Nuclear Technology Pathways to a Carbon-Neutral Energy System

J.F. Clarke¹,², J. Edmonds², C. Geffen³

Abstract: Climate change is one of the most critical scientific and economic challenges facing the world today. Stabilizing the atmospheric carbon concentration will require fundamental changes in the energy system worldwide over the next century. Novel energy technologies, such as carbon capture and sequestration, and biomass production enhanced by advanced biotechnology, may be required. However, currently deployed non-carbon energy technologies, such as nuclear or wind energy, will also need to be developed further if they are to emerge as a significant source of electricity or hydrogen in the carbon-neutral energy system that is required to address anthropogenic climate change.

This paper evaluates the economic and technological potential for advanced nuclear technology systems to contribute to the development of a carbon-neutral energy system within the context of postulated future carbon and energy policies. We find that, depending on the technology development pathway followed by, nuclear energy might supply from ten to thirty five percent of the world’s electricity by 2100. With a policy to stabilize atmospheric carbon at 550ppm nuclear reactors might produce a similar share of the world’s total energy if they could produce hydrogen economically.

Thus nuclear technology, which is the largest source of non-carbon energy today, will be pivotal in addressing climate change in the future. It is too crucial an element in the global struggle to stabilize the carbon content of the atmosphere for it to evolve by drift and inertia. Just as atmospheric stabilization requires a carbon-neutral energy system in the long-term, nuclear energy requires both fissile fuel breeding and fuel processing to be sustainable. However, along an evolutionary nuclear technology development pathway, the climate impact of fission energy could be limited by the long-term availability of fissile material. Consequently, we find that nuclear research and development that transcends the near-term needs of the nuclear industry will be required to ensure a substantial contribution to the stabilization of the atmospheric carbon concentration. There is a need for a substantial increase in both publicly supported, long-term nuclear research and development activities and international collaborative efforts, particularly with respect to the technology and governance of the fuel cycle, to assure that nuclear energy can make a sustainable contribution to climate stabilization.

¹ Corresponding author, contact at the Pacific Northwest National Laboratory, Joint Global Change Research Institute, University of Maryland at College Park, 8400 Baltimore Avenue, Suite 201, College Park, MD 20740-2496. Tel: +1 (301) 314-6746; Fax: +1 (301) 315-6760. email: j.f.clarke@pnl.gov.
² INSTITUTIONAL AFFILIATIONS: Joint Global Change Research Institute, a collaboration between the Pacific Northwest National Laboratory and the University of Maryland at College Park.
³ INSTITUTIONAL AFFILIATION: Pacific Northwest National Laboratory, Richland, WA 99352
Introduction:
Global climate change is one of most critical challenges facing the world in the 21st century. Both research and observation implicates increasing atmospheric carbon dioxide in global warming. Addressing climate change will involve a portfolio of responses including research to improve scientific understanding of climate change processes and impacts, adaptation to climate change at regional and local levels, and emissions mitigation and control. Whatever responses emerge over the coming decades, it is clear that technology development, and particularly energy technology development, will shape both the scope of the climate change problem and the cost of mitigation.

The Global Energy Technology Strategy Program (GTSP) was initiated in 1997 “to assess the role that technology can play in addressing the long-term risks of climate change” with collaborative participation by a wide array of international research organizations.

During the course of Phase 1 of the GTSP a number of important observations and conclusions were reached. Among them are the following:

- Climate is a long-term problem, which demands near-term actions in policy formation, scientific research and investment in technology development.
- Stabilizing the concentration of CO2 means fundamental change to the global energy system, eventually requiring an energy system with no carbon emission.
- An integrated portfolio of new energy technologies as well as vastly improved conventional technologies will be required to stabilize the carbon content of the atmosphere.
- Current investments in energy technology R&D that could reduce the cost of stabilization of greenhouse gases are inadequate.

The revolutionary nature of attempting to manage carbon emission is illustrated by the fact that virtually all reference projections of future greenhouse gas emissions find stunning changes in the global energy system over the course of the 21st century. Under ‘business as usual’ (BAU) the Intergovernmental Panel on Climate Change (IPCC) scenario IS92a projects an increase in fossil fuel carbon emissions from approximately 6 Gigatons of Carbon (GtC)/year in 1990 to approximately 20 GtC/year by 2100. This in turn implies an increase in the concentration of CO2 in the atmosphere from the pre-industrial 280 parts per million (ppm) to more than 700 ppm. Worse, the projections have carbon concentration still rising by century’s end.

It is important to recognize that, as high as the anticipated CO2 concentrations are in reference scenarios, they would be considerably higher were it not for the major technological improvement that are simply assumed to occur under a BAU scenario. These include improved versions of current energy supply technologies such as nuclear, solar, wind, and commercial biomass in addition to large efficiency improvement in demand side technology. This is illustrated in Figure 1 by the gap between future carbon emissions using only 1990 technology and those resulting from the improvements in technology assumed to be produced by market forces in the BAU scenario.

However, the advanced energy technology produced by BAU market decisions leads to continued carbon emissions. Government decisions and investment in technology
development will be necessary to close the gap between the rising BAU emissions trajectory and one leading to the zero carbon emissions consistent with a stabilized atmosphere.

Nuclear energy is the largest source of non-carbon energy today and will be a very pivotal technology in addressing climate change in the future. However, nuclear energy technology has many forms and technology development pathways, only some of which are market driven. Nuclear technology development is needed to achieve the BAU market trajectory but additional development is needed if it is to help close the atmospheric stabilization gap. This paper addresses the potential for nuclear power to contribute to the carbon-neutral energy system of the future, outlines the significant technological development challenges and discusses the implications of alternative technology development paths for the sustainability of its global scale deployment.

Nuclear Technology and Climate Change

Although nuclear energy currently supplies about 16% of the world’s electricity, the Energy Information Administration (EIA) projects (3) that through the year 2020, the supply of nuclear energy is likely to decline as a fraction of both the US and world energy supply systems. It is also possible that the relative stagnation of the nuclear market expected over the next two decades combined with continued public concern over reactor safety, nuclear wastes and proliferation of nuclear weapons will lead to a long-term decline for nuclear energy, with the technology condemned to play a relatively minor role in the future energy supply. Indeed, under the latter scenario it is argued that there is little incentive to undertake advanced nuclear technology development (4) that might improve the economics and ease the ancillary concerns.

However, the EIA projections are based on extrapolation of current market conditions. In the long-term, which is defined by climate concerns, there will be significant changes in both technology and market conditions. A more dynamic analysis is required to account for the possibilities inherent in long-term technology development. The modeling to be discussed in this paper suggests that, depending on the choice of R&D investment and the technological progress achieved, nuclear technology might supply over a third of all electrical energy needs by the end of the century – and a similar percentage of total energy if it can supply hydrogen for transportation (5).

![Carbon Emissions](image)

**Figure 1** Achieving a carbon-neutral energy system will require both evolutionary and revolutionary technology change. Both market and government technology investment will determine the technology development pathways that will set the cost of climate stabilization.
World energy use is projected to increase significantly over the next decades. Primary sources of energy vary across the globe and economic development will require a portfolio of energy technologies. While acknowledging the seriousness of nuclear security concerns, nuclear power remains one of a very few large-scale energy sources capable of supporting global economic development in all regions while contributing to atmospheric stabilization. Increased investment in both nuclear technology development and in a secure global management regime for nuclear fuel will be needed to create a favorable competitive market environment to realize the benefits of nuclear power. This will be the case with or without climate policy. However, nuclear technology investment takes on added significance because of climate concerns. When considering potential remedies for a significant global problem such as climate change, the absence of nuclear technology would be as influential as its presence.

The Evolutionary Nuclear Technology Pathway

Despite the limited investment in new reactors, the nuclear industry has continued to develop its technological base in order to improve competitiveness with fossil-fuel electricity generation. Significant improvements have been made to the first generation of deployed nuclear technology (hereafter referred to as Gen-I reactors), including advances in fuel lifetime, reactor operations, and upgrades in reactor components. These improvements served to lower the cost of fissile fuel, to raise plant capacity factors from around 60% to over 90%, and to increase the power output of existing plants. This significantly upgraded set of reactors constitutes, in effect, a second generation of nuclear power: the Gen-II reactors.

The International Energy Agency (IEA) studied the cost of nuclear power produced by modern Gen-II reactors in several countries of the Organization for Economic Cooperation and Development (OECD). The study concluded that the range of both fuel and operating costs for modern nuclear plants was lower than that of either coal or gas plants. On the other hand, they also found that, because of the relative high capital cost of these nuclear plants, the total cost of nuclear electricity could be lower or higher than fossil electricity depending on fossil fuel prices, interest rates, construction times, and other regionally specific variables.

Competitive electricity markets are driven primarily by short-term economic considerations but the competitiveness of current nuclear reactor power is not just a technological or an economic issue (8,9). There are strong and opposing views on the desirability of using nuclear power and decisions to construct or retire a nuclear plant can be affected by politics. This increases investment uncertainty, provides a considerable disincentive to further investment in new nuclear plants, and drives up the investor’s desired rate of return, which increases the already high capital cost. Thus, aside from improving reactor safety and preserving the low operating costs of operating plants, the major development efforts for the next generation of nuclear reactors (referred to as Gen-III reactors) have focused on reduction of capital cost, which in the opinion of the industry is a major factor in deciding to deploy a new nuclear plant (10). Current Gen-III nuclear reactor designs aspire to generate electricity for between 3.6¢/kWh to 4.6 ¢/kWh, which is believed to be competitive in future electricity markets (11).

However, to attract private investment in the near-term, the Gen-III designs must also elicit high confidence that they can be built and attain these costs. Continuity with
existing, widely accepted designs is an important element in getting a proposed nuclear facility and/or site licensed and attaining the projected performance. Thus, the deployable Gen-III reactor designs and fuel cycle technology have built heavily on the safety and operations experience gained from the dominant thermal-spectrum, light water reactors over the last two decades.

Other reactor technologies, for which a far narrower experience base exists, would require additional non-industry support to reach a deployable status (12). However, there has been little government support for nuclear technology development in recent years (13,14). In the United States, for example, the government role with respect to Gen-III reactor development is confined to easing unnecessary licensing or regulatory barriers to deployment. In general, in spite of substantial public opinion that advanced energy technology should play an important role in the future (15), government and industrial investment in all advanced energy research and development has been declining.

The Nuclear Fuel Cycle Challenge
Any near term increase in nuclear deployment will reduce carbon emissions. However, from the longer-term perspective of climate change, carbon-neutral energy technology must be deployed at very large scale and for a very long time to be significant. As noted above, carbon emissions will eventually have to approach zero to stabilize the atmosphere. To make a significant contribution to this goal, nuclear power should be able to generate hundreds of exajoules of electricity per year from thousands of reactors for hundreds of years. Moreover, this scale of energy production would be significantly increased if nuclear hydrogen production were feasible. Thus, we require that the entire nuclear system be sustainable at a global-scale over a very long period. While certainly necessary and adequate for the short-term, evolutionary Gen-III technology is probably not sustainable on the long-term climate time-scale because of the inherent low efficiency with which it uses fissile fuel. Just as atmospheric stabilization requires a carbon-neutral energy system in the long-term, nuclear energy requires both fissile fuel breeding and fuel reprocessing to be sustainable within that energy system. The sustainability of nuclear energy fuel cycle will depend on the near term technology investments that foreshadow future nuclear deployment paths.

Figure 2 illustrates the essential components of the basic nuclear fuel cycle (solid lines) and the reprocessing option (dotted lines), which would extend the nuclear fuel supply. Currently, the cost of natural uranium is a small fraction (~30%) of the total nuclear fuel cost and the total nuclear fuel cost is a small fraction (~20%) of the total nuclear electricity cost (16). With current fuel costs and reprocessing technology, recycling the fissile material that is left in the reactor’s spent fuel is a marginal economic proposition (17), at best (18). Consequently, most Gen-III reactors would be expected to use a once through fuel cycle.

Life extension of currently deployed Gen-II reactors plus the potential deployment of evolutionary Gen-III reactors are likely to ensure that thermal, light water reactor technology and the once through fuel cycle will dominate the nuclear and natural uranium market for decades—at least past mid century.

One might be tempted to conclude from the above that the cost of uranium will remain a minor issue in determining the competitiveness of nuclear energy. However, in a competitive market, even small marginal cost changes can have a disproportionate
impact on market share. Thus, changes in the cost of the fissile fuel for large-scale deployment are just as important as changes in any other cost component in determining the long-term market share of nuclear energy.

For nuclear energy, the relative contribution of capital and fuel to energy cost is much more complicated than with fossil energy. Different nuclear reactor technologies can produce, as well as consume, fissile fuel by using the large resources of fertile uranium and thorium. Use of these abundant fertile resources would allow a major and sustainable nuclear contribution to the global energy system for hundreds if not thousands of years. However, this would require the development of economic and socially acceptable technology both for breeding fissile material in advanced reactors and for reprocessing spent reactor fuel to recover the new fissile material. Without the development of both advanced nuclear reactor and fuel cycle technology, nuclear power will not be able to make a sustainable contribution to reducing carbon emissions in the long-term. Neither technology advance is likely to emerge simply because of current market forces that favor an evolutionary Gen-III nuclear technology pathway.

The Potential for Sustainable Nuclear Technology
Over the last few years, representatives of the nuclear nations, the Generation IV International Forum (GIF) (19), performed a comprehensive assessment of the potential for nuclear technology development and examined the criteria for sustainability in the longer-term. The six categories of potential reactor and fuel cycle technology that they identified are summarized in Table 1. Of these, only the fast reactors and the thorium cycle MSR could provide the scale and duration of energy generation needed to contribute significantly to climate stabilization.

Figure 2 The basic “once through” fuel cycle is shown by the solid lines. A sustainable nuclear fuel cycle would include reprocessing of spent fuel and burning the fissile material in advanced reactors, which might also burn minor actinide wastes.
The SCWR and the VHTR have the advantage of producing high temperature heat that might be used for hydrogen generation but both are net consumers rather than producers of fissile material. Modeling indicates that with a 550ppm carbon stabilization policy more than one third of final energy services could be provided by hydrogen by the end of the century (20). As valuable as nuclear produced hydrogen might be within a carbon-neutral energy system, successful development of these reactors would generate a significant additional demand for fissile fuel. Thus, from the perspective of sustainability, the reactor types shown in Table 1 must be considered as elements in a balanced nuclear fuel cycle rather than as individual technologies.

Table 1 Generation-IV Nuclear Energy Systems comprise the nuclear reactor operated in a fissile breeder (B) or converter (C) mode, as well as all of the facilities in the entire fuel cycle, from ore extraction to reprocessing to actinide burning to final waste disposal.

<table>
<thead>
<tr>
<th>Generation IV Reactor System</th>
<th>Fuel Cycle</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-Cooled Fast Reactor System</td>
<td>B/C</td>
<td>GFR</td>
</tr>
<tr>
<td>Lead-Cooled Fast Reactor System</td>
<td>B/C</td>
<td>LFR</td>
</tr>
<tr>
<td>Sodium-Cooled Fast Reactor System</td>
<td>B/C</td>
<td>SFR</td>
</tr>
<tr>
<td>Molten Salt Reactor System</td>
<td>C</td>
<td>MSR</td>
</tr>
<tr>
<td>Supercritical-Water-Cooled Reactor System</td>
<td>C</td>
<td>SCWR</td>
</tr>
<tr>
<td>Very-High-Temperature Reactor System</td>
<td>C</td>
<td>VHTR</td>
</tr>
</tbody>
</table>

The Generation IV Technology Roadmap (21), which identified the research and development needed to realize the potential of these different reactors, reinforced the point that all nuclear energy technologies are ultimately related through the nuclear fuel cycle. In addition to elaborating on the unique possibilities of each category of reactor-fuel-cycle technology, the Gen-IV Roadmap also pointed out that there were additional opportunities for technological synergism inherent in developing an integrated fuel cycle from the various combinations of breeder and converter reactors that might be deployed over the next century. If successfully developed, a Gen-IV reactor system could constitute much of the sustainable carbon-neutral energy system required to stabilize the atmosphere.

However, given the essential integration provided by their fuel cycles, the nuclear technology development pathways that might evolve from the technical possibilities inherent in the Gen-III and Gen-IV Roadmaps are interdependent. Assessing the sustainability of potential nuclear technology development pathways within more comprehensive global development scenarios requires a quantitative model of both the Gen-III and Gen-IV the fuel cycle.

**Modeling the Nuclear Fuel Cycle**

The sustainability of nuclear energy depends fundamentally on the supply of the only natural fissile resource: the small fraction of $^{235}$U found in natural uranium. The efficiency with which this resource is used is determined by a fuel technology factor, $F_{ft}$, defined here as the exajoules of energy that would be produced by a million tonnes of natural uranium in a specific type of nuclear reactor (22,23). As with fossil fuels, this factor depends on the reactor thermal efficiency but unlike fossil fuels, it also depends
on the specific reactor technology, its fuel cycle technology, the technology for fuel fabrication and reprocessing (if used), and the waste disposal method.

Each of the reactor technologies and their associated fuel cycles that have been discussed in the Gen-III and Gen-IV Roadmaps can be characterized by different values of the technology parameters that determine \( F_{\text{fr}} \). As illustrated in Figure 3, each generation of nuclear reactor system allows a wider potential range for the fuel technology factor. Using typical parameters, we find that the fuel technology factor has improved from less than 100 for Gen-I reactors, to about 130 for Gen-II reactors. Much of this past improvement has been from higher fuel burn-up, which has increased considerably over the past few decades as improved fuel fabrication technology has allowed longer fuel lifetime in the reactor. However, continuing this trend of longer residence time in the reactor requires higher fuel enrichment, which tends to offset the advantage of higher burn-up. Further, increases in \( F_{\text{fr}} \) will depend mainly on improved thermal efficiency and/or spent fuel recycling technology.

In the future with technology development, the value of \( F_{\text{fr}} \) for Gen-III reactors might rise to around 175 if improved thermal efficiency can be attained or to around 300 if some fuel recycling is also employed. Much larger values might be attained for Gen-IV reactors with high thermal efficiency, high fuel conversion, and reprocessing. The highest values would describe fast neutron spectrum plutonium breeder reactors with complete fuel recycle.

From a modeling perspective, only the resultant value of \( F_{\text{fr}} \) and the cost of natural uranium are important. Thus, we can model the evolution of the nuclear fuel cycle during the next century by increasing \( F_{\text{fr}} \) to represent the portfolio of improved reactors and fuel cycles that might be produced by different investments in nuclear technology development.

For example, if it is commercially successful, market driven Gen-III technology will dominate the deployment of nuclear reactors through the middle of the century. Since the lifetime of those evolutionary reactors could be greater than 50 years, the average fuel technology factor of deployed reactors is likely to be at the lower end of the potential GEN-IV technology performance range by 2100, even if fuel reprocessing is eventually used by Gen-III reactors and if advanced Gen-IV reactors are developed and deployed.
Modeling Long-Term Nuclear Technology Pathways

We will use the PNNL integrated assessment model to evaluate the consequences of various nuclear technology pathways within more general global development scenarios. For this analysis, we selected the B2 scenario from the IPCC Special Report on Emissions Scenarios (SRES) (24). This scenario posits a medium energy-intensity, environmentally sensitive, and economically heterogeneous world. The resulting energy demand is in the middle range of the SRES scenarios and so should not bias our results toward more or less nuclear energy.

The PNNL integrated assessment model (MiniCAM) draws on a variety of scientific disciplines to assess the various climate change policies and technology strategies over long time scales. The model runs in 15-year time steps from 1990 to 2095 and includes 14 distinct geographic regions (25). It is capable of incorporating carbon taxes and carbon constraints in conjunction with numerous carbon-management technology options including carbon capture and disposal. The economic core of the model is the Edmonds and Reilly partial equilibrium model (26), which has been continuously updated (27,28) to incorporate a full suite of energy and carbon management technologies in the current MiniCam model.

The MiniCAM includes a large number of electric generation technologies including gas turbines, nuclear fission, commercial scale biomass, fusion energy, fuel cells, and fossil systems with geologic CO₂ sequestration, wind turbines, terrestrial solar photovoltaic power (PV), and space solar power (SSP). Technologies in the MiniCAM are described by fuel costs, non-fuel costs, and, for electric generation, generation efficiencies. The electricity supply sector incorporates both carbon-based and carbon-free generation technologies, and all available energy technologies compete to satisfy market demand. The agriculture and land-use component of the model projects agriculture and forest product outputs and tracks the demand for managed and unmanaged land. The agriculture and land-use module also supplies biomass products for energy, while the energy module determines the level of demand for biomass energy.

Although all technologies within MiniCam compete based on cost, the model uses a statistical description to account for geographic and economic heterogeneity within regions (29). This allows higher cost technologies to contribute to the overall generation mix, as they do in the real world.

We will use this modeling structure to evaluate the potential market penetration paths of advanced nuclear energy by exploring the two dimensions of technology development and carbon policy. In the carbon policy dimension, we consider the case of no carbon emissions policy versus a global policy that stabilizes the atmospheric carbon concentration. If a global policy to limit carbon emissions is adopted, some value must be placed on emitted carbon to raise the relative cost of fossil fuels either directly or because of the additional carbon capture and disposal technology required. The model includes this effect by applying a global carbon tax adjusted over time to gradually reduce net carbon emissions from the energy system to zero in an economically efficient manner. In the following, we choose the carbon policy case in which the carbon concentration of the atmosphere is eventually stabilized at 550ppm, approximately twice the pre-industrial concentration. Of course, the assumed carbon tax would also stimulate the use of other carbon-neutral technologies such as biomass, solar, wind, and...
fossil electricity with carbon capture and disposal, all of which compete with nuclear fission for market share.

The technology development dimension has two aspects. The first aspect is the relative success of the particular technology development that is attempted: i.e. Will Gen-III technologies actually attain their development goals? The second, and more significant, aspect for public policy involves the choice of whether or not to invest in advanced nuclear technology development at all, and if so, with what limitations, emphasis and timing.

**Modeling Nuclear Deployment Pathways – The Fuel Cycle**

The cost of the nuclear fuel cycle depends on both the cost of natural uranium and the cost of subsequent enrichment and processing. Thus, a cost increase for natural uranium due to resource depletion might be offset by a cost decrease in processing cost due to technology improvement. Both costs are dependent on technology development but in significantly different ways and each will have a different effect on the evolution of fuel cycle.

**Uranium Resource Cost:** In discussing the availability of uranium, we emphasize that the availability of the fertile nuclear materials, uranium 238 or thorium 232, is not the concern. In fact, Th$^{232}$ is plentiful and most of the $^{238}$U mined will be relegated to the tails from the enrichment process. Our concern with nuclear fuel availability is actually with the consumption of $^{235}$U, the small, naturally occurring fissile component of the uranium ore, upon which all fission energy depends. The consumption of $^{235}$U depends on details of the nuclear fuel cycle such as the required enrichment, which are captured by the fuel technology factor. However, the $^{235}$U consumption is expressed in terms of the uranium ore that is mined to extract the fissile material.

The cost of recovering natural uranium depends on the abundance, concentration and chemistry of natural uranium deposits and on the development of mining technology. The latter, like other technologies, might be expected to improve with time and technology investment. The competition between resource depletion and mining technology improvement will ultimately determine the cost of natural uranium but this should not necessarily be assumed to lead to lower costs as consumption increases. (30).

The International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) have produced the most authoritative estimate of the future cost of known and undiscovered conventional uranium resources as a function of cumulative production, the ‘Redbook’ (31). As we will show below, the potential consumption of uranium during the next fifty years could substantially exceed the Redbook estimate and modeling beyond mid-century requires a more extensive estimate of uranium in unconventional resources.

Figure 4 shows two alternate uranium supply curves. The first, denoted as the Crustal Model, was prepared by the Gen-IV Fuel Cycle Crosscut Group (FCCG) (32). The FCCG employed a heuristic geological estimate of the distribution of uranium in the earth’s crust (33,34). Using the estimate for those ores -- in the tail of this distribution -- that contained more than 1000ppm of uranium, The FCCG inferred an elasticity for resources as a function of concentration of those ores. The FPCC combined this estimate with the assumption that production costs scale inversely with concentration to
obtain a cost elasticity of cumulative uranium production. In a second approach the FCCG used sparse EIA historical data on the forward cost of uranium reserves by mining method (35) to infer an alternative cost elasticity. While plausible, the resulting FCCG supply curves are not a good fit to the IAEA Redbook uranium cost estimates.

We can obtain a better fit to the Redbook estimates by considering the geological concentration estimate and the production cost separately (36). Accepting the geological estimate of the elasticity between uranium abundance and ore concentration, we define a mining cost elasticity to relate production cost to ore concentration. The mining cost elasticity can be simply estimated by fitting the model to the Redbook cost estimates. The result is the PPM-Cost Model, which matches all of the Redbook estimates quite well. In this paper, we adopted the PPM-Cost Model to extend the Redbook supply curve.

Finally, it is frequently noted that the largest potentially accessible resource of uranium is contained in the world’s oceans. If it were recoverable at reasonable cost, it would eliminate concern over $^{235}$U supplies. However, this resource is so dilute that, it has been suggested, one might expend more energy in extraction and concentration of the uranium than would be produced in a nuclear reactor (37). In any case, estimates of cost and of the practicality of recovery are widely varying. Costs might be greater or lower than $1000/kg U but probably not lower than $250/kg, which is higher than the uranium cost estimated from the terrestrial supply curves for most cases during this century.

We will use the Redbook estimate of known and speculative uranium resources below $130/kg (11.5MT), the estimate of uranium in dilute phosphate ore (22MT) and the total uranium estimated to exist in all formations currently being exploited –that is all ores with a uranium concentration above 1000ppm in the geological estimate -- (70MT) as indicators of the magnitude of uranium consumption relative to terrestrial resources.

**Uranium Processing Cost:** As will be seen below, achievement of the GEN-III capital cost targets would result in a large expansion of nuclear energy over the next century and the cost of uranium will rise with increased uranium consumption. Adoption of climate stabilization policies also lead to increased uranium consumption irrespective of the degree of success in reactor technology development. Thus there will be incentive for continual improvement in nuclear fuel cycle technology even along a market driven technology pathway.

We represent this incentive with a technology learning-by-doing model (38). Specifically, we assume that technology learning based on the cumulative amount of uranium processed will be able to reduce uranium processing costs. We use a typical industrial
progress ratio (the relative unit cost after a doubling of cumulative output) of ~80%. Incorporation of this learning model allows fuel processing costs to decline more rapidly if, for example, uranium consumption were to increase with a public policy to stabilize the carbon content of the atmosphere. With this learning model, resulting cost index for nuclear fuel processing technology declines with cumulative uranium consumption to about 30% by 2095 for all of the pathways discussed below.

With this representation of nuclear fuel cycle costs we can model alternative nuclear technology development pathways that could result from various technology development strategies and assess the consequences for climate change.

**The Evolutionary Gen-III Pathway:**

Earlier we discussed the market drivers that have governed commercial nuclear technology development in recent years and that have led to the evolutionary Gen-III reactor designs. Under business-as-usual conditions, these drivers are likely to remain dominant for the next several decades. Consequently, the nuclear technology pathway is likely to be based on further development of evolutionary Gen-III reactors using a once through fuel cycle. If successful, this development will realize the Gen-III cost goal of about three cents/kWh. If unsuccessful, the nuclear fixed cost could remain at today’s level. Given the variety of potential Gen-III designs, we model successful technology development along this evolutionary pathway by gradually reducing the capital cost of the Gen-III reactor class from current reactor costs at a rate of about 0.9%/year until 2050. This reduces the fixed cost from that of current reactors to the Gen-III goal of about 3¢/kWh in 2050.

Figure 5 shows resulting global electricity production assuming successful Gen-III development. Capital cost reduction — combined with improved social acceptance associated with the attractive technology features of Gen-III reactors — results in a significant increase in nuclear electricity generation. Private R&D investment and technology learning is expected to be higher in this growing nuclear market. With this investment, evolutionary Gen-III technology can gradually reduce its capital cost and increase its market share throughout the century. Although the global market share of nuclear electricity initially decreases consistent with current trends, it recovers by mid century and increases throughout the remainder of the century reaching 19% by 2050 and 24% in 2095.

This deployment and the increased scale of the global energy market results in a very large uranium demand. By 2050, NEA/IAEA known and undiscovered conventional uranium resources are exceeded by the large commitment to deployed GEN-III reactors. Despite the cost reduction in fuel processing, this leads to an increase of 65% in nuclear fuel cycle costs as a
percent of total cost. Given this fuel cost increase, the Gen-III fuel reprocessing can be expected to receive increased private sector investment. We model the expected introduction of improved fuel reprocessing and recycling technology by smoothly increasing the Gen-III fuel technology factor, Ftf, with time to span the potential range illustrated in Figure 3. By 2095, improved fuel technology and this recycling reduce the nuclear fuel cost increase to 31%.

Nonetheless, the shaded area in Figure 6 illustrates the range of uranium consumption that could result from the evolutionary (BAU) technology pathway. The large market penetration shown in Figure 5 would be reduced if the Gen-III reactors did not achieve the expected capital cost reduction. The lower bound of each area on the graph represents this development ‘failure’ and the legend on the right indicates the corresponding reduction in nuclear market share. We find that even if Gen-III electricity costs were to remain at today’s levels, the uranium commitment would substantially exceed currently estimated resources by the end of the century. With successful technology development, the uranium commitments to installed Gen-III reactors could substantially exceed even the uranium resource estimated in phosphates!

With the implementation of a global policy to stabilize atmospheric carbon at 550 ppm, the cost of carbon based electricity would rise and the demand for evolutionary Gen-III technology would increase even further. The resulting global electricity production is shown in Figure 7. The climate policy virtually eliminates the decline in nuclear market share, even in the near term, and by the end of the century, nuclear energy supplies 36% of the world’s electricity.

Figure 7 also illustrates the importance of nuclear energy relative to the other non-carbon electricity sources in controlling carbon emissions. Nuclear energy exceeds that delivered by all of the other non-fossil electricity technologies that enter the market under a 550 ppm carbon policy.

By mid-century, accelerated Gen-III deployment leads to a 52% increase in fuel cycle cost as a percent of total cost. However, as a result of R&D and the introduction of fuel recycling after 2050, nuclear fuel cost as a percent of total electricity cost has...
increased by only ~ 24% by 2095 in spite of much higher uranium cost. Thus, climate policy stimulates a large growth in nuclear market share and the associated private sector investment in fuel cycle technology serves to minimize effect of uranium cost increases. However, as can be seen from the upper area in Figure 6, which represents to a 550ppm carbon policy, the uranium commitment to deployed Gen-III reactors exceeds NEA/IAEA estimates of known and undiscovered conventional resources before 2050 in spite of increased fuel efficiency. Introduction of fuel reprocessing after 2050 improves the fuel efficiency of Gen-III reactors significantly but cannot limit the large draw down of uranium resources resulting from increased global demand. The uranium commitment continues to increase, reaching almost twice the estimates of the uranium content of phosphates by 2065. Again, failure to achieve the Gen-III capital cost reduction goals would reduce nuclear market share— and also the nuclear contribution to carbon stabilization – but even in the event of development ‘failure’ the total uranium commitment would still exceed 20 million tonnes under a 550ppm carbon policy.

As noted above, estimating the uranium supply curve is a very uncertain business. If the geological estimates of high-grade uranium resources are too low, the large commitments to evolutionary Gen-III reactors might seem less significant. On the other hand, the uranium demand could be higher than indicated in Figure 6, since we have not included any use of nuclear energy for producing hydrogen. If nuclear hydrogen production turns out to be economically feasible, the resulting demand could significantly increase the indicated uranium consumption.

Moreover, even if nuclear energy only supplies electricity, the large uranium commitment could still be of concern from the perspective of effecting a timely transition to a sustainable nuclear energy system. Depending on its fuel burn-up (GWe per tonne of fuel), a 1 GWe LWR produces about 40% of its energy by in situ burning of part of the $^{239}$Pu that is bred from $^{238}$U. The remaining $^{239}$Pu, which is contained in the spent fuel could be separated and either burned in other LWRs or used to start up a fast breeder reactor. However, fast reactors demand rather large specific fissile inventories (kg/kW). Thus, the rate of deployment of a sustainable nuclear energy system -- based on a breeder or highly efficient Thorium converter reactor -- depends either on the accumulated inventory of $^{239}$Pu produced by Gen-III reactors or on the economic availability of 235 U from ore for which the Gen-III reactors would strongly compete.

Along the evolutionary-technology pathway, the $^{239}$Pu inventory is likely to be smaller rather than larger, since the economic incentive is to recycle plutonium and to increase fuel burn-up. For instance, in recent years, LWR burn-up has risen from 33 to 42 GWe/t, and it is reasonable to expect that this trend will continue in the future. Of, course as the burn-up increases more $^{239}$Pu is consumed in-situ and less remains in the spent fuel. One can estimate that for burn-up in the range 42-80 GWe/t a Gen-III reactor using a once through fuel cycle would produce between 0.22-0.17 tonnes of $^{239}$Pu per year. Since a fast reactor requires a fuel inventory of 7-8 tonnes of fissile material to start up, it would take about 30-50 years for a Gen-III reactor to produce enough $^{239}$Pu to replace itself with a sustainable breeder reactor. Thus, assuming a once through fuel cycle, the self-replacement time is on the order of the Gen-III reactor lifetime.

However, in order to reduce fuel cost after about 2050, our modeling with climate policy optimistically assumes that technology is developed, which allows complete recycling of all of the $^{239}$Pu in the spent fuel in the Gen-III reactors. Hence, little plutonium would
accumulate. If most of the $^{239}$Pu produced by Gen-III reactors were to be recycled in order to reduce the consumption (cost) of natural uranium, the transition from evolutionary Gen-III reactors to a sustainable Gen-IV nuclear energy system could be elongated. (39, 40)

Alternately, if the Gen-III reactors do not recycle the fissile material in the spent fuel, their fuel technology factor will be reduced and the uranium consumption will be even larger than that estimated above. Although an enormous stock of $^{239}$Pu would then accumulate around the globe, additional security and deployment problems could arise if there were no international convention on plutonium management and/or if no advanced reactor technology was available to consume it in a secure and sustainable manner.41

Given the uncertainty in uranium resources in the face of large potential consumption, it seems rash to assume that following the evolutionary Gen-III technology pathway throughout this century will result in a timely transition to a sustainable nuclear energy system without the early introduction of breeder reactors.

**Alternative Nuclear Technology Development Pathways:**

Clearly, early development of more advanced nuclear reactor and fuel cycle technology would reduce the consumption of fissile material and the treat to sustainability. However, this technology development pathway would require a significant increase in public investment in long-term nuclear technology development. Moreover, this pathway could be blocked by concerns that development of advanced nuclear fuel cycle technology would exacerbate the proliferation of nuclear weapons. In a recent series of international workshops on the new challenges and opportunities for nuclear energy, all of the participants with a wide breadth of perspectives agreed that “security issues must come first no matter what civilian nuclear future is advocated or emerges” (42). In fact, motivated by security concerns, a recent MIT study on the future of nuclear energy over the next fifty years (43) has recommended that the DOE nuclear R&D program be realigned to focus exclusively on Gen-III reactors with an open, once-through fuel cycle. This precautionary approach would extend to halting development of advanced fuel cycles or reactors pending an international uranium resource assessment and the completion of a nuclear system analysis somehow resolved the four critical fission energy challenges of cost, safety, waste and proliferation.

Halting public sector investment in advanced nuclear technology for an extended period of time and mandating a once-through fuel cycle would significantly change the evolutionary Gen-III technology pathway throughout the century. By itself, a once through fuel cycle on the evolutionary pathway would lead to an accumulation of fissile plutonium in waste repositories, and provide a $^{239}$Pu reservoir from which a sustainable nuclear energy system might be developed in the future. However, the proliferation concerns are not lessened by increasing the stock of $^{239}$Pu, albeit embedded in spent fuel. Thus the MIT report also favors permanent disposal of spent fuel in deep boreholes. This would lead to a steady reduction in useable fissile material and worsen the problem of nuclear sustainability. Consequently, these bold recommendations lead us to analyze two alternative and contrasting nuclear technology development pathways.

In the first pathway, which we will call the **restricted-technology pathway**, we will assume that the recommendations in the MIT report are followed and that economically
successful development and deployment of evolutionary Gen-III reactor technology occurs using a once through fuel cycle with permanent plutonium disposal.

The contrasting nuclear technology development pathway, which we will call the sustainable-technology pathway, assumes enhanced public investment in the development of advanced reactor and fuel cycle technology. This pathway is assumed to lead to the economically successful deployment of advanced Gen-III reactors with the early development and introduction of advanced fuel reprocessing and/or Gen-IV reactors when the cost of natural uranium increases sufficiently.

In order to accommodate the legitimate proliferation concerns outlined in the MIT study, the sustainable-technology pathway would have to be approached as an international venture from the beginning in order to simultaneously craft a secure, as well as technologically advanced, nuclear fuel cycle. This sustainable-technology pathway would allow Gen-IV technology to evolve so that it covers the full range of nuclear fuel technology factor improvements indicated in Figure 3 and within an integrated internationally managed fuel cycle.

Since we are comparing conceptual and relatively undefined nuclear systems, we will require that these two contrasting pathways will result in the same electricity cost range and, hence, the same energy production and carbon reduction as the evolutionary Gen-III pathway presented above. This corresponds to the postulated nuclear deployment in the MIT study and allows for a straightforward comparison of the alternative technology pathways.

The resulting uranium commitment for the restricted-technology pathway is shown in Figure 8 and for the sustainable-technology pathway in Figure 9.

The restricted-technology pathway is similar to the evolutionary Gen-III pathway until 2050. However, by the end of the century increasing global demand requires more than double the number of reactors deployed in 2050. Without reprocessing, deployment of technologically successful (lower capital cost) Gen-III reactors requires the commitment of essentially all of the ore in the earth’s crust that is estimated by the geological model.
to contain more than 1000 ppm of uranium. Permanent disposal of the $^{239}$PU contained in the spent fuel from these reactors would prevent, or at least significantly delay, the deployment of advanced fission reactors to replace the Gen-III reactors that would be operational by 2100.

By contrast, the sustainable-technology pathway assumes that Gen-IV reactors are developed from near-term technology investments so that they can be deployed after 2050. If this development is fully successful as shown by the upper solid curve in Figure 9, Gen-IV reactors begin replacing their lower-fuel efficiency Gen-III forebears after 2050 and the rate of growth of the uranium fuel commitment is gradually reduced. Once high breeding ratio reactors are deployed, they could provide energy for hundreds of years using only the $^{238}$U in the tails from Gen-II reactor uranium enrichment.

For less successful development, or with the slower deployment in the absence of an atmospheric stabilization policy, the replacement of Gen-III reactors is slower and the uranium fuel commitment is still growing at the end of the century. In any case, and in spite of the availability of GEN-IV technology by 2050, the uranium commitment by the end of the century is still roughly twice the Redbook estimate of uranium resources that might be available at less than $130/kg. This indicates that assuring the availability of a sustainable nuclear energy contribution to a carbon-neutral energy system requires the earliest possible introduction of advanced reactors and fuel cycles.

**Technology Development Implications**

A few of the current Gen-III reactor designs are potentially deployable in some regions within the next decade. Since there will be continued market pressure to reduce costs by various means, the capital cost of Gen-III technology should decline further as experience is gained with operation. Consequently, we have modeled the success of Gen-III technology development along the evolutionary pathway by assuming that nuclear reactor fixed costs decline slowly with time at ~0.9%/y until 2050 and increase only slightly thereafter as the fraction of MOX fuel increases. The assumed Gen-III capital cost index along the evolutionary-technology pathway is shown in Figure 10 along with the capital cost indices for the contrasting restricted-technology and sustainable-technology pathways. Since we require the same nuclear electricity cost, and hence same market share, for all of the pathways, the latter two capital cost curves represent technology development targets that would make one indifferent to pathway, at least with respect to energy supply and carbon reduction in this century.

As expected, the required capital cost reduction is greatest for the restricted-technology pathway that is associated with the largest uranium consumption. In order to compensate
for the rising fuel cost along the restricted-technology pathway, the capital cost of the reactors would have to decline 33% by 2095 relative to the evolutionary Gen-III reactor cost in 2050. This magnitude of cost reduction would probably require new reactor technology well beyond the Gen-III envelope. It would certainly not be possible without an intensive nuclear technology development program, which, in addition to the learning associated with the vast expansion of nuclear fuel production, would vitiate the rational for pursuing this pathway in the first place.

On the other hand, the capital cost target for the higher fuel-efficiency Gen-IV reactors can be higher than for the Gen-III reactors because of the reduced fuel consumption resulting from a gradual increase in the average fuel-efficiency. The average capital cost of the evolving Gen-III/Gen-IV portfolio can rise about 20% relative to the evolutionary Gen-III standard by 2095. This cost increase is at the optimistic end of past estimates of relative fast breeder and light water reactor costs and achieving this cost target would also require an intensive nuclear technology development program including both reactor and fuel cycle development. However, we find large uranium consumption even with the introduction of relatively fuel-efficient Gen-IV technology by 2050. It appears that achieving the sustainability goal may also depend on an early start to the technology development programs to allow an even earlier introduction of economically competitive Gen-IV reactors.

In the conclusion of his pioneering analysis of the uranium distribution in the earth’s crust, Deffeyes (33) expressed confidence that there would be enough fissile material to supply a greatly expended nuclear energy system for centuries. However, he also frankly acknowledged the large uncertainty in statistical estimates of uranium resources. His optimistic conclusion was based on his recognition that, if it could be developed, fusion energy would provide the ultimate backstop for providing fissile material. Relative to fission, the fusion reaction is energy poor and neutron rich. One fusion reactor might be able to produce enough fissile material for a dozen breeder reactors of comparable power (44). Given the need to develop a significant and sustainable nuclear component of a carbon-neutral energy system by the middle of this century, and the associated fissile fuel requirements, that fusion backstop might be needed on that same timescale as Gen-IV reactors.

**International Development and Security Implications**

The nuclear technology development path that is chosen has the most significant consequences for global development and carbon stabilization after 2050 when the
energy demand and carbon emissions of currently developing nations is expected to peak.

This global distribution of energy demand is particularly important for nuclear technology development. Although sensitive to long-term environmental change, developing nations must address many immediate problems with limited resources and the major investment in the development of more sustainable, longer-term energy sources will have to be made by the advanced nations. Advanced nuclear technology, which has high potential as a sustainable global energy supply, is a case in point. In this vein, the Council of International Nuclear Societies concluded, “advanced nations should strive for the development of advanced nuclear power plants, especially the fast breeder reactor system with plutonium recycling” (45). However, as decades of international discussion about nuclear development and its relation to proliferation have revealed, this can not be interpreted as a recommendation for independent investment in nuclear technology by the developed nations.

Figure 11 shows the global distribution of the succession of nuclear reactor technologies along the sustainable-technology pathway discussed above. The current nuclear nations and the rest of the world (ROW) will deploy nuclear technology differently over the next century due to differing energy demands associated with their development rates. Referring to the uranium commitment shown on the sustainable-technology pathway in Figure 9, one can see that, because GEN-III reactor deployment occurs predominantly in the nuclear states early in the century, most of the world’s low cost uranium would be committed to the reactors deployed in these states. By contrast, the developing nations in the ROW are found to deploy a smaller number of GEN-III reactors and to satisfy the bulk of their development needs later in the century using GEN-IV reactors and fuel cycles – assuming that these have been developed.

The potential commitment of the lower cost uranium supplies to the developed nations provides the ROW a strong incentive to develop and deploy advanced fuel cycles and reactors. Conversely, this sequence of technology development also provides a strong incentive to the nuclear states to develop an international reactor and fuel cycle development regime that will prevent uncontrolled proliferation (46).

Discussion and Conclusions
Based solely on its technological potential, it might seem that nuclear energy could play a very significant role in providing the world’s future energy for hundreds if not thousands of years. However, there are difficulties in realizing this potential.

Given the expected scale of global development over the next century, satisfying all of the Gen-IV sustainability criteria would involve developing and deploying—simultaneously or sequentially but in an internationally coordinated manner—a variety of nuclear reactor designs that are intimately linked through their interdependent fuel cycles. However, in an increasingly competitive global economy, market decisions to invest in developing and deploying energy supply technology are made sequentially based on local conditions and near-term market expectations. The motivation for investment in energy development involves riskier estimates of long-term market evolution and uncertain future technology requirements. Thus, there is little commercial motivation for supporting investment in the long-term development of a sustainable nuclear energy system.
Given the bold objective of the Framework Convention on Climate Change, the public sector should be motivated to undertake advanced nuclear technology development. However, in spite of the significant foundation laid by the organization of the GIF, there is yet no effective international effort to actually develop an advanced nuclear energy technology system. Many nations maintain nuclear development programs but, while total nuclear development resources are not inconsequential, many national efforts are duplicative and individually sub-critical relative to past development efforts that resulted in Gen-II reactors and the potential Gen-IV system concepts. In particular, the transition and developing countries, which will provide the greatest long-term energy demand, cannot afford independent nuclear development programs commensurate with their future needs. In the developed countries, the reduction in public sector funding for energy makes it unlikely that even the wealthier nations will provide the necessary investment to produce individually the integrated advanced nuclear system envisioned by the Gen-IV Roadmap.

As foreseen by statesmen in the earliest days of fission development, international integration of nuclear governance, as well as technology, will be necessary for the development of a sustainable global fission energy system. Their pioneering efforts succeeded in establishing an international inspection regime under the IAEA but nuclear technology development has remained largely the province of individual nations.

In the past, uncoordinated global development of different nuclear technologies had the benefit of exploring a wide variety of nuclear science and technology and made little difference for the relatively small-scale market deployment that has occurred. However, the Gen-III technologies that have evolved because of market forces have relatively low thermal and nuclear fuel conversion efficiencies and are likely to depend on once-through fuel cycles until the middle of the century.

If these Gen-III technologies were to be highly successful, their large-scale deployment would deplete current uranium resources and increase the relative cost of nuclear electricity. While this might not be a serious impediment to Gen-III deployment in the first half of the century, the resulting scale of fissile fuel consumption could prejudice the sustainability of nuclear energy on a climate timescale. And, even if natural fissile resources are larger than geological estimates suggest, the uneven regional distribution of the lowest cost resources and development patterns could lead to unacceptable regional dependences on foreign fissile fuel supplies, which could result in tensions analogous to those resulting from the distribution of oil and gas resources today. While small nations such as Korea can import 97% of their energy today, it is unlikely that large countries such as the EU, China and India would find such a nuclear fuel dependence to be attractive in the future.

Both the resources required for developing an integrated Gen-IV technology system and the limited amounts and uneven distribution of low-cost fissile resources, argue for a more coordinated international development effort to support sustainable global-scale nuclear energy development in the future. Nuclear energy is too pivotal an element in the global struggle to stabilize the carbon content of the atmosphere for it to evolve by drift and inertia.

A successful paradigm for international development of advanced nuclear technology is available in the successful development of the ITER collaboration. In the last fifteen
years, the ITER process has integrated decades of national fusion efforts into a global program of shared science and joint technology development to enable the critical next step in fusion energy development. If successful, the ITER experiment will generate half a gigawatt of fusion power and provide the science and technology information needed by any of the participants to develop fusion energy (50). Gen-IV fission reactors and fusion energy technology are alike in that, while neither is absolutely necessary for the next fifty years, it is hard to construct a sustainable global energy portfolio on the climate change time-scale without a substantial contribution from one or both. Sustainability on the climate time-scale, the security motivation and the very nature of nuclear technology all argue for this new degree of international technology cooperation.

While there are clearly major challenges that need to be addressed, nuclear technology, particularly the advanced designs currently contemplated in the R&D stage, may provide an energy alternative for many parts of the world that would advance our ability to address climate change. As suggested by the MIT study, a deeper analysis of the costs, benefits, and technical feasibility of various new fission reactor designs is needed. However, we also need to understand the consequences for the global nuclear fuel cycle of the sequential deployment of nuclear technology on a global scale over the next century -- rather than just the next fifty years. We need a better understand the technology evolution and competitive role of nuclear as compared to other technology options in the context of the larger global energy system that will grow from the effort to stabilize the earth’s climate.

Achieving a carbon free global energy system is a major challenge. Nuclear energy will be a pivotal technology in meeting this challenge but its sustainability will depend heavily on when and how it is developed and deployed. Our results show that it is very important to understand the details of a global fuel cycle for these advanced nuclear systems, and to integrate that understanding into an economic and environmental analysis that recognizes regional development differences. Finally, we find that an international approach to develop and regulate a global nuclear fuel system rather than just to develop new reactor technology will be an important factor determining the future sustainability of a global nuclear fuel cycle.

Acknowledgements: The authors are grateful for informative discussions with W. Sailor (Los Alamos National Laboratory), Ken Tomabechi, JAERI (Retired), Scott W. Heaberlin, Walter Apley and Michael Lawrence (Pacific Northwest National Laboratory), N. Nakicenovic (International Institute for Applied Systems Analysis) and Steve Fetter (University of Maryland).

1 GTSP Phase I was sponsored by a broad spectrum of international organizations drawn from both the public and private sectors, including the Battelle Memorial Institute, British Petroleum, EPRI, Exxon-Mobil, Kansai Electric Power, National Institute for Environmental Studies (Japan), New Energy and Industrial Development Organization (Japan), North American Free Trade Agreement–Commission for Environmental Cooperation, PEMEX (Mexico), Tokyo Electric Power, Toyota Motor Company, and the U.S. Department of Energy.


At a 5% discount rate nuclear power is more economically efficient than fossil in five of the nine OECD countries, which have high natural gas prices. At a 10% discount rate, nuclear electricity was more expensive in all OECD countries.


Grimston and Beck (Endnote 8) discuss the myriad economic, technological, regulatory and social issues affecting the prospects for the near-term deployment of nuclear plants in different regions. They also emphasize that the perception, and reality, of such matters can change on the decadal time scale natural to the energy industry.


The Westinghouse AP600, the GE ABWR or ESBWR and the FANP SWR 1000 were judged potentially deployable in the US within the next 20 years. All are thermal, light water reactors. Gas cooled designs were less likely to be deployable unless supported by additional government or private technology investment. See Endnote 10.


Dooley et al (Endnote 13) note that governments and utilities in deregulated environments are shifting their nuclear R&D away from reactors toward the back end of the nuclear fuel cycle, waste disposal and reactor decommissioning.


With then current reactor and reprocessing technology, Endnote 16 concludes that uranium prices would have to approximately triple to make MOX recycle economically competitive. This study showed an insignificant fuel cycle cost advantage of the direct disposal option versus disposal via reprocessing. However, since then uranium fuel costs have declined even further.


The GIF, initiated in January 2000, is an international collective of leading nuclear nations. The United States, Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, Switzerland, and the United Kingdom are members. The IAEA and OECD/NEA participate as observers.


Clarke et al (Endnote 22) define a general reactor and fuel cycle model, which allows specification of $F_T$ in terms of the parameters that characterize individual reactors, or reactor types, and their associated fuel cycles.

25 The geographic regions are: USA, Canada, Western Europe, Japan, Australia & New Zealand, Former Soviet Union, Eastern Europe, China & Centrally Planned Asia, Middle East, Africa, Latin America, India, and (the rest of) S&E Asia.


28 The MiniCam model has been continuously up-graded and calibrated through participation in national and international collaborations. The model’s most recent updates are documented in Endnote 27.


30 The expectation of lower cost with improved uranium mining technology is plausible but not assured. Unlike other industrial production processes for which the inputs can be more readily controlled, or substituted, as knowledge accumulates and technology changes, the production of a mineral depends essentially on its concentration and chemistry within natural geological ores. The modal value of the progress ratio (the relative unit cost after a doubling of cumulative production) found from studies of many diverse production programs is about 80%, with a standard deviation of about 13%. However, using USGS historical data for 67 minerals provided by W. Sailor (Los Alamos), we estimating a learning rate for mining of 97% with a standard deviation of 12%. One might interpret this to mean that the depletion of high grade resources of the specific mineral being produced can raise unit costs at the same rate, or even a faster rate, than the specific mining technology can adapt.

31 Uranium Resource, Production and Demand (IAEA, Vienna, Austria, 2001).


34 Deffeyes et al (Endnote 33) construct an elegant, but admittedly heuristic, argument for estimating the geological abundance uranium ores. Considering that a sequence of random geological processes is responsible for the distribution of uranium concentration, they note that one might estimate the abundance of higher concentration ores by using the central limit theorem to justify a log-normal distribution of concentration. Unfortunately, for a finite number of stochastic processes, application of the central limit theorem provides very little information about the tails of the actual distribution. Nonetheless, the authors conclude that the trend of geological concentration in the tail of the estimated distribution seems to guarantee an ever increasing uranium supply as the uranium prices justify mining lower grades of ore. They did not estimate the production cost at lower uranium concentration. (See also Endnote 30)


36 We use the FCCG estimate of the elasticity relating uranium abundance and concentration: \( \frac{Q}{Q_0} = \left( \frac{C_0}{C} \right)^{2.5} \). We then assume that the mining cost is related to ore concentration by a general form \( \frac{P}{P_0} = \left( \frac{C_0}{C} \right)^{\alpha} \) so that

\[ \frac{Q}{Q_0} = \left( \frac{P}{P_0} \right)^{2.5} \]

A value \( \alpha = 1.29 \) gives an excellent fit to the Redbook estimates.


Speaking to the Uranium Institute, then Minister Adamov of Minatom flatly stated that “in the case of single use of MOX fuel in LWRs we reduce the potential to deploy fast reactors by more than half, and with multiple use of MOX fuel we totally eliminate the possibility for large scale nuclear power based on fast reactors.” (Endnote 39). Of course, at some economic penalty, one could stop recycling in order to accumulate the needed plutonium, or equivalently start a new generation of fast reactors with enriched uranium. In either case, because of a lower fuel technology factor, the uranium consumption and cost of fissile fuel would increase and the transition to fast reactors could be delayed.


Center for Global Security Research, 2004, “Atoms for Peace after 50 Years”, Lawrence Livermore National Laboratory, UCRL-TR-200297


Tomabechi and Velikhov (Endnote 41) make a strong case for an international regime to minimize the risks of misusing Pu. Placing the Pu to accumulated from the deployment of Gen-III reactors under an international control system could also smooth the transition to a sustainable global nuclear energy system in the future, by providing a mechanism to facilitate supplying Pu for the initial inventories of fast reactors in both developed and developing regions.


The current ITER participants are the European Union, China, Japan, Korea, Russia, and the United States. “The ITER project is a unique model for effective international collaboration in science and technology. By pooling their resources and expertise and by having access in common to all the information coming out of the work, the ITER participants realize much greater returns on their inputs to the project than they could do alone.” http://www.iter.org/