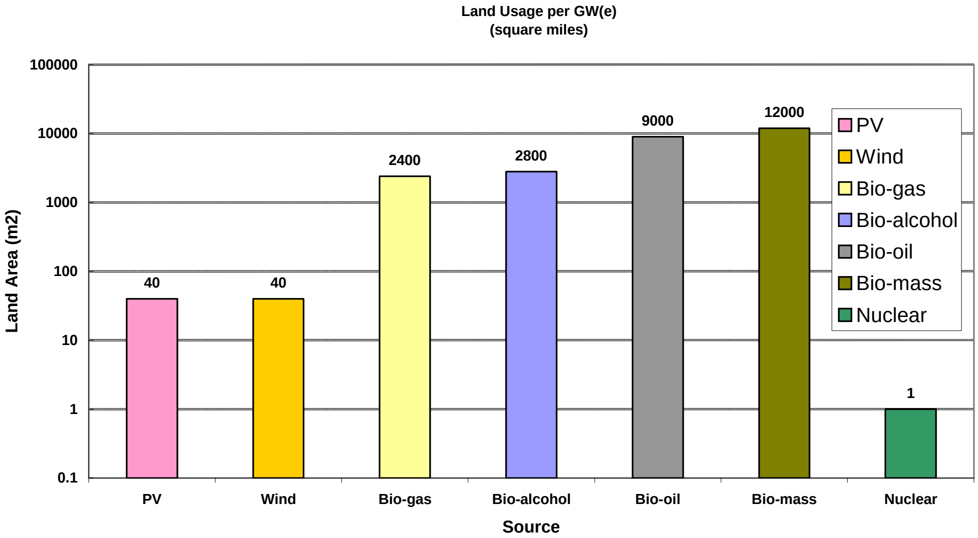

Figure 2: The footprints needed for energy supply

Relative costs are always controversial and are sensitive topics given the business and market implications. The cost of nuclear energy is cheaper than the alternatives, even the alternative of reducing power demand by efficiency improvements. This has been demonstrated in repeated independent studies, most recently by the Ontario Power Authority (OPA) [38], and internationally by the OECD [1]. In these comparisons, nuclear energy generating costs were compared to those of natural gas, coal, wind and hydropower. The assumptions that are made on future gas prices and energy security are crucial, as recent price hikes and international trade tensions also show. Typical low generating costs for new nuclear plants are about \$50[1]/MWh, depending on the details of the financial model assumptions, and are significantly less than that for new plants using natural gas at current market prices**.** With this assumed cost, and the differential versus the options, including the emissions equivalent of sequestered or "zero emissions" coal, the expectation is that nuclear energy could retain an economically viable 60 to 80% market share [15]. This is an investment choice, and has already been shown to be viable in a large industrialized economy, namely France [41] where 80% of electricity is nuclear based, and is also exported to UK, Switzerland, Germany, Italy and others. This is consistent with the model fraction adopted above required to stabilize emissions and climate change potential.

5. The introduction of fuel switching

Electricity and hydrogen form the two complementary energy "currencies" that are essential to sustainable energy use [42]. We can show that adopting base-load nuclear energy synergistically enables both hydrogen production and the introduction of significant wind power. This is not only a totally new concept [36] but is also a new imperative if a significant "wedge" of hydrogen production and renewable wind power is to be introduced, as part of achieving global emissions reduction and unconstrained energy production.

Growth in energy use increases emissions, due to the current practice of using carbon-based fuels This is particularly true for transportation, since this not only accounts for some 20-30% of world energy (using refined oil) use, but also since each auto produces about 5t of GHGs each year using current technology, (or about 21/2t if using a gasoline-electric hybrid). Advances in auto technology and efficiency are to be expected, but the real issue is the increased number of vehicles that are almost inevitably going to be on the roads and highways in developing countries over the next 20 to 50 years. This will overwhelm the needed gains from any efficiency improvements.

The projected increase in emissions is largely driven by increased use of private vehicles, even in China [43]. Climbing the carbon fuel (oil) ladder leads to steadily increased energy imports, increased atmospheric emissions, and rising and/or volatile prices as world demand inexorably increases. This is simply the global economic market at work.

Recognizing the present and future problems of increased oil demand, regional locations of major suppliers, reduced supply amounts, GHG issues (of which transportation is a major part), and rising fuel prices, most major automobile manufacturers are pursuing research on alternate fuels. Mostly hydrogen-based, the automakers, major academic and industrial partners are

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[1] Throughout this paper, US dollars are used.

examining variants of hydrogen combustion (ICEs), hybrid propulsion and electric power using fuel cells and/or batteries.

In addition, users of carbon fuel as natural gas for hydrogen production in the hydrocarbon, petrochemical and plastic industries are seeking alternate sources before high natural gas prices and reduced supply lead to excessive manufacturing costs.

To supply this demand, the general “wedge” answer is vagaries, intentions and promises about increased production from use of non-carbon energy such as renewables (wind and solar); and postulated energy use reduction by efficiency improvement and “conservation”. The need for distributed supply is also stated, since transportation of hydrogen and storage are both costly, with concerns on new “infrastructure” costs and safety (pipelines, tanks, transport and filling stations). However, this concern seems to be somewhat contradictory or inconsistent. Today, large new LNG terminals are being planned to ship huge quantities of gas worldwide, mainly from Russia and the Middle-East suppliers, to supply burgeoning gas demand in Asia and North and South America, and replace depleted offshore supplies in Europe. With some adaptation, the large natural gas pipelines being installed today in Europe from Russia and Norway could potentially be used for hydrogen distribution tomorrow as supplies and price dictate.

We have examined increased deployment of non-carbon energy sources, including distributed hydrogen production. In our studies of the IPCC’s 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, at least 2.5 times as much of carbon-based input would be displaced [44].

To set the needed scale for hydrogen production, a useful “rule of thumb” result can be derived from the typical efficiencies of electrolysis, average current automobile usage, and fuel cell designs. Since 1 kgH_2 is produced by about 50 kW.h of electricity, calculation shows that one (1) GW(e) nuclear reactor at 90% capacity factor can produce ~140,000 t/y hydrogen, which is sufficient to supply ~930,000 (fuel cell) vehicles. Note that, as made clear by Scott’s terminology [42], fuel cells are simply an embedded technology not an energy source.

During the early years of hydrogen’s use as a vehicle fuel, penetration of the market will be small. This favours a transition interval of about 20-30 years for distributed production by local electrolysis powered by the existing electricity distribution system, which avoids the scale-dependent costs of distribution of hydrogen from centralized plants.

The best approach to producing low-cost electrolytic hydrogen is to use nuclear reactors to supply electricity to the grid at times of peak price and demand and to use the electricity to make hydrogen at other times. This is in accord with the concept of distributed energy generation (hydrogen) coupled with efficient centralized production and a diversified portfolio of energy production technologies [45]. Hydrogen production by water electrolysis (at either low or high temperatures) is one way that has been suggested 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.

The other key component is emissions reduction in recovery of the world's immense oil sands deposits. Since oil products will continue to be needed, in any future, there is a real demand that must be met to increase energy security, and stabilize the costs and emissions from the heat and hydrogen needed for extraction and upgrading [46]. Nuclear energy is now seen as a viable alternate contributor to that technology, reducing both projected emissions and natural gas usage [47]. Significant amounts of hydrogen are required for hydrocarbon upgrading and other chemical processes [48]. The Alberta oil sands bitumen deposits comprise one of the largest sources hydrocarbon in the world, and have emerged as the fastest growing, soon to be dominant, source of crude oil in Canada. About 1 M bbl/d are produced now, with increases planned of many times more. The oil industry has made great strides in improving the effectiveness of gathering this resource [49]. The main challenge that remains is the large quantity of energy needed in the process of extracting the oil and upgrading it to commercial levels. For a typical in-situ extraction project, about 18% of the energy content of the oil produced is used up in the extraction process, while a further 5% is used in generating hydrogen to upgrade the bitumen to synthetic crude oil.

Given the large energy requirement for the oil sands extraction process, the opportunity for nuclear reactors to provide an economical, reliable, virtually zero-emission source of energy for the oil sands becomes very important. Over the last few years, developments in oil sands extraction technology, and developments in nuclear technology have converged so that a practical, economical match of nuclear energy to the oil sands is now available. An independent study by CERI [46] compared the economics of nuclear-supplied energy with natural gas. A common economic model was also developed, using parameters such as gas and electricity costs based on recent norms, but without attempting to extrapolate or forecast future prices.

Two different configurations give consistent results indicating about a 10% cost advantage of nuclear technology over natural gas, at a relatively low-end natural gas price assumption. This is true even without any credit for foregone SO_2, NO_x and VOC's emissions, which would be worth 3-4% in cost reduction, while full credit for CO_2 emissions reduction, at $15/tonne, would have a value of about 18%.

To determine the economics of hydrogen production, five variables have been used to optimize total revenue from electricity and hydrogen sales in a mixed nuclear-hydrogen system [36]. The variables were:

1. the main threshold price, P_t, above which electricity would usually be sold to the grid;
2. a higher threshold price, P_u, below which hydrogen would be produced when the reserve of hydrogen in storage was below a set minimum level of storage, S_{min};
3. the size of the electrolysis installation, E; and
4. the size of hydrogen storage in hours of average production, S_{max}.

This procedure was applied over a wide range of operating conditions (applying between 15 and 90% of the electricity produced to production of hydrogen) to produce a function of total revenue for each of the three sets of price data.

The exact mix of hydrogen to electricity production is market and cost dependent, and is in fact dynamically varying, depending on the demand variation of the market electricity price (Figure 3) and the capital cost of hydrogen production and storage. Our NuWind© model [50, 51] has been used to calculate the production costs for hydrogen, using the actual prices of electricity paid by the Alberta Power Pool in 2002 and 2003 and by the Ontario Grid for 2003.

The analysis shows clearly that by optimizing the co-production of hydrogen and electricity (referred to as the H_2/e process) the cost for hydrogen produced using current technology can be produced at a target cost of ~3000 $/t. Because of its lower availability factor, renewable (wind-produced) electricity cannot meet this cost target unaided. The potential market penetration of renewable energy sources, wind and solar, is constrained by their intermittent and unpredictable availability. The proponents of these technologies have often suggested that they could be freed from this limitation by using their electricity to produce hydrogen, creating a way of storing energy on a large-scale.

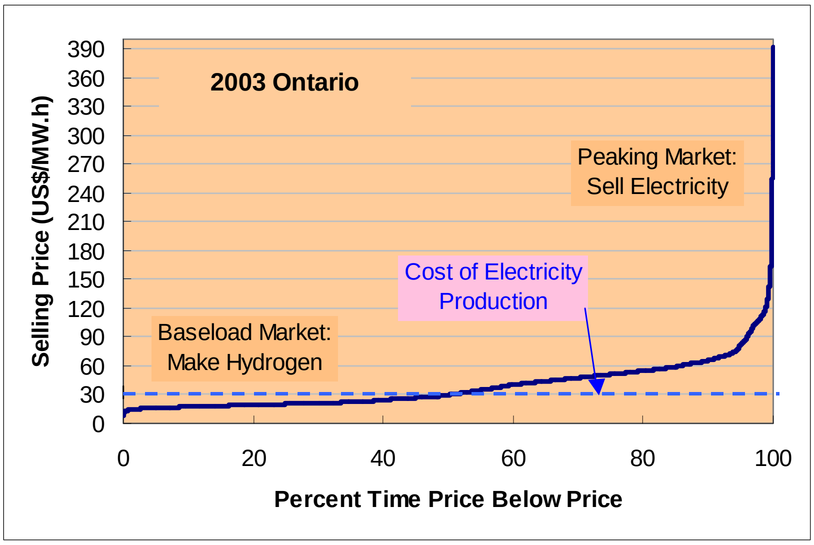

Figure 3: Typical modern electricity market price curve

If wind power availability can reach a capacity factor of ~35%, as predicted for high wind zones in UK and elsewhere [51] an intermittent supplementary current of wind-generated electricity may economically be fed to an electrolytic plant primarily supplied by nuclear power. Wind-generated electricity is generally considered to be more economically advanced than photovoltaic with claimed production costs of 40 $/MW.h and prospects of achieving 30$/MW.h. These costs are, of course, highly dependent on the proportion of power produced relative to nameplate capacity. Figures of 35% capacity factor are claimed to be attainable in favourable locations, though the extensive Danish experience seems to indicate a much lower value. However, even with 35% of nameplate capacity and at 50$/MW.h, the economics of this concept cannot match a baseload generator with the same power cost, and the needed and necessary standby power must also be further added to both the capital requirements, and the transmission and generating prices.

To resolve the conflicting economic and design needs, we solved the problem using our optimization program NuWind© [51]. Because hydrogen production is interruptible, the hydrogen-production cells (and their associated peripherals) have to be oversized to allow recovery after interruptions. As the proportion of electricity assigned to producing hydrogen falls, the absolute level of hydrogen production capacity will be reduced. The optimization, however, constrains the rate of decline so that it does not fall as rapidly as hydrogen production. This rising proportion of spare capacity presumably occurs to provide a sufficient rate of replenishment. However, the important point to appreciate is that the proportion of unused wind capacity is rising.

Electrolysis systems can also have another form of excess capacity, since the cells can operate at higher current densities though with a penalty of increased energy use. This is not usually considered worthwhile, but it could make sense where electricity price varied extensively and created an opportunity to operate the cell with extra current when electricity was cheap. To permit operation with higher currents also requires system modifications to allow extra volume for gas disengagement and additional compressor capacity.

The electrolysis system for these analyses was sized to handle the nuclear output at their nominal current density and wind-generating capacity was added with the constraint that the cells could not operate above their maximum current density. The ratio of wind to nuclear capacity was not constrained but was left as a variable for optimization. The installed cost of the electrolysis system was increased by ~10% to allow operation up to this higher current limit. Wind availability is site-specific and so our generalized analysis treated it in a very simplified manner. An overall capacity factor of 35% was assumed and the distribution of electricity production derived from actual wind generation data in a high wind speed area.

In NuWind© the variables are optimized to give the lowest possible cost for electrolytic electricity consistent with never running out of hydrogen. The NuWind© model accommodates wind as a supplementary source of electricity, where the proportion of hydrogen production will continue to be a specified percentage of the total. So, for example, a wind installation of 35% of the nuclear capacity with the lesser average wind speed would add an average of ~11% to the total power production so the model is required to produce ~11% more hydrogen. Hence storage capacity (and its cost) is proportionately increased. Rather than attempt to optimize the ratio of additional wind to the nuclear base, it is examined over a range of values up to 45% of the nuclear installation.

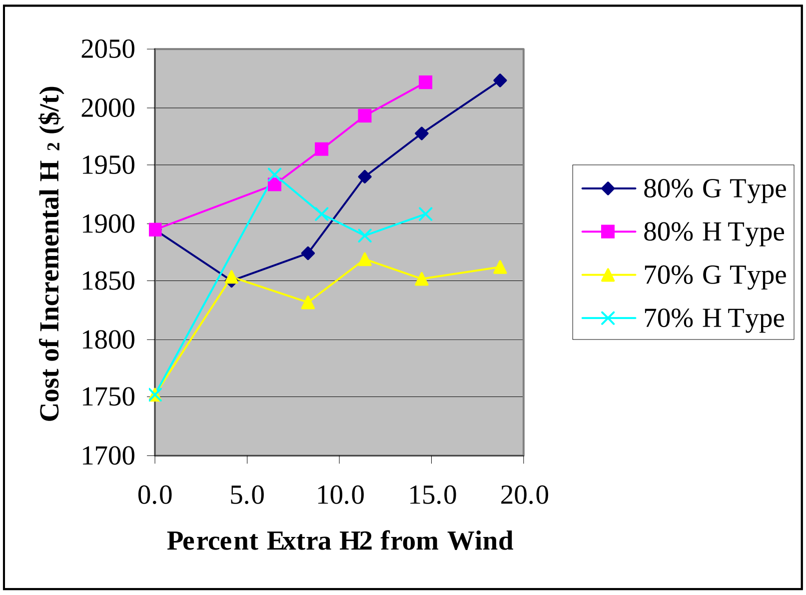

Figure 4: Cost of hydrogen using wind (actual Alberta Electricity Market Data)

The combination of nuclear and wind does indeed appear capable of absorbing wind's variability and of producing hydrogen from wind-produced electricity far more cost-effectively than would be possible with wind alone. It also accommodates the seasonal variability of wind. The results for the hybrid analysis are summarized in Figure 4. Optimization indicated that the proportion of wind that could be handled should be increased as the proportion of output used to produce hydrogen decreased. This is understandable since earlier analysis of the purely nuclear scenarios had optimized with more electrolytic spare capacity at lower proportions of hydrogen generation.

This coupled strategy allows a greater introduction of wind power without subsidies and avoids the cost penalties due to low capacity factor. This works because hydrogen is traded, with optimized storage, between the primarily base-load nuclear plants and the unpredictably peaking windmills.

6. The management and reduction of waste streams

Traditionally, nuclear energy from nuclear reactors has relied on a simplified "once-through" use of uranium in reactors, and major uranium fuel suppliers like Canada, Australia and Africa have exported uranium without developing added value or significant pre-processing into actual fuel rods (equivalent to the exporting of crude oil versus more refined products like chemicals and plastics).

To date, this has served global energy markets well by avoiding additional development of the sensitive and expensive uranium enrichment and separations technology. However, the global environment today has changed. Enrichment capacity and enrichment technology is more widely available and less expensive, and many jurisdictions want to increase the amount of energy obtained from the mined uranium and reduce the amount of spent fuel requiring disposal by using enriched fuels. In addition, the general concern about long-term (or local short-term) availability of uranium, and the difficulties being experienced by some in managing the quantity of spent fuel arising, is driving a growing trend to the development and use of reprocessing and recycle of spent fuel. Manufacturing of enriched fuels has already proceeded in France, Japan, India, Russia, China, Brazil, Argentina, Germany, South Korea, UK, and the USA. Recycling of spent fuel from current power reactors, along with development of more advanced reactor concepts optimized for the use of such recycle fuel products is underway or planned in a number of these countries. So far, such developments have ignored and/or not actively pursued large-scale transnational deployment and implementation of sophisticated fuel cycles, optional enrichment capabilities, spent fuel recycling, advanced fuel cycles, waste minimization or, fuel lease-back strategies. However, advanced designs and “closed” cycles are now being considered and re-appraised.

It has been wrongly suggested (perhaps as another dogma) that nuclear energy is constrained and bounded by limited availability of fuel (uranium) supplies. Overall, nuclear energy uses an otherwise useless resource (mined uranium and thorium ore) to make energy by fission. The “spent” fuel is then returned to storage and ultimately (in less than a thousand years) naturally decays in radioactivity and toxicity to its natural background level, as before its use.

Conventional reserves of fissionable uranium (U^{235}) worldwide are estimated at four to six million tonnes (at a price less than $50-100/kg), in countries like Canada and Australia. For a reactor delivering just 10,000 MW(th) d/tonne U (after allowing for the rejected tails from an enrichment plant), 1 EJ/a requires approximately 1200 tonnes U^{235}/a.

Hence 120 EJ/a of nuclear energy requires around 440,000 tonnes/a of uranium as U^{235}, and the world’s uranium reserves, at a recoverable price of less than $50/kg would suffice for barely 14 years. However, uranium ore miners and suppliers [52] suggest that at $50/lb U3O8, supplies would last until 2085, so we would have 80 years of reasonably assured reserves, plus 155 years at cost less than $80/lbU3O8, which is close to the top of current ranges, if supply were an issue. The current low rate of exploration and growth of assured reserves is a direct result of low uranium prices and lack of exploration investment over the last number of years. The idea that we would soon run out of fissile resources before we really started, is therefore clearly a fallacy that excludes any investment in new development and exploration. Political dogma and mantras allowing, we can adopt the following known technology options:

1) recycling or re-use of once-used uranium and plutonium fuel, which can easily double the energy availability (~2 times now);
2) utilizing thorium (Th) as a fuel, which has at least three to four-times more crustal abundance than uranium and enables higher fuel utilization and is already in use in India (~100 times now);
3) exploiting additional unexplored and unconventional uranium sources (many times now); or
4) using breeder-reactor technology where the fuel is recycled and new fuel bred from “fertile” but otherwise useless elements like U^{238}(more than 100 to 1000 times now).

In total, in both the long- and short-term, we have technically available options for providing the equivalent of about 200 to 1000 times the present known U^{235} reserves, or enough fuel/ore supply for about 2,800 to 14,000 years, at least. Hence, uranium and thorium resources do not appear to constrain the sustainable global energy scenarios.

Nevertheless, the current, wasteful approach to uranium utilization, which converts much less than one percent of the available energy to heat in a once-through cycle, will have to be improved. The precise details are unimportant and variations of a few exajoules per annum should not be debated. Even the energy scenario details are of secondary importance, though B1 (as the least energy-intensive of the IPCC's scenarios) is the most tractable.

Many alternate nuclear fuel cycles have already been studied, including use of spent fuel as recycled uranium (RU), Pu as MOX, DUPIC, Tandem fuel cycle, and actinide burning, and Thorium cycles [41, 47, 52, 53]. However, the majority of current fuel cycles remain open, once-through systems. While uranium was cheaply available, there was not a strong enough economic driver to adopt enriched or more advanced fuel cycles. Fuel costs are currently a small fraction of the capital and operating cost of a nuclear electric plant. Further, while spent fuel management and disposal are not major issues from either a cost or policy perspective, there is also no driver from that direction to move away from once-through fuel cycles, nor any penalty globally, nationally or market-wise.

In France, Russia, UK and Japan, there has been a move to mixed oxide (MOX) fuel cycles and recycling, due mainly to local shortages of indigenous fuel supplies and corresponding concerns over energy security. The resulting national plans are to develop fast-spectrum reactors (FBRs) for burning the reprocessed fuel or for breeding new fissile resources from the left-over U^{238}. Such reactors are not competitive based on capital cost considerations alone, but their introduction and use are driven in part by considerations of energy security. However, it is becoming recognized by many that even in a system of fast reactors using recycled fuel there is a role for economic, neutron efficient thermal reactors and other advanced concepts.

In the nuclear power sector worldwide, the trend more and more focuses on the nuclear fuel cycle. Driven in part by repository issues in the USA, domestic availability and/or cost of uranium in India, Japan, France and China, and by environmental and sustainability concerns, there are growing concerns about access to long-term uranium supply or national energy vulnerability. This can clearly be seen in the rationale for the US GNEP initiative [54], which is at least in part about closing the fuel cycle. In Japan, France and China strategies are to pursue the Fast Breeder Reactor route to recycle and breed fuel to extend uranium resources, while in Russia a complete fuel cycle using fast breeder reactors has always been the focus. In India the stated plan [52] is to develop fast breeder reactors and the thorium fuel cycle to address its limited Uranium but abundant Thorium resources, while in Japan there is a major investment in a new reprocessing plant.

With expansion of nuclear worldwide, we are and will continue to see more focus on extending and securing long-term Uranium supplies, and on investing in securing enrichment technology and capability worldwide. To address the potential proliferation concerns associated with enrichment capability and with the growth of civilian plutonium stockpiles in spent fuel inventories, we are also seeing the development of spent fuel “take-back” or fuel lease concepts [55].

On top of these international trends are overlays of the extreme urgency being expressed by many countries to develop and deploy additional nuclear energy capacity to meet rapidly growing energy demands.

Given constraints on waste disposal, and the fact that much more energy can be extracted from today’s used fuel, the picture on waste disposal and “phased management” of used fuel is changing [22]. Today, most reactors internationally operate on a once-through nuclear fuel cycle using mainly natural uranium fuel. This is mainly because the economics or market demand, until now, has not been constrained by uranium availability or cost. However, with expectations of significant expansion in nuclear power programs worldwide, and with resultant concerns about uranium availability and price, as well as a growing desire to extract more energy from each tonne of mined uranium before disposal, and concerns about establishing of disposal facilities for spent fuel from once-through fuel cycles, attention is now being focused on fuel cycles that will be much more energy efficient and result in a substantial reduction of ultimate waste disposal requirements.

To ensure a sustainable future, there have been a number of other significant global developments, with the advent of the Generation IV International Forum [21] ideals of sustainable fuel cycles, and reduced waste streams. A new sense of urgency has arisen in the USA since capacity of the planned repository (Yucca Mountain) is envisaged to be already fully committed for spent fuel from existing reactors, potentially restricting the expansion of nuclear power and future builds. Hence, reprocessing, separation, and recycling is being considered, plus the burning of the separated actinides in fast-spectrum burner reactors (FBRs). Fear of proliferation has multiplied on the grounds that spent fuel should not be left unused and widely dispersed. This has led Australia to propose “lease-back” of fuel, and Russia to proposing to host fuel storage facilities. The IAEA is also on record as supporting the concept of regional fuel cycle centres to address concerns related to potential proliferation of sensitive technologies.

To leverage this advantage, significant studies, ideas and initiatives are underway which examine integrated optimization of “burner” and spent fuel minimization cycles with interfaces to existing reactors, fast spectrum reactors and fuel from separation streams, with the automated estimations of isotopic composition and heat loading for spent fuel. This implies integrated optimization of fuel cycles, for uranium, plutonium and thorium, including bundle recycling, and heterogeneous core loadings.

Development of integrated spent fuel interim storage, storage and handling, fuel waste management, and adaptive phased management of waste streams and spent fuel will all reduce waste streams, potentially by factors of up to ten [56].

7. The effectiveness of available and future nuclear technologies

Humans are not setting the timescales; nature and our energy use are. All scenarios up to about 2035 show that there is almost nothing that can now be done to change planetary warming for the next 30 to 40 years. The World is going to become warmer. But, if immediate actions are taken, the rise thereafter can be slowed. If appropriate non-CO_2-emitting technologies are deployed, even the energy expectations of developing countries can be supplied without greatly adding to the stresses on our planet's climate. By 2050, measures beyond our nuclear plus hydrogen ($N+H_2$) suggestions will likely be *needed* but, by then, hopefully new technologies will also be available.

The development potential must consider the even larger market penetration worldwide both by nuclear energy and by hydrogen fuels in the time-frame 2025 or later. For the more distant future, beyond 2030, we will be building advanced designs tailored to hydrogen and power production in distributed and competitive energy markets worldwide. A number of concepts have already been identified in the Generation IV Roadmap produced by the Generation IV International Forum [21]. These are to meet the energy market requirements that are potentially even more challenging than those envisaged today.

We have shown [57] that developing such advanced nuclear concepts is feasible in an evolutionary manner. For example, filling the primary system of a water-cooled reactor with higher pressure supercritical water (SCW) can raise thermal efficiencies to over 40%. Extremely compact existing supercritical (SC) turbines operate today at sizes from 300MW(e), and can be deployed without any further development [58]. Turbine inlet temperatures of up to 600ºC are already possible so it is simply a matter of matching the evolutionary reactor design to the turbine, not the other way around. Further reheating and the use of existing ultra-supercritical turbine technology will raise the cycle efficiency to over 55%.

Future reactor technology is expected to continue to evolve to produce lower capital-cost, higher efficiency (higher steam temperature) Generation IV designs. Significant changes in steam supply characteristics are expected to occur over a period of two decades, which would be applicable to later oil sands development [59].

Increased thermal efficiency and multiple product streams are also both inherent from higher operating temperatures. We have been studying both the promise and the problems of such concepts for some time [57]. Such demanding market goals - in our view - will be met by employing significant system simplification.

8. Conclusions

Nuclear energy is now being recognised as an important contributor to energy security, supply and sustainability.

Advanced concepts for nuclear reactors are now being studied by many countries, which address continuous improvement in the areas of economics, safety, sustainability and non-proliferation.

These goals must be achieved whilst also meeting the market needs, minimizing investor risk, and satisfying all regulatory and environmental requirements.

The conclusion of importance is that a manageable deployment of nuclear, solar, wind and any other non-carbon sources of electricity has the potential to alter profoundly the future prospects for the Earth's atmosphere.

A particularly important role for nuclear power in the future will be its links to the hydrogen economy. The future could well become the Hydrogen Age. We show that a major reduction in GHGs worldwide can be obtained by nuclear-electric production of hydrogen, thus alleviating their potential effects on future generations. This need can be met by deployment of current and advanced reactor designs, and the integration of the electric grid with the hydrogen economy.

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