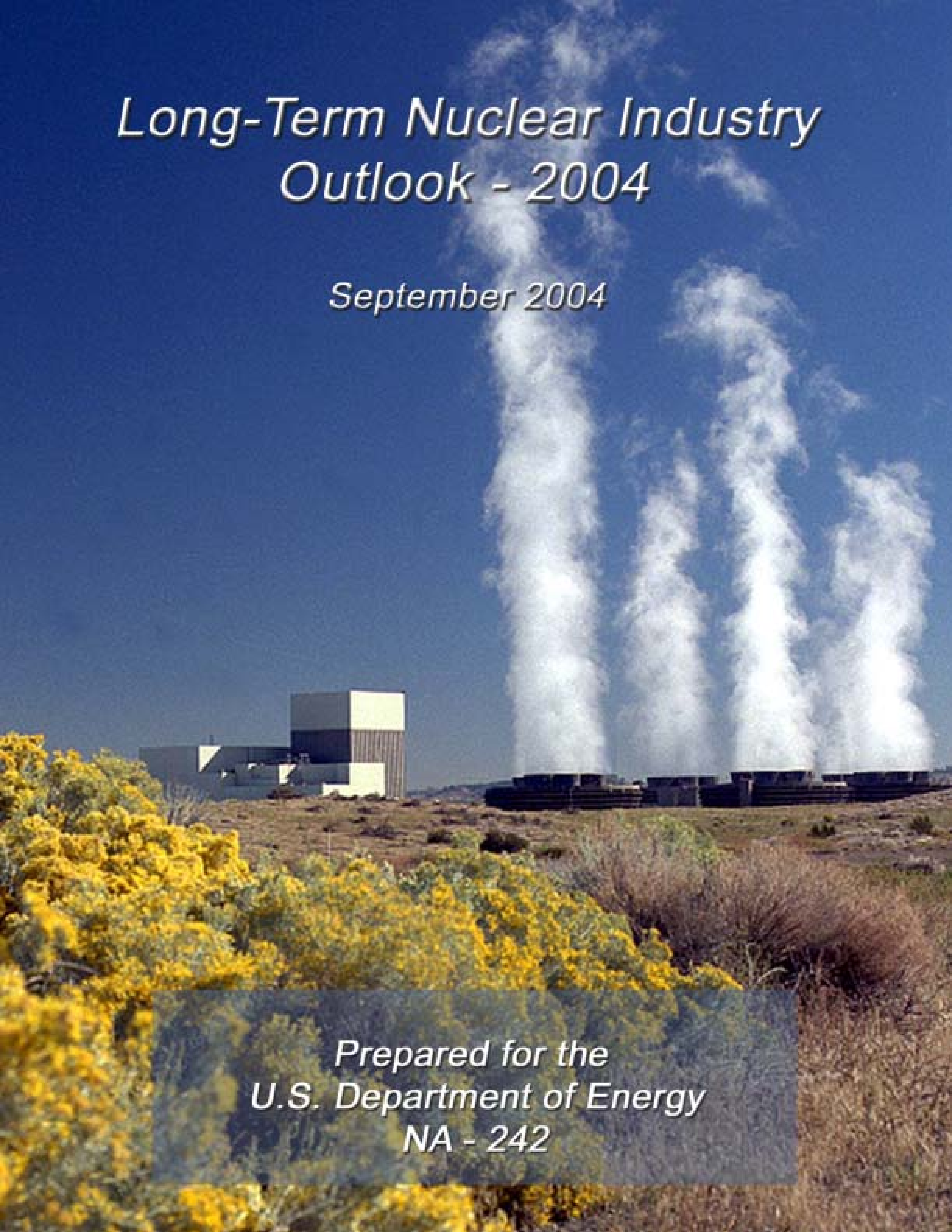
Long-Term Nuclear Industry Outlook - 2004

September 2004



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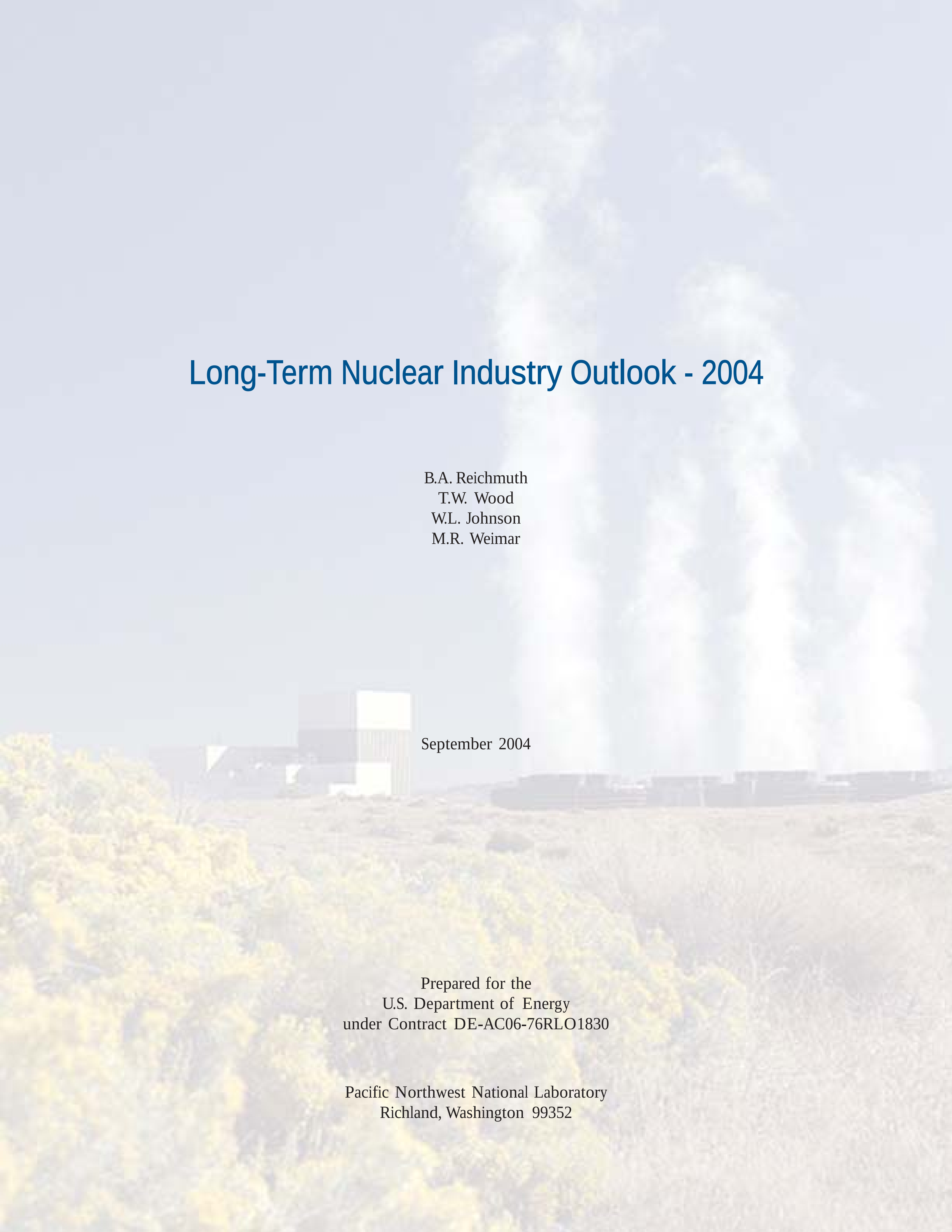

Long-Term Nuclear Industry Outlook - 2004

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Contents

Executive Summary

The nuclear industry has become increasingly efficient and global in nature, but may now be poised at a crossroads between graceful decline and profound growth as a viable provider of electrical energy. Predicted population and energy-demand growth, an increased interest in global climate change, the desire to reduce the international dependence on oil as an energy source, the potential for hydrogen co-generation using nuclear power reactors, and the improved performance in the nuclear power industry have raised the prospect of a "nuclear renaissance" in which nuclear power would play an increasingly more important role in both domestic and international energy markets.

Conversely, history reveals four obstacles for the industry to overcome: 1) nuclear electricity generation costs that are not competitive with the generation costs for alternative approaches, 2) real and perceived concerns about plant safety in terms of accidents and terrorist attacks, 3) the waste management issue, and 4) the non-proliferation issue (i.e., avoiding the diversion of nuclear materials from nuclear plants to nations or organizations that could use the materials in weapons or as a threat). From an economic perspective, nuclear plants that have the potential to be profitable will support a viable industry, which will find solutions to safety and waste management concerns. The cost barrier may prove to be the overriding decision factor in whether the industry begins to decline or expands. These contrasting future possibilities largely determine the possible geographic distribution of nuclear power reactors and the character of economic and research and development (R&D) activities related to the industry. As such, these distinctly different possibilities provide the global context for global nuclear technology commerce and export controls of nuclear technology.

The U.S. role as a dominant supplier of technology for the nuclear industry worldwide, in particular, is subject to significant change that will depend on the direction taken by the industry over the next 10 years. In fact, the U.S. role as a dominant technology supplier is already becoming misaligned with the current forecasts for new plants, the majority of which will be located in developing Asia). This market domination is largely an artifact of past investment and cannot be sustained indefinitely, particularly if all of the new plants ordered will be built outside the United States.

The recent (i.e., the last two decades) historical paradigm for the nuclear power industry can be described as construction of few new plants globally, consolidation of vendors for the industry, and a shift toward developing Asia (e.g., China, India, and Korea) as the growth area for new reactors. Nuclear power is viewed a "private good" in most parts of the world and it gets treated as such.

This market economic paradigm has also been evident in the R&D domain as well. There has been a general acceptance that nuclear-generated electricity needs to meet a competitive price point (without carbon credits) and that the industry needs to meet safety, waste acceptance, and non-proliferation constraints. This paradigm has been applied to many reactor design concepts, each of which has (at least to date) received insufficient development support to achieve significant market penetration.

Long-Term Nuclear Industry Outlook

A new paradigm for thinking about nuclear economics and R&D, based on the following two factors, may be emerging.

1. Recognition that the carbon benefits resulting from the use of nuclear power to generate electricity are public in nature and are increasingly valuable in the context of sustainable economic development.

2. The possibility of re-inventing the transportation fuels sector using hydrogen as the fuel of choice, and the technical attractiveness of nuclear power as a process heat source for hydrogen production. The scale at which hydrogen production would be required implies that government involvement will be necessary.

These factors, along with the restructuring that has occurred in the nuclear industry, will help determine whether the U.S. nuclear industry faces graceful decline or experiences profound growth. This report examines these possible futures and some of the implications of U.S. export control policy which might be impacted.

In its report entitled *The Future of Nuclear Energy*, the Massachusetts Institute of Technology recently concluded that an expanded use of nuclear power is needed in order to avoid billions of tons of CO_2 emissions to the atmosphere (MIT 2003). The report recommends that government resources be refocused on only one or two once-through fuel cycle designs, thereby streamlining the design effort and abandoning the current multiple/parallel research paths for competing fuel cycle and reactor design concepts.

Only a future in which nuclear reactors are used for hydrogen production creates both significant cost advantage and large numbers of new plants in the U.S. or Western Europe. Such a future would require a “new” (beyond current light water technologies) reactor technology and a *broad international R&D program* to bring it on line in a timely fashion. The development consortium will likely be a global entity (comprised of both industrial and multi-national government partners). Export control policy for such a reactor design will also likely be undertaken in a new multilateral framework formed by the countries in the development consortium.

1.0 Background and Context

In 1999, the National Nuclear Security Administration initiated a project at Pacific Northwest National Laboratory (PNNL) to evaluate the effects of globalization on the nuclear industry and the resulting impacts on export controls. To address these issues, PNNL organized the project (known as the Globalization Project) into phases. The first phase considered whether or not the nuclear industry was in fact globalizing. Globalization was defined by Wood et al. (2000) as a phenomenon in which "…a company attempts to integrate all aspects of asset management, production, and sales in such a fashion as to *minimize the constraints associated with national boundaries*…" The major findings from this first phase are briefly described below.

- The nuclear industry is significantly global in character and is becoming more so.
- Industry consolidation is occurring and is complementing other factors that promote globalization.
- To the extent that a global firm is designed to expedite the sharing of technology and the flow of information among its operating divisions, significant "export" transactions will be masked or missed.
- Several large nuclear technology firms exhibit the salient characteristics of a global corporation.
- Traditional export control mechanisms have not kept pace with technological developments.
- Better understanding and reform of export control regimes is needed.

The second phase of the Globalization Project examined the characteristics of a global nuclear renaissance and its broad implications for industry structure and export control relative to nuclear technology (Wood et al. 2001). The conclusions of this research were that modest improvements in the costs of nuclear power plants, coupled with the recent record of substantially improved operational performance, continued steady increases in power demand, and concerns over fossil fuel emissions, could result in the realization of a nuclear renaissance within the next several decades.

In the third phase of the Globalization Project, an in-depth look at the nuclear fuel fabrication sector was undertaken to assess the degree to which globalization had occurred in this sector and the potential impacts of rapid transfer of materials production technologies across the globe. Research supported the consolidation trend in the fuel fabrication sector, but stopped short of labeling the sector as having become globalized (Wood et al. 2002). The key differentiators were the fact that the consolidation was driven by economics in the industry—consolidation to meet economies of scope and scale—and the absence of a wholesale relocation of manufacturing plants to areas of low labor cost. Even though the fuel fabrication sector has not reached complete globalization, industry consolidation to a small number of global suppliers still poses significant challenges for the existing export control regimes under current policies and measures. Recent focus on export control policy reform also presents an opportunity to address nuclear material, equipment, and technology transfer in the context of the "global supplier".

This report, *The Nuclear Industry Outlook*, documents the next phase in the assessment of the role nuclear-generated power will play in the global energy future and explores its ramifications on export controls. An enormous increase in global energy demand, driven by standard-of-living improvements and population growth (particularly in the developing countries), projected shortages in fossil fuel resources, and the requirement for clean energy on a global scale, provides the backdrop against which the next two to three decades of nuclear industry development will occur. Coupling this set of factors with the desired move to a "hydrogen economy" could precipitate changes in the nuclear industry more fundamental than any it has experienced since its inception. The nuclear industry currently is poised at a crossroad in its development, a point beyond which it could move toward a graceful decline or a renaissance. This paper examines the prospects for nuclear commerce in the world this century and discusses the ramifications of this revival for export controls.

The Nuclear Industry Outlook report is organized as follows. Section 2 provides an overview of the current state of the global nuclear industry, and Section 3 assesses energy demand projections, population growth, and other factors likely to influence energy demand, including the transition to a hydrogen economy. Energy supply factors are presented in Section 4, including an assessment of the state of reactor technology R&D and the transition to a hydrogen economy. Finally, Section 5 provides an assessment of these potential changes to the nuclear industry on export controls.

2.0 Current State of the Nuclear Industry

In the last three decades, the global nuclear-generated electricity industry has come of age as a competitive economic sector. It has transitioned from an industry launched by generous national investment and protected from price competition in regulated monopolies to one in which the laws of economics are the governing tenets in much of the developing world. Countries utilizing nuclear power represent two-thirds of the world's population (Figure 1).

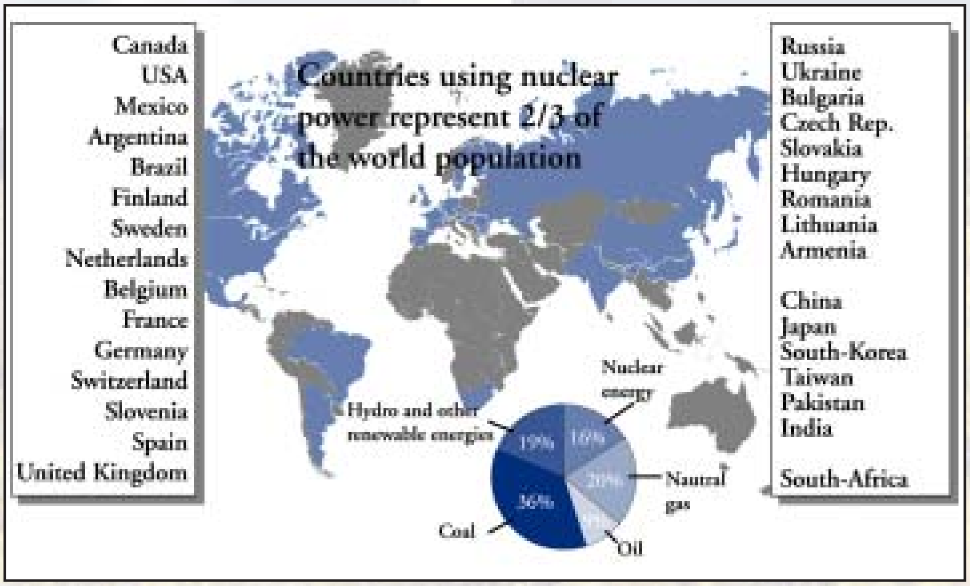

Figure 1. Global Representation of Nuclear Power Use (ICONE 2003)

For four consecutive decades, including the 1990s, nuclear power has been the fastest growing major energy source in the world (World Nuclear Association 2003). There are now 438 commercial nuclear reactors, with a total capacity of 365,852 MWe, operating in 31 countries (Nuclear News March 2004). Figure 2 shows the mix of countries with their respective shares of nuclear-generated electricity.

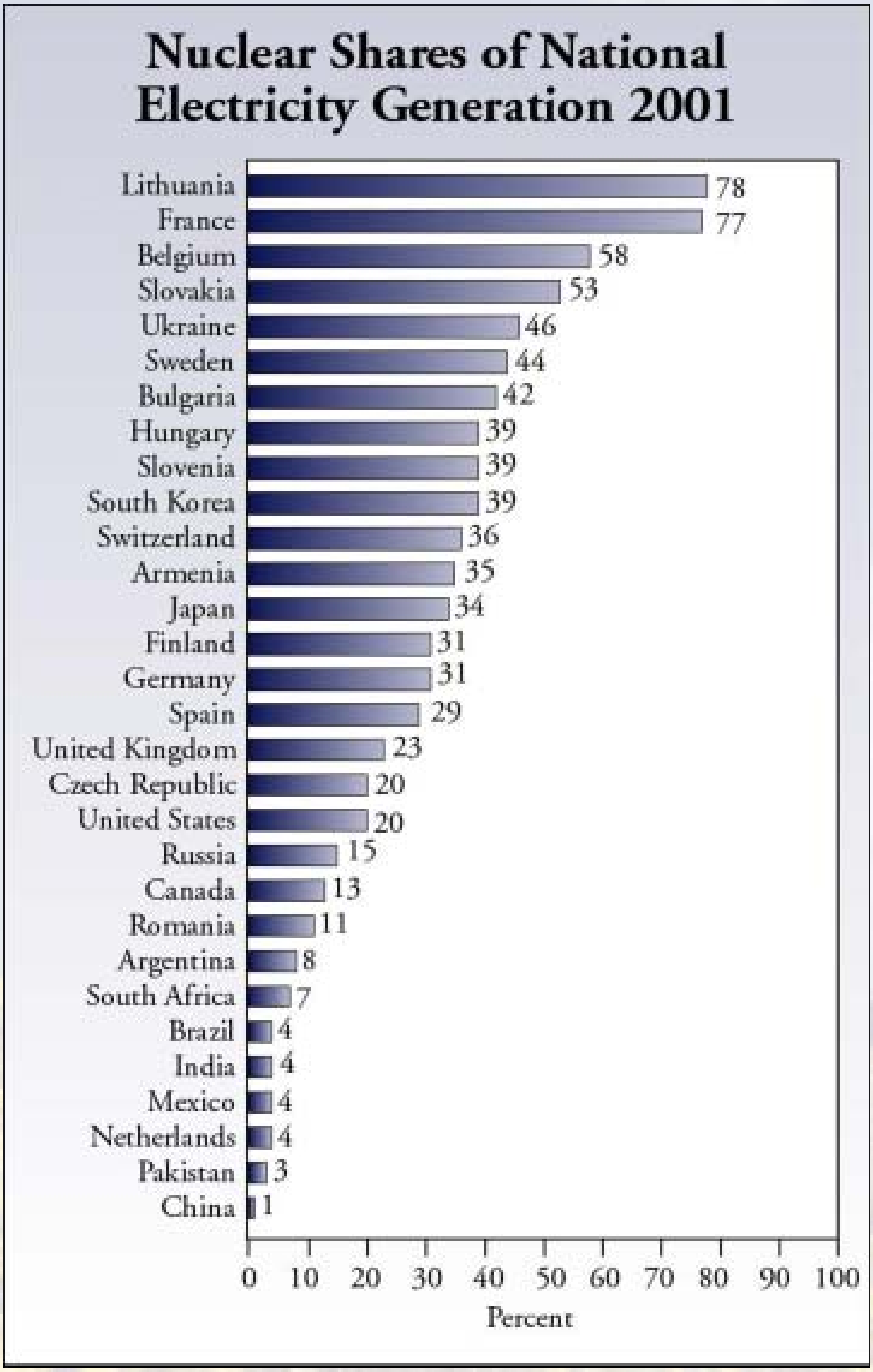

Figure 2. Nuclear Share of Electricity Generation (EIA 2003)

Worldwide, the nuclear industry has seen an increase in production capability that up to now has come primarily from upgrades at existing plants and from significantly improved operational efficiency in the existing nuclear power plants designed to generate electricity. Figure 3 shows the leading industrial contractors and their respective power generation sources with nuclear energy in dark blue. Today's electricity-generating nuclear power plants run very efficiently and compete successfully with all other types of base-load generating plants. Safety statistics continue to improve, downtime for refueling outages continues to decline, and the cost per kilowatt-hour (for already depreciated nuclear plants) is very competitive with the operations cost of other electricity-generation sources. However, these operational improvements have likely reached a sustainable plateau and can no longer be viewed as a significant source of future increases in production capacity. To a large degree, future nuclear growth will come from new plants.

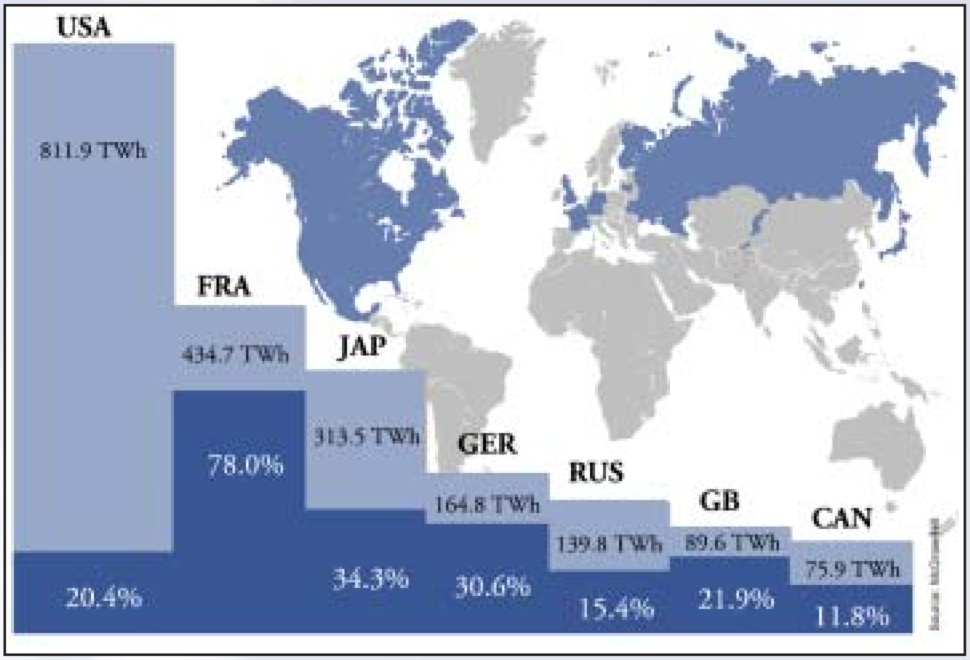

Figure 3. Nuclear Power Gneration (in TWh as a Percentage) in Leading Industrial (G8) Countries
Source: Dr. Ralf Guldner (ICONE 2003)

The MIT report concluded that, **"over at least the next 50 years, the best choice to meet these challenges is the open once-through fuel cycle."** An underlying premis is that there are adequate uranium resources to support this choice under a global growth scenario. Specifically, the MIT report recommends:

- Realigning the DOE R&D program to focus on an open, once-through fuel cycle. This program should include an international uranium resource assessment and establish a large *"nuclear system analysis, modeling, and simulation project"* to assess alternative nuclear fuel cycle deployments relative to the four critical challenges (cost, safety, waste, and proliferation). The development and demonstration of advanced fuel cycles or reactors should be halted until the results of the nuclear systems analysis project are complete.
- Supporting the DOE 2010 initiative to reduce costs through new design certifications, site banking, and combined construction and operation licenses.
- That the governments share "first mover" costs for a limited number of power plants that represent safety-enhanced evolutionary reactor design. A tax credit for up to $200/kWe of the plant's construction cost was proposed.
- Federal and state portfolio standards should include incremental nuclear power capacity as a carbon free source.

- The DOE should broaden its long-term waste R&D program, to include improved engineered barriers, investigation of alternative geological environments, and include a system of central facilities for the long-term storage of spent fuel prior to geologic disposal.
- The IAEA should have authority to inspect all suspect facilities and should develop a worldwide system for materials protection, control, accounting.

The paradigm for construction of new nuclear power in the last two decades can be described as follows: few new plants have been ordered, no new plants have been ordered in the United States until this year, and the trend is toward constructing new plants in the developing regions of Asia (Figure 4). In assessing this new construction paradigm, it is relevant to note the geographic distribution including the fact that 20 of the 54 (or 37%) construction sites are in Asia. The United States for the first time in decades shows a planned addition of 3 pressurized light-water reactors (PWR's) forthcoming at the Wolf Creek Nuclear Plant in Burlington, Kansas. An increase in the number of countries with nuclear-fuel-cycle and power-plant facilities would result in new and increased demands for safeguards against the diversion of nuclear materials. In summary, the current trend in construction of new nuclear power plants tends to be toward the faster growing and poorer countries that do not have ready economic access to fossil fuels. The geographic distribution of this growth raises significant challenges for export control and non-proliferation generally.

Russia's Federal Atomic Energy Agency (formerly known as Minatom) will likely continue expanding exports of nuclear fuel and nuclear power plant construction while increasing its production of electricity in the near term. In the longer-term, if long-run cost estimates prove to be correct, Minatom likely will be unable to subsidize unprofitable production.

Country	Units	Total MWe
Argentina	1	692 *
Brazil	1	1,275
China (including Taiwan)	5	5,210
Czech Republic	2	1,824
Finland	1	1,600
India	8	3,580
✔ Iran	1	915
Japan	5	4,842
✔ North Korea (KEDO)	2	2,000 *
Romania	4	2,620 *
Russia	6	5,275
Slovakia	2	810 *
South Korea	8	8,800
Ukraine	5	4,850 *
United States (3 PWR's Forthcoming)	3	3,603
	54	47,896

*Construction suspended indefinately

✔ DOE Country of Special Concern

Figure 4. New Nuclear Plant Construction and/or Plants Forthcoming. (Nuclear News March 2004)

The factors likely to influence nuclear power demand include global energy demand, forecasted population trends, global climate change, and the potential transition to a hydrogen economy. These factors are explored in Section 3.

3.0 Energy Demand

Nuclear energy will thrive or decline in the context of broader markets for energy—specifically electrical power and (in a hydrogen economy) transportation fuels. Even without the special factors that constrain the use of nuclear power, the evolution of global energy markets is highly uncertain.

Reliable energy supplies are a major factor in social and economic development. Energy policy in the twenty-first century must address multifaceted and interrelated issues such as the unequal access of the world's population to energy, the risk to the earth's environment from climate change caused primarily by the production and use of fossil fuels, and with the advent of the war on terrorism, a focus on energy security and national defense due to the international dependence on oil.

Generally, total demand and total supply drive any industry. In the market for nuclear-generated electricity, a relatively small change in market share equates to a large change in the number of nuclear power plants needed to support that market share. In addition, the geographic distribution of nuclear power plants, the type of reactors in use and under construction, and government R&D into advanced reactor designs and fuel cycle enhancements are of particular interest because of the ramifications on export policy. This section deals primarily with the factors likely to impact the demand for nuclear power, including the transition to a hydrogen economy and its potential to dramatically alter world energy markets generally and nuclear markets specifically.

3.1 The Global Energy Dilemma

Several standard energy forecasts describe a stark dilemma for global energy use. Of the nearly 6 billion people on earth today, almost 2 billion have no access to modern commercial energy (IAEA 2002). Overwhelmingly, these people are among the world's most impoverished people. The United Nations predicts the ranks of the poor will triple in the next 50 years within a world population that is expected to grow to over 8 billion people by 2050 (Figure 5). The region defined as "developing Asia" (including India, China, North Korea, South Korea, Taiwan, etc.), which has approximately 54% of the existing world population, has a projected electricity demand at 2025 that exceeds current generating capacity by a factor of 2.5 (IEO 2003). If the population growth is coupled with the use of traditional, fossil-fuel-based sources, climate-altering emissions will grow dramatically also.

A number of different scenarios for energy consumption were reviewed for periods that span the next 25 years, the next 50 years, and through the end of the twenty-first century (about 100 years). Regardless of the source, projections over this time frame show tremendous energy demand primarily driven by increased economic prosperity, particularly in developing countries, and significant increases in world population. In many cases, however, these forecasts are based on assumptions that limit their information content for nuclear power, including constant real prices, constant shares of energy demand among fuels, etc., (EIA 2003). The underlying assumptions for these economic factors vary for among scenarios, but, none of the forecasts calls for the type of nuclear renaissance that would be likely in a "hydrogen economy". A review of international forecasts made by the World Energy Council (WEC) and the U.S. Energy Information Administration (EIA) follows.

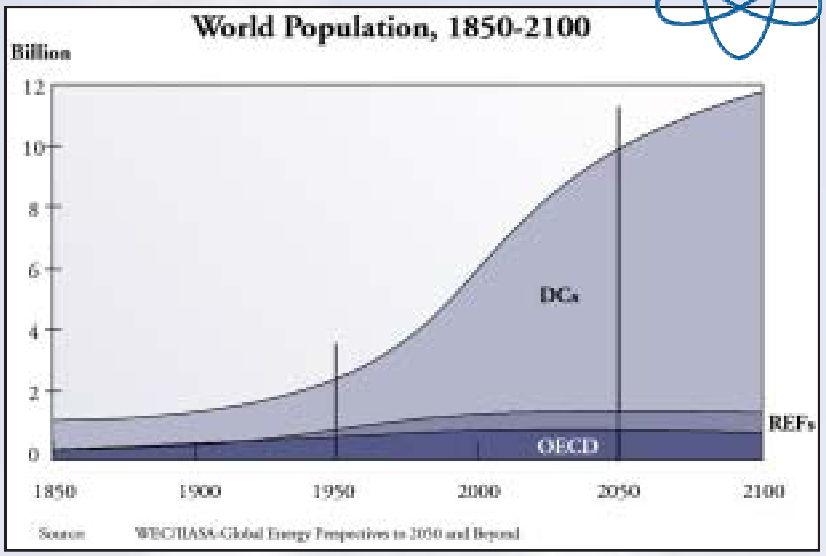

Figure 5. Historical World Wide Population Projections for the Twenty-First Century

3.1.1 World Energy Council Forecasts

The WEC energy forecast as depicted in Figure 6 projects significant and sustained energy growth anticipated through out the twenty-first century under a range of different scenarios, even in the low-growth scenario. As a point of reference, the midrange forecast calls for a growth rate about 40% greater than the average growth rate from 1950 to 2000, a period of rapid growth in the nuclear industry. In the WEC forecast, fossil fuels (coal, oil, or natural gas) are expected to continue their domination of the energy mix, although consumption of petroleum shows continued declines in the projections. Renewable sources of power (i.e., geothermal, solar, wind, tidal and wave energy, and biomass), taken as a group, will grow faster than other energy sources. However, they will still make only a small dent in global energy demand by the year 2030 because they start from such a low base. According to the World Energy Outlook 2002 (IEA 2002) other renewables share in total generation will grow from 1.6% in 2000 in 4.4% in 2030.

The WEC multiple scenario approach attempts to cover a wide range of possibilities. Each scenario is created using a number of building blocks, such as population projections, economic prospects, changes in energy efficiency, shifts between the various fuels (fossil and non-fossil), more or less successful technology innovation and diffusion, stronger or weaker efforts to engage environmental problems, larger or smaller mobilization of available investment funds, and more or less effective institutions and policies. WEC assumes that the "high case" represents a high-growth scenario in which there are significant increases in global economic activity,

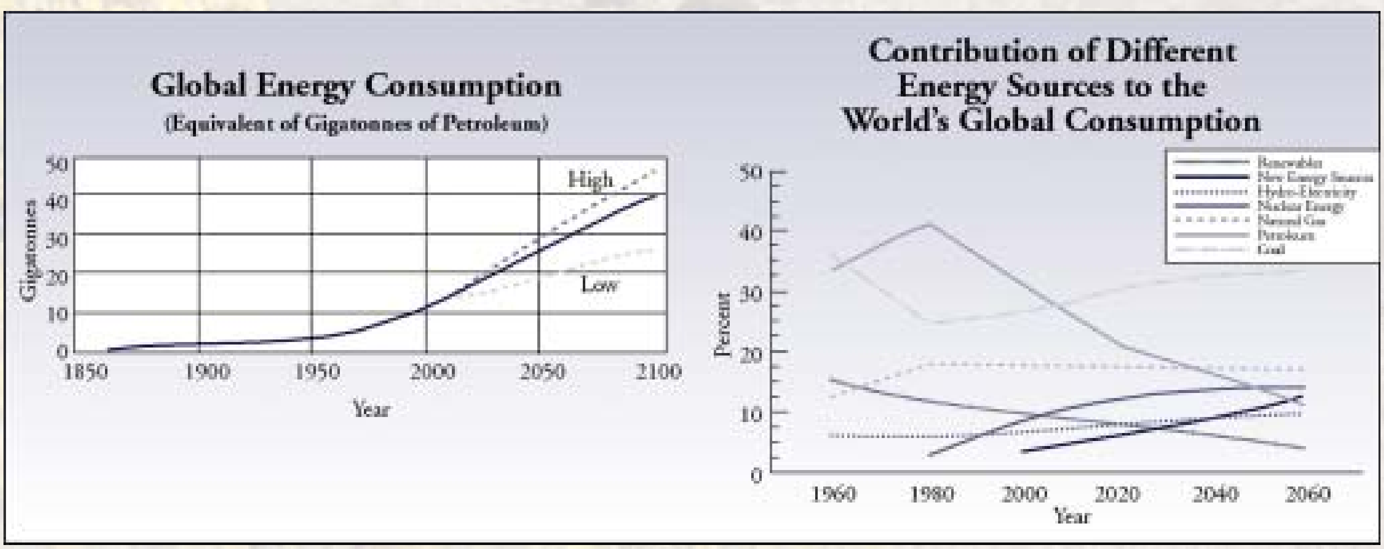

Figure 6. Global Energy Consumption and Sources of Energy Consumption (Diaz-Balart 2002)

energy consumption (particularly in developing countries), energy efficiency, and technological advancements. The middle, or reference, case represents a more moderate growth scenario with moderate growth in energy consumption in developing countries and incremental improvements in energy efficiency. Finally, the "low" case represents an ecologically driven case that promotes energy efficiency, technological innovation, and lower greenhouse emissions with the lowest estimates in energy consumption driven by policies intended to reduce emissions.

For context, using the WEC low-case scenario (a minimal economic growth scenario) to assess projected increases in energy consumption would require more generation capacity to be added in the next 20 years than the total capacity added in the last century. Assuming current energy market share distributions, this would lead to (Diaz-Balart 2002):

- Total daily oil consumption of 90 million barrels, an increase of 25 million barrels a day over the current consumption level of 65 million barrels.
- Annual consumption of 7 billion tons of coal, a nearly threefold increase over the 2000 consumption level of about 2.5 billions tons annually (IEA 2002).
- Annual natural gas production of 4 trillion cubic meters, an increase of 1.5 trillion cubic meters over the 2000 level of 2.5 trillion cubic meters.

3.1.2 Energy Information Administration Forecasts

The EIA's *International Energy Outlook 2003* (IEO2003) also projects robust increases in energy demand, particularly in the developing areas of Asia (including India and China) under a wide range of scenarios. EIA uses economic modeling to track and trend cyclical changes in worldwide economic growth. The forecasted prices of oil and the impact of these oil prices on economic expansion are significant factors that are considered in these models. Current projections indicate that the energy mix will still be dominated by fossil fuels. Although concerns about the supply of fossil fuels is evident, EIA projects that supplies will take us to the end of the 21st century at current expenditure rates. These projections are based on the assumption that prices will continue to remain relatively low and the cost of generating energy from other fuels will not be competitive. EIA does not have a scenario that assesses the impacts of changes in government polices designed to limit or reduce greenhouse gas emissions. Irrespective of source (i.e., EIA, WEC, etc.) significant increases in energy demand are projected over the next 25 years, the next 50 years, and throughout the twenty-first century.

3.2 Electricity Demand

When the focus shifts specifically to electricity, the EIA reference case (the moderate economic growth scenario) projects that, by 2025, worldwide demand for electricity will increase by a factor of about 1.77 times over the 2001 level (or to 24,673 billion kilowatt-hours, an increase from 13,934 billion kilowatt-hours). Demand for electricity is projected to increase 2.4% per year through 2025 based upon rapid growth in electricity use for a variety of electrical appliances in developing countries as the standard-of-living improves. This trend is particularly evident in developing Asia where growth in electricity demand is projected to increase by about 3.7% per year during this period as a result of rapid population growth, increased access to electricity, rising standards of living, and economic expansion. In the industrialized world, growth is projected at much slower rates, around 1.7% per year, because of lower population growth rates and incremental economic activity.

The developing world, represented by nations that belong to the Organization for Economic Co-Operation and Development (OECD), are still expected to be the primary electricity consumers in the world. Figure 7 summarizes the electricity demand for the world's industrialized and developing countries.

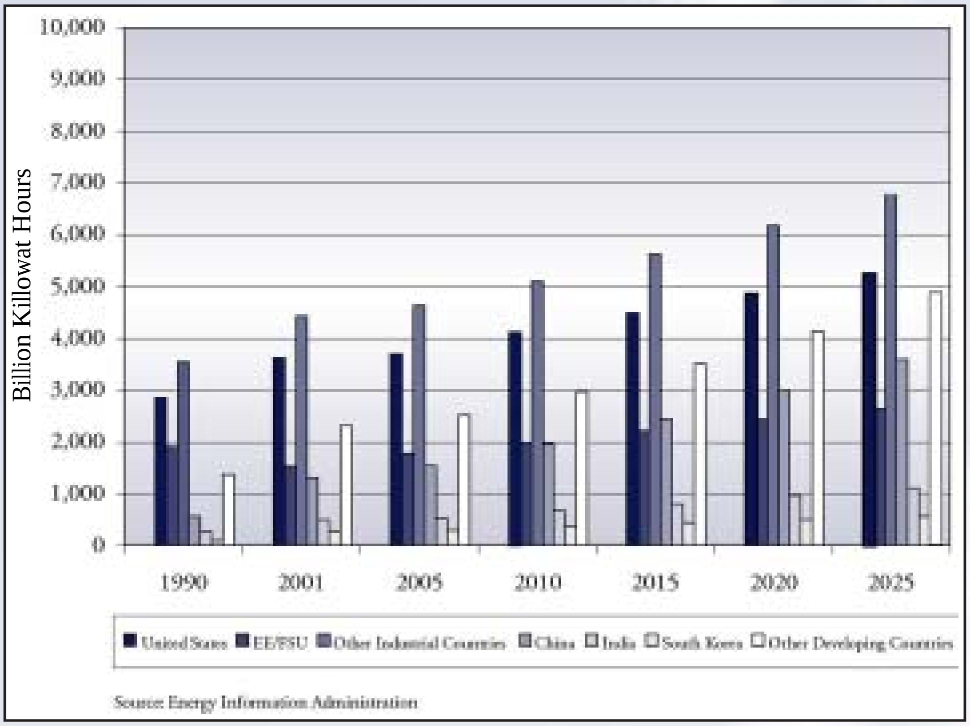

Figure 7. Projected Electricity Consumption for the World's Largest Users (EIA 2003)

According to the EIA forecasts, increases in electricity generated by natural gas, coal, and renewable energy sources and, to a lesser extent, by nuclear plants are expected to meet the projected increases in demand. EIA assumes continued public opposition to nuclear power, nuclear waste disposal issues, concerns about nuclear arms proliferation, and the economics of nuclear power *vis-a-vis* other electricity generation sources - in short, no nuclear renaissance.

3.2.1 Nuclear-Generated Electricity

Figure 8 shows the WEC current global distribution for energy sources used in electricity and primary energy distribution. In targeting nuclear-generated electricity specifically, both the *IEA 2002* and the EIA's *International Energy Outlook 2003* (IEO 2003) show relative declines in the share of nuclear-generated electricity in the world energy mix from its current rate of about 19% to 12% in 2025, despite a net increase in world nuclear capacity as a result of new construction and continued operation of the existing fleet of nuclear power plants. These forecasts are based on market-driven assumptions about supply and demand and the reality that, given current government policies and compared to the availability of natural gas or coal in countries

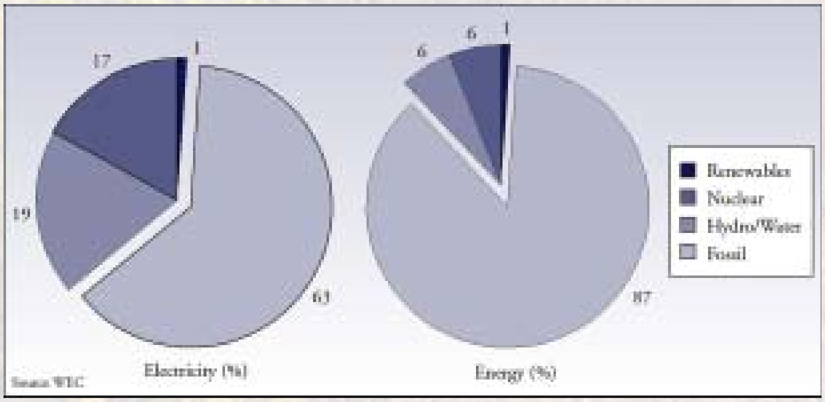

Figure 8. Shares of Energy Sources in Electricity and Primary Energy Generation

with inexpensive access to these resources, nuclear power is a relatively expensive option for electricity generation when new construction is needed.

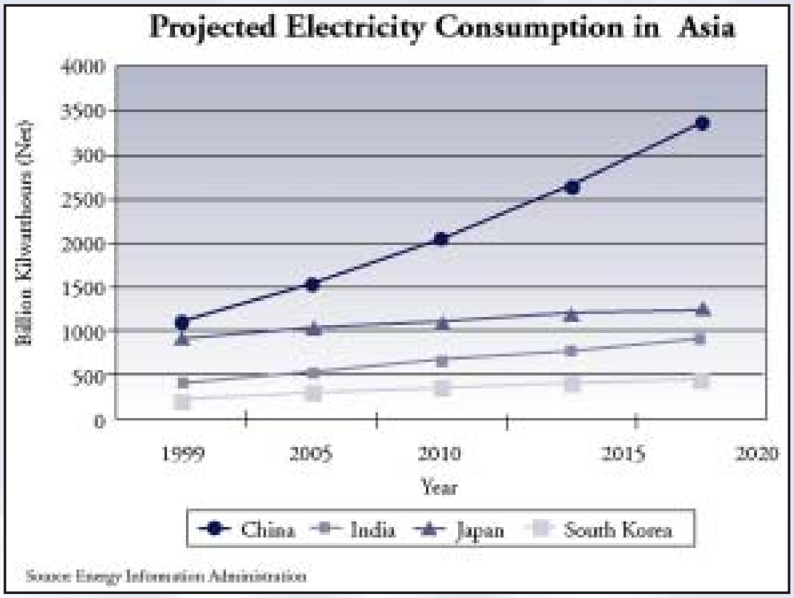

Figure 9. Projected Electricity Consumption in Asia

The exception to projected declines in nuclear-generated electricity comes from Asia, where both absolute and relative growth is projected. Figure 9 summarizes the projected electricity demand in developing Asia upon which the increased nuclear capacity projections are based. Japan, Korea, China, and India all have active nuclear energy construction projects and anticipate further growth in nuclear energy necessitated by their projected population increases and increases in their standards of living. In addition, Russia has embarked on an ambitious life extension program for many of their existing reactors and has announced its intention to replace retired nuclear capacity by new construction (at the same site), thereby validating their commitment to an ongoing nuclear program.

Future policy actions that might be taken to reduce CO_2 emissions (e.g., carbon credits and/or emissions trading), loan guarantees, changes in the price of natural gas and or oil, and pro-nuclear changes in a country's elected officials could all potentially impact assumptions of the share of electricity to be supplied by nuclear power in the future. According to Wood et al. (2001), "...a modest increase in the share of the nuclear power electrical market results in a very significant change in the number of plants under construction."

Although most long-term energy forecasts do not predict growth in nuclear power, the EIA forecast does show a high-case scenario in which nuclear energy does increase to about 567 net gigawatts (GWe) from the current level of 353 GWe—approximately 1.6 times current plant capacity as shown in Figure 10. Given the current global plant inventory of 444 (excluding new construction), this would mean **an additional 266 plants needed by 2025.** Assuming a 5-year construction schedule, this forecast would result in an additional 53 plants under construction at any given time. This level of international nuclear technology commerce would represent roughly an 8 to 10 fold increase over current levels and could challenge export control regimes depending on anticipated reforms and the ability to accomodate growth of this magnitude.

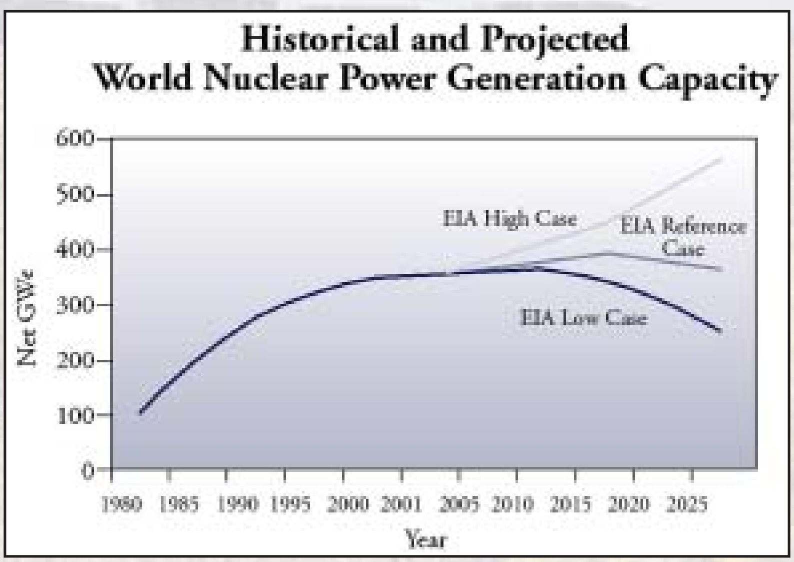

Figure 10. Historical and Projected World Nuclear Power Generation Capacity
Source EIA (IEO 2003)

Industry organizations like the World Nuclear Association, WEC, Nuclear Energy Industry, the International Atomic Energy Agency

(IAEA), and trade publications like *Nuclear News* proclaim that there is not a question that a nuclear renaissance will occur, merely a question of when it will happen and how significant it will be. According to John Ritch, III, of the World Nuclear Association, nuclear energy is at a "moment of truth" because of improvements in reactor technologies, probable shortages in fossil-fuel supplies, climate change concerns, and the transition to the hydrogen economy.

On the issue of capacity replacement, the EIA's *International Energy Outlook 2003* (EIA 2003) predicts that, based on the estimated construction costs of new nuclear plants versus the cheaper option of constructing fossil-fuel plants, old nuclear plants will not be replaced by new construction as they are retired. However, as cited above, new construction is highly sensitive to changes in the market share, which will more realistically drive additional reactor construction around the world.

3.2.2 The U.S. Nuclear Power Market

The United States, as one of the pioneers in the development and application of nuclear power and the world's leading nuclear power producer, serves as a very important indicator of the status of nuclear power and its future challenges. Based on the current global nuclear power status, the U.S. nuclear power industry appears to be a mature and stable market. Over the past 20 years, the average capacity factor in U.S. commercial nuclear plants has increased from about 60% to over 90% as depicted in Figure 11. This increase in capacity factor for existing plants is the equivalent of building 23 new plants (Foulke 2003). The fleet of current U.S. nuclear plants includes 103 operating reactors with a total generating capacity of approximately 99,034 MWe. The operational safety record of the fleet has also been excellent and, in addition to increased capacity factors, operations and maintenance costs have improved primarily because the frequency of refueling outages has been reduced from the once standard 12 months to 18 months, with the expectation of further extensions to 24 months. With improved fuel designs, the lifetime of fuel has increased significantly. Figure 12 shows the average duration of refueling outages reduced by a factor of 2.8. However, it should be noted that the reasonable upper limits of operational improvements have probably been reached so this area should no longer be viewed as a significant source of future increases in production capacity.

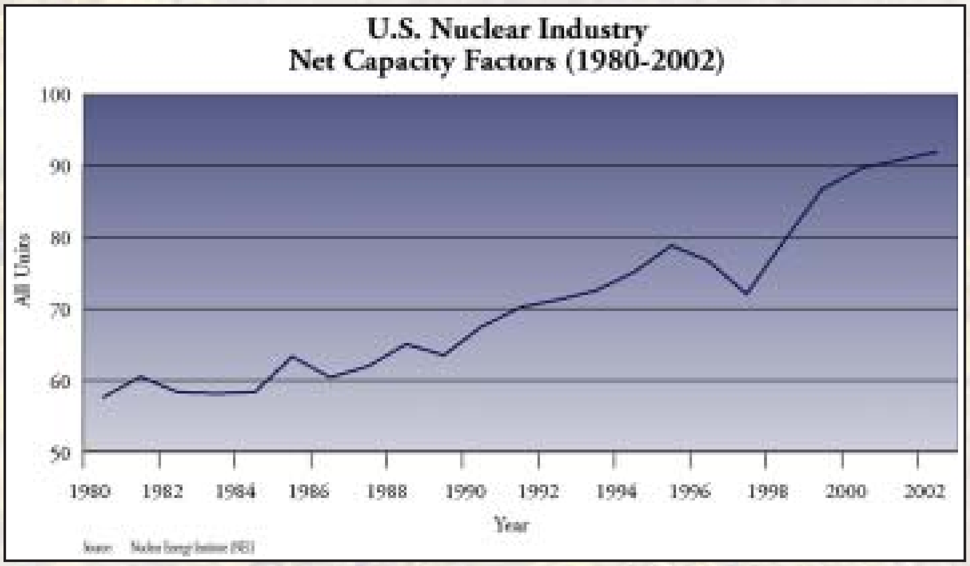

Figure 11. Net Capacity Factors in the U.S. Nuclear Industry (NEI 2003)

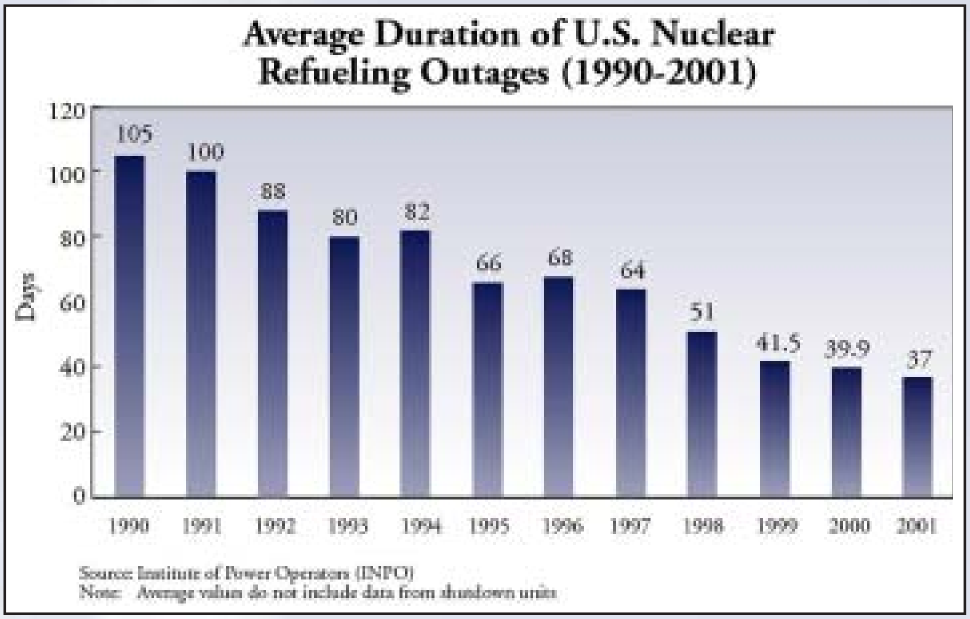

Figure 12. Average Duration of U.S. Nuclear Refueling Outages

The cost factor is sited as one of the most significant barriers to new nuclear plant construction. Nuclear power plant construction costs must include the cost of special safety factors and the cost of long-term waste disposal. U.S. licensing, inspection and certification delays in the 1970's were thought to have added large amounts of time and cost to the construction of nuclear plants built at that time. In addition, most of these plants were one-of-a-kind which created inefficiencies and forced cost up.

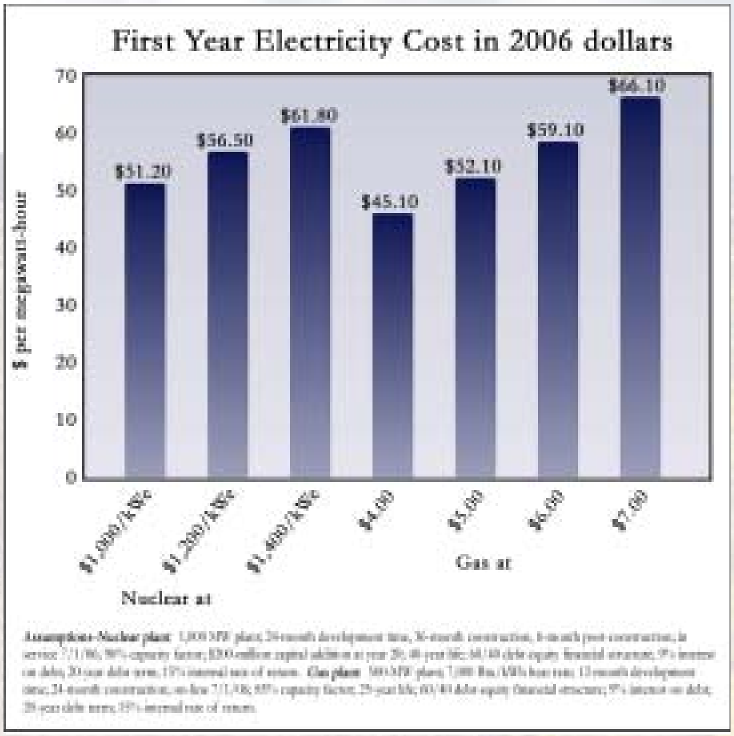

Figure 13. Competitive Position of New Nuclear Power Plants to Natural Gas Plants

No new nuclear plants have been ordered in the U.S. in nearly three decades, thus the cost to build a new plant today is uncertain. Technological advances via new reactor designs and an improved NRC licensing proces will likely help bring the cost down. In order to be competitive with coal fired and natural gas plants for base-load capacity, the nuclear industry believes that the capital cost of new nuclear plants must be in the range of $1,000-$1,200 per kilowatt of capacity. New reactor designs currently certified by the NRC, but yet to be constructed in the U.S., have an initail capital cost of $1,400-$1,500 per kilowatt. Figure 13 shows a Nuclear Energy Institute (NEI) comparison of the competitive position of new nuclear plant construction at different natural gas prices. Average natural gas prices in August of 2004 were approximately $5.75 which would indicate that nuclear would indeed need to be below $1,200 to be price competitive.

In a privatized nuclear power industry, private companies have been unwilling to invest in new nuclear construction. In order to ensure that nuclear power remains a feasible option, governments (either alone or in international collaboration) may need to provide stimuli for new construction. Policy approaches could be put in place to enable reliable construction schedules, faster licensing review procedures, and carbon emission cost incorporation to spur new construction.

When comparing the costs of various primary energy sources for electricity generation, nuclear-generated electricity is among the cheapest electricity available **once the plant is built and depreciated** with the production costs ranging from 1 cent/kWh to 2 cents/kWh. Electricity production costs (excluding capital costs)for nuclear, coal-, gas-, and oil-fired generating plants in the United States from 1981 to 2001 are compared in Figure 14. Figure 14 also illustrates the sensitivity to variations in the cost of fossil fuels (oil and gas) over the past 5 years. Current electricity production costs using oil and gas have increased to levels greater than 3 to 4 cents/kWh more than the cost to produce the electricity using existing nuclear power plants. Even with this significant cost incentive, the pratical limits of net capacity factors will soon be reached. This cost advantage does drive an increased interest in life extension for existing plants.

While there have been no new plant orders in the United States since 1978, many of the U.S. nuclear reactors are approaching the end of their original NRC license period and are requesting or will request license renewals for extended operating periods. The original U.S. nuclear power plant-operating license has a 40 year period; however a provision was made to allow the operator to petition for a 20 year extension. According to the U.S. Department of Energy (DOE) in their EIA Annual Energy Outlook 2003, the NRC approved 10 license extensions as of October 2002, is currently reviewing 16 additional renewal applications, and as many as 23 additional applicants have announced intensions to pursue license renewals over the next 5 years indicating a strong interest in maintaining the existing stock of nuclear plants. That accounts for at least 40 of the 103 (39%) of U.S. reactors continuing operation for the next two decades with the remaining 63 likely to follow the same path in the future.

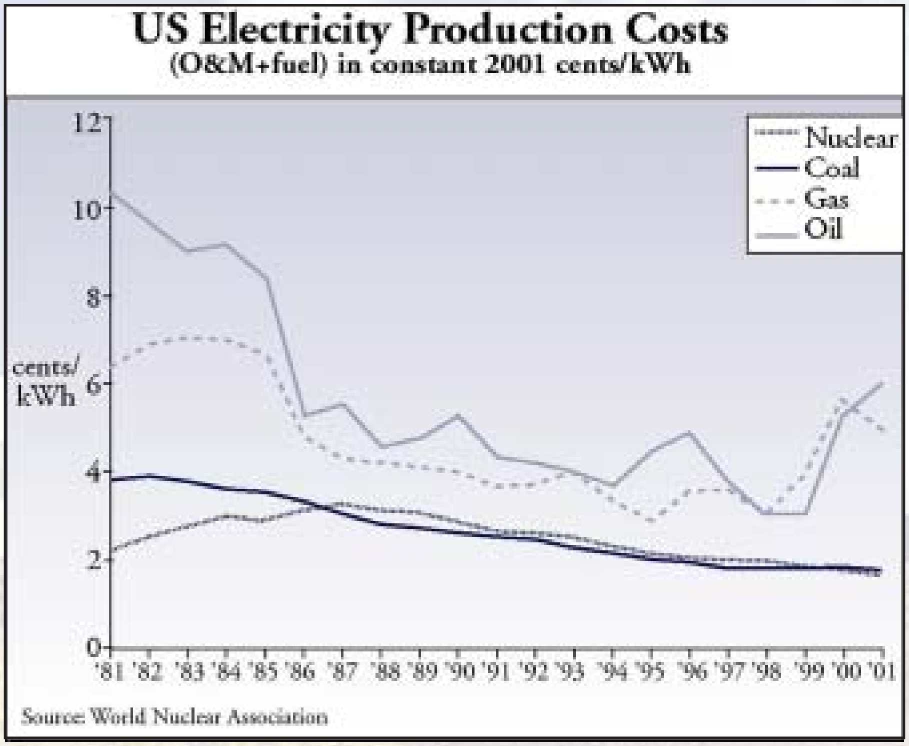

Figure 14. U.S. Electricity Production Costs (excluding capital costs)

The other important renaissance indicator in the United States is the Bush Administration's energy plan which calls for an expansion of nuclear energy as a major component of its national energy policy. DOE has set a goal of 2010[(a)] to build the next generation reactor and has selected the Idaho National Engineering and Environmental Laboratory as the site for this reactor, which also has a stated goal of hydrogen production in addition to electricity generation. The U.S. Congress has been working to provide a range of incentives to spur new reactor

(a) Recent DOE-NE press releases cite 2012 as a more attainable target date.

construction including loan guarantees, streamlined licensing and siting processes, and government furnished support for advanced reactor design, but they have stopped short of granting carbon credits or developing guidelines for emissions trading.

The final factors likely to influence the demand (and supply) for nuclear power are the implications associated with global climate change and the potential transition to a hydrogen economy. These factors are discussed in the next section.

3.3 Climate Change and Energy Demand

There is increasing global pressure within the framework of sustainable development to ensure that energy production and use is conducted in a way that does not further compromise environmental sustainability. Clean energy sources are those that do not add to the levels of CO_2 and other greenhouse gases in the environment. In 1992, the United Nations held its Framework Convention on Climate Change (FCCC). Article 2 of the FCCC Directive addresses the concerns of global climate change in the following goal, "…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

The Kyoto Protocol, a framework for prevention of climate change, proposed a reduction of greenhouse-gas emissions of industrialized countries by 5% below 1990 levels or approximately a 12% reduction in current emissions by 2010. These targets are widely believed to be unachievable, because there is so much momentum built into the current rate of carbon release and some of the world's major industrial countries (including the United States) have not subscribed to the Kyoto Protocol.

The EIA estimates that approximately 80% of the CO_2 emissions caused by human activities are from the use of fossil fuel. According to the Joint Global Change Research Institute, the cumulative CO_2 emissions ultimately determine the concentration of anthropogenic concentration in the atmosphere (Edmonds, 2002). Current economic variables favor the continued use of fossil fuel. Both the FCCC Directive and the Kyoto Protocol are responses to the perception that governments around the world must take immediate, comprehensive steps to avoid exacerbating the situation.

The region known as developing Asia, with 54% of the current global population, is also plagued by serious regoinal climate problems. The "Asian Brown Cloud," thought to be the result of very inefficient fossil fuel use in much of Asia, is shown in Figure 15. The United Nations Environmental Program (UNEP) commissioned a report on the impacts of the Asian Brown Cloud, a visible haze of air pollution estimated to be two miles (three kilometers) thick and extending over the entire Indian subcontinent from Sri Lanka to Afghanistan (Figure 16).

The UNEP report cites that the cloud originated from burning biomass and industrial emissions, both of which are common in the region. This haze has reduced the sunlight reaching the ground by 10 to 15%, thus altering the region's climate by cooling the ground and heating the atmosphere. Growing global pressure to deal with emissions of CO_2, combined with the burgeoning population, energy shortages, and increasing standards of living in the region, has already stimulated new nuclear construction in both China and India.

In a recently released report, *The Future of Nuclear Power* (MIT 2003), the possibility of using nuclear power to address concerns about CO_2 emissions around the world was considered. The report authors concluded that, in the next few decades, there are only a few realistic options for reducing CO_2 emissions from electric generating plants.

- Increase efficiency in electricity generation and use.
- Expand use of renewable energy sources (e.g., wind, solar, hydroelectric, and geothermal).
- Capture carbon dioxide emissions at fossil-fueled (especially coal) electric generating plants and permanently sequester the carbon.
- Increase the use of nuclear power.

Figure 15. Photograph of the South Asian Brown Haze Over the Nepalese Town of Phaplu (taken on March 25, 2001). Source: Impact Study, The Asian Brown Cloud: Climate and other Environmental Impacts

The report found that billions of tons of CO_2 emissions to the atmosphere could be avoided only by drastically increasing the generating capacity of nuclear plants to 1000 GWe by 2050 (from 353 GWe today).

The issue then becomes how to meet the projected increases in demand with existing and supplemental electricity capacity in a manner that does not compound the CO_2 emissions problem. Market driven economies will not provide incentives to change emissions levels unless the societal cost of emissions are included in energy prices. Companies will need some incentive to change the emissions levels, and carbon taxes and emissions trading policies can provide that incentive.

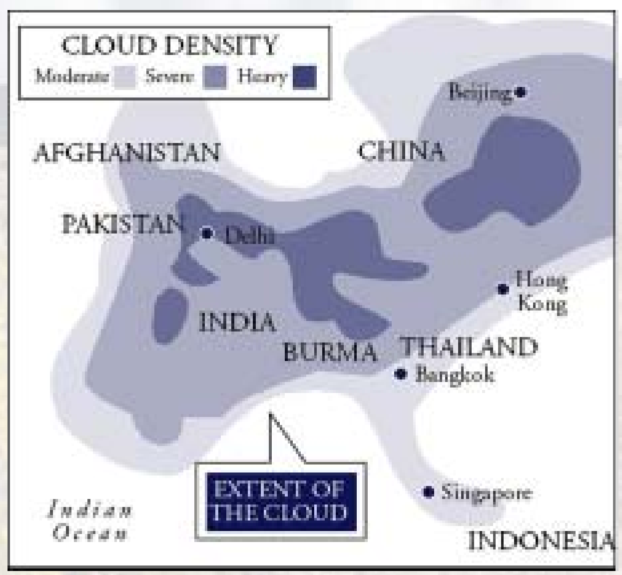

Figure 16. Cloud Density and Areal Extent of the Asian Brown Cloud. Source: Asian Brown Cloud: Climate and Other Environmental Impacts (UNEP 2002)

Carbon taxes are taxes levied on the consumer in an amount proportional to the amount of CO_2 produced by the fuel used by a plant. Thus, their imposition would affect the cost to produce energy from fossil-fuel sources to a greater extent than the cost to produce energy from energy sources that emit lower amounts of or no CO_2. Coal, for example, contains 0.03 tons of carbon per million Btu of energy, while oil and natural gas contain 0.024 and 0.016 tons of carbon per million Btu of energy, respectively; therefore, coal would be taxed in greater proportion than oil or natural gas. In the United States, just over 33% of total CO_2 emissions come from the electric power sector, and nearly 82% of those emissions came from coal-fired plants. A carbon tax added to coal emissions, with other factors remaining equal, would drive a shift away from the higher priced coal to other fuel sources for electric power generation.

Government policy can and will influence the energy mix and nowhere is that influence more relevant than in the case of nuclear power. Nuclear power does not bear any of the costs associated with reducing carbon emissions to the environment; therefore, it would become a more economical source of energy when taxes are imposed than carbon-based resources. The nuclear industry believes that nuclear-generated power, which continues to provide electricity on a large scale with comparatively minimal impact on the environment, is part of the solution to minimize world-wide CO_2 emissions.

3.4 Transition to Hydrogen Economy

The transition to a "hydrogen economy" gained prominence as a U.S. priority in President Bush's 2003 State of the Union Address. A hydrogen economy represents a future where hydrogen consumed by fuel cells powers the world's transportation vehicles. It is important to the viability of such an economy that the hydrogen be produced with little carbon release as possible. Nuclear energy provides a carbon-free energy source ideally suited to this purpose. The use of nuclear reactors to produce hydrogen (although highly spectulative at this early juncture) could likely be the single largest driver of additional growth in the nuclear industry, especially in the United States. Coupling electricity generation with hydrogen production at nuclear plants may fundamentally alter the character of not only the nuclear industry but could significantly impact world energy markets. A future hope of the U.S. nuclear industry is the prospect of using high-temperature, gas-cooled reactors (HTGRs) to produce hydrogen in the massive quantities needed for a potential future hydrogen economy. The pathway to that economy is a dynamic system, with competing technologies likely to come down to the relative cost-effectiveness of each.

Even in a modest economic growth scenario and at the current rate of nuclear technology growth, the transition from the current fossil-fuel economy to a hydrogen economy expected to take off in about 2050 would create a need for additional nuclear power generation capacity (Figure 17).[b]

In the short term, hydrogen could be produced by electrolysis of water using off-peak nuclear power; however, this approach is not economical. In the future, direct thermo-chemical conversion of water into hydrogen and oxygen using high-temperature reactors is a distinct possibility. To date, nuclear power has been used only as a base-load supplier of electricity. The use of hydrogen to store energy for transport opens the possibility of operating nuclear plants to meet demand at peak-load requirements and using all excess power for the hydrogen production process. Since efficient hydrogen production (either via methane reforming or steam electrolysis) requires high temperatures, existing light water reactors are poor candidates for this role in a hydrogen economy. New reactor

(b) Personal communications with John Clark and Jae Edmonds, Joint Global Change Research Institute, University of Maryland, 8400 Baltimore Avenue, Suite 201, Collge Park, MD 20740-2496.

designs (gas-cooled high temperature reactors) would have a great advantage. Thus the ability to produce hydrogen using electricity from nuclear power plants will drive development of new reactor technologies, and the demand for hydrogen could create a new generation of reactors. Because of the significance of this factor on the nuclear industry, a further exploration of the use of nuclear power for hydrogen production is presented in the next section, Energy Supply Factors.

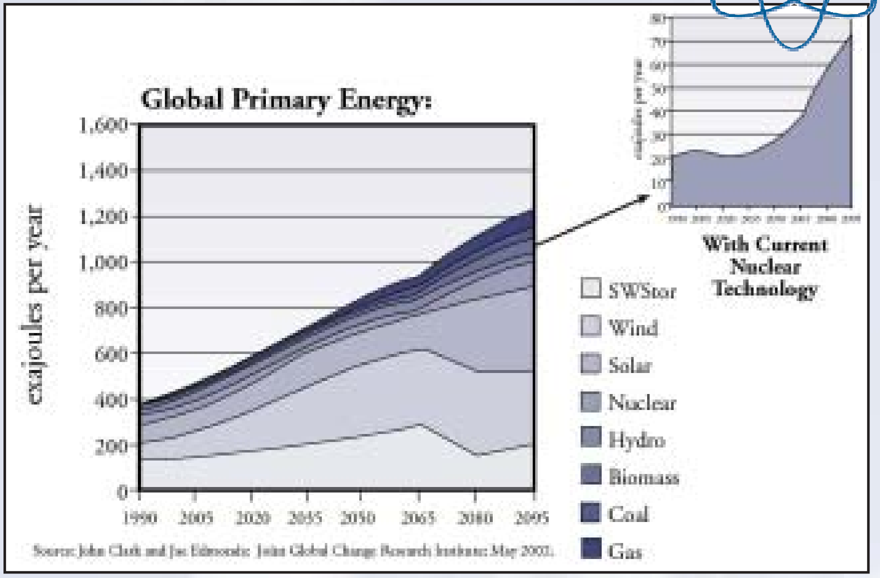

Figure 17. Projected Nuclear Growth Using a 2050 Hydrogen Economy Departure

Predicted population and energy demand growth, concerns about global climate change, the desire to reduce international dependence on oil, and the improved performance in the nuclear power industry are all factors that could contribute to a "nuclear renaissance" in which nuclear power would play an increasingly more important role in both national and world electrical energy markets. The nuclear industry has worked to make nuclear power more economical. It has achieved record capacity factors, improved safety, lowered operating costs, and the profit margins realized for already depreciated nuclear power plants are relatively high. The current international focus on the next generation of reactor designs and the transition to a hydrogen economy could factor into the economics of nuclear power.

4.0 Reactor Design Options and the Prospects for Global Nuclear R&D

Other than sale of power plants or major components thereof, the conduct of major R&D programs on an international scale represents the largest opportunity for the diffusion of nuclear technology. Nuclear R&D is currently conducted on a broad international basis, driven by safety, operational performance, and economic incentives. It is briefly described in this section, ending with a focus on R&D for a nuclear-hydrogen future.

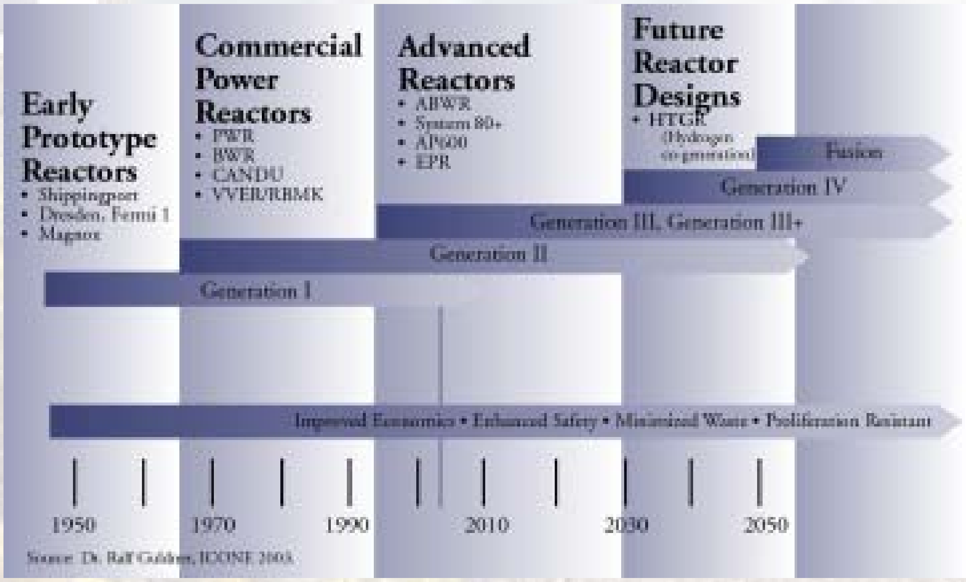

Figure 18. The Evolution of Nuclear Power

Figure 18 describes the evolution of nuclear power reactors between 1950 and 2030. The "generations" shown represent generally accepted industry classifications as defined by DOE (DOE NERAC 2002). Second-generation (Gen-II) reactor designs are now being succeeded by the next generation designs. A breakdown of the nuclear power plants in commercial operation around the world at the end of 2001, primarily GEN-II reactors, is presented in Table 1.

Table 1. Summary of Nuclear Power Plants in Commercial Operation Around the World in 2001
Source: World Nuclear Association (April 2002)

Reactor Type	Main Country	Number in Use	GWe	Fuel	Coolant	Moderator
Pressurized Water Reactor (PWR)	US, France, Japan, Russia	252	235	Enriched UO_2	Water	Water
Boiling Water Reactor (BWR	US, Japan, Sweden	93	83	Enriched UO_2	Water	Water
Gas-cooled Reactor (Magnox & AGR)	UK	34	13	Natural U (metal), enriched UO_2	CO_2	Graphite
Pressurized Heavy Water Reactor "CANDU" (PHWR)	Canada	33	18	Natural UO_2	Heavy Water	Heavy Water
Light Water Graphite Reactor (RBMK)	Russia	14	14	Enriched UO_2	Water	Graphite
Fast Neutron Reactor (FBR)	Japan, France, Russia	4	1.3	PuO_2 and UO_2	Liquid Sodium	None
Other	Japan	5	0.2			
	TOTAL	**435**	**364**			

The third-generation (GEN-III) reactors are the current state of the art in reactor technology and are the reactors that have been licensed for construction and commercial operation. GEN-III designs are light water reactors that have passive safety features and standardized design features to reduce capital costs and construction times. The first GEN-III reactors have been operating in Japan since 1996. The most important distinctions between current designs and these advanced reactor designs are the passive or inherent safety features that require no active controls or operational intervention to avoid accidents and the standardized design and licensing approach used to reduce the capital construction costs. Traditional reactor safety systems are active in the sense that they require a directed mechanical operation to occur to prevent or avoid an accident.

The capital cost of a new nuclear power plant accounts for 80% of the generation cost of a new plant. As discussed previously, the widely used industry threshold of capital cost per kW of electrical capacity, in a market where natural gas is readily available, is about $1000 per kW. Currently licensed GEN-III reactor construction costs are in the range of $1300 to $1500 per kW of electrical capacity. GEN-III+ and GEN-IV designs are aimed at the $1000 per kW threshold. The basic economic user requirement for nuclear energy is that it be at least as cost-effective and as attractive an investment as its competitors.

4.1 Reactor Technology Implications

Research and development of new reactor designs are very active worldwide. The United States, Japan, France, Germany, Russia, and Canada all have active corporate, government, or joint R&D ongoing efforts focused on improving safety features, bringing construction cost down, and increasing the proliferation resistance of next-generation designs. Appendix A provides a summary of current GEN-III and -III+ reactor designs that are under development. This section gives an overview of the diversity of reactor designs, identifies the companies involved in the development of these advanced reactors, and the provides the projected capital cost for new construction.

The United States, in partnership with other countries and developers, leads the R&D activity with four reactor designs being developed. General Electric is on track to offer an ABWR in the United States at a capital construction cost of $1200/kW to $1400/kW (Foulke 2003). The development and licensing of these new designs for commercial application represents a substantial investment for any company, or group of companies, and thus can be considered a strong indicator of intent.

In addition to those GEN-III+ and early GEN-IV designs already under development, the U.S. Department of Energy (DOE) has created the Generation IV International Forum (GIF) to focus on the collaborative development and demonstration of one or more fourth generation nuclear energy systems. This forum, which is led by the United States, is made up of representatives from 10 countries: the United States, Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, Switzerland, and the United Kingdom. Six of these participants, the United States, Canada, France, Japan, South Korea, and the United Kingdom, are in the top 10 nuclear power generating countries in the world (refer to Figure 19).

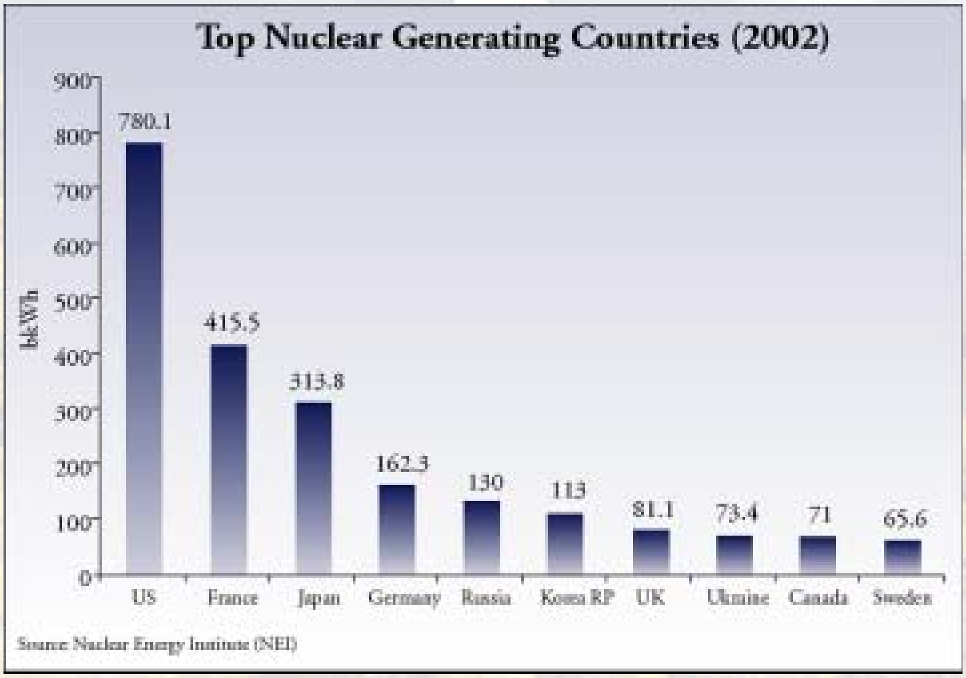

Figure 19. Top Nuclear Power Generating Countries

The DOE *Generation IV Roadmap* (DOE NERAC 2002) established the following goals for the technology underlying GEN-IV reactor designs:

- *Sustainable Nuclear Energy*. Focus on extending the nuclear fuel supply into the future, with an enhanced focus on the environmental impacts of energy production and use.
- *Competitive Nuclear Energy*. Focus on the economic variables such as reducing the construction costs and financial risks of nuclear energy systems.
- *Safe and Reliable Systems*. Focus on increasing safety features and enhancing public confidence in nuclear energy.
- *Proliferation Resistance and Physical Protection*. Focus on providing continued effective proliferation resistance through improved design features and improving the physical protection against terrorism by increasing the robustness of new facilities.

The roadmap has identified six reactor technologies for further research (see Appendix A for a summary discussion of the six recommended technologies). Hydrogen production and/or hydrogen co-generation considerations are an important part of the research being conducted under the roadmap. The differentiating characteristic when considering hydrogen versus electricity generation is the fact that hydrogen production is most efficient at very high temperatures (>1000^{o}C). All six of these reactor designs operate at higher temperatures than today's mostly Gen-II and GEN-III reactors; however, only the High Temperature Gas Reactor (HTGR) is expected to produce temperatures high enough for efficient hydrogen generation. All six systems represent advances in sustainability, economics, safety, reliability, and proliferation resistance. However, they have varying degrees of technical uncertainty inherent in their design.

The International Project (INPRO) is another multinational initiative adopted by IAEA member states looking at longer-term development of nuclear energy. Like GIF, INPRO is looking at innovative approaches to address concerns about economic competitiveness, safety, waste and potential proliferation risks. GIF is focused primarily on industrially developed countries while INPRO is expected to involve non-nuclear stakeholders. There is significant overlap in these multinational initiatives and efforts are underway to identify synergies on innovative nuclear technology development.

4.2 Reactor Technology Vendors

The question of how many designers and global firms might be viable in a nuclear renaissance will depend to some degree on market niches and to some degree on the timing at which the design is market-ready. Wood et al. (2001) asserts that at most three to five designs will be economically viable (with a strong focus on only one or two primary design concepts). The structure of the industry will be coupled to the number of new reactor designs deployed. The number of reactor designs, the geographic dispersion of their deployment, and the associated trade in reactor technology and fuels will interact to frame the global export controls environment. As indicated in the previous globalization work, the nuclear industry has seen consolidation. Several of the large nuclear technology firms exhibit the salient characteristics of "global firms." To the extent that a global firm is designed to expedite the sharing of technology and flow of information in its operating divisions, significant "export" transactions will be masked or missed. Figure 20 provides a summary of the industry consolidation among the large nuclear suppliers.

A significant increase in global nuclear commerce is likely to have dramatic impacts on the number of vendors and many of those impacts will be driven by the number of reactor technologies deployed in new construction.

Nuclear Vendors: A Consolidated Global Market

In the last 4 years, the competitive landscape has changed considerably worldwide.

March 1999:	Acquisition of Westinghouse by BNFL
December 1999:	Acquisition of ABB Nuclear by BNFL-Westinghouse
January 2000:	GE-Toshiba-Hitachi joint venture for BWR fuel
1999-2000:	Preparation of Framatome-Siemens joint venture
January 2001:	Start of Framatome ANP
September 2001:	Creation of AREVA Group, including Framatome ANP and Cogema,
April 2002:	Acquisition of Duke Engineering & Services, Inc. by Framatome ANP

Figure 20. Consolidation Among Nuclear Vendors. Source: Dr. Ralf Guldner (ICONE 2003)

4.3 Implications of a Hydrogen Economy for the Nuclear Industry

As mentioned previously, although highly spectulative hydrogen production could likely be the **single largest driver** to spur additional growth in the nuclear industry. There are a number of different possibilities for hydrogen production and this section addresses the implications of possible hydrogen production using nuclear power, including a discussion of how the nuclear industry might be transformed by the success of this concept. Coupling nuclear power with hydrogen production may fundamentally alter the character of the nuclear industry and could also significantly impact world energy markets. The need for a demonstrated source capable of generating the large amounts of energy needed for hydrogen production may spur the energy industry to view nuclear power's potential contribution to the transition to a hydrogen economy in a new light.

The hydrogen economy in which hydrogen consumed by fuel cells powers the world's transportation vehicles does not exist today. Such an economy will require production, storage, delivery, and end-use capabilities for most of our portable power needs. Hydrogen is already produced and used in the petrochemical industry and for National Aeronautics and Space Administration (NASA) activities. However, at this time, the hydrogen economy is not mature enough for commercial production of all the equipment and infrastructure necessary to support a functional transportation system, and the transportation fuel cell and associated vehicles are only in the prototype stage of development.

A number of studies have been completed on hydrogen-production methods, and several approaches may ultimately prove cost effective. Figure 21 depicts several approaches to producing hydrogen from different energy sources. Heat can be used with chemicals and water (the thermo-chemical approach) or water can be charged with an electric current (the electrolysis approach) to break water molecules into its elemental constituents, hydrogen and oxygen. Other separation processes combine heat and electricity (steam electrolysis) to breakdown water into hydrogen and oxygen. Hydrogen can also be produced using most primary energy sources such as fossils fuels, renewable energy, and nuclear power through partial oxidation, steam methane reformation, cracking, etc.

Some current concepts for Generation-III+ reactors could produce electricity and hydrogen simultaneously with thermochemical conversion of biomass and/or fossil fuels. To produce both hydrogen and electricity simultaneously, process temperatures above 500°C must be available. Generation-III+, high-temperature gas reactors (HTGR) typically operate at temperatures around 530°C.

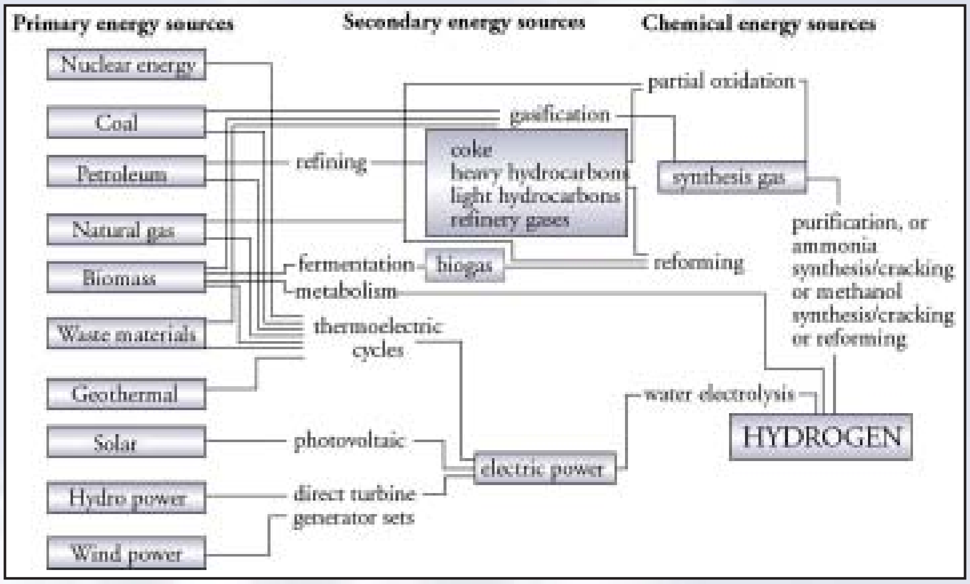

Figure 21. Primary and Secondary Energy Sources & Processes Required to Convert Materials into Hydrogen. Source IAEA, 1999

Generation-IV HTGR nuclear power plants will likely have three streams of thermal throughput: one to produce electricity with high temperature gases (around 1000°C); another to produce high temperature steam (about 530°C); and the remaining thermal throughput to provide seawater desalinization or other thermal uses. Steam turbines used to generate electricity operate at a conversion efficiency of 40 to 43%, while gas turbines operate at up to 48% efficiency. By using a combination of steam and gas turbines to generate electricity, the Generation-IV reactor may reach an operating efficiency of 50%.

As discussed previously, the cost of constructing new nuclear power plants under strictly market driven conditions to produce electricity is high when compared with the cost of constructing facilities for other electrical production sources. Several questions must be answered when considering the role that hydrogen might play in power production: will hydrogen production processes be economical enough to be useful, what are the trade-offs between using nuclear power to produce electricity and/or hydrogen, and where does nuclear power enter into this picture. An analysis conducted at PNNL of the economic implications of nuclear/hydrogen co-generation was conducted in FY2003 and is reported in the proceedings of Global 2003 (Weimer et al 2003).

The PNNL analysis found that hydrogen production using high temperature steam reformation with an HTGR is an especially low-cost approach. Hydrogen costs based on nuclear power compare favorably with partial oxidation and biomass gasification methods. HTGR nuclear power plants, depending on their final capital and operating costs, could become key producers of hydrogen. Given their high-quality, high-temperature process heat, the nuclear power plant's throughput could be channeled to the power type with the highest return.

PNNL analyzed the costs of using nuclear power to produce both electricity and hydrogen in a 3000 MWt HTGR and examined the economic and environmental trade-offs between the production hydrogen and electricity. For a 3000-MWt HTGR, the trade-off between producing hydrogen through steam methane reformation and producing electricity strongly favors hydrogen production in an economy where hydrogen fuels can compete with gasoline on an energy-equivalent bases. The magnitude of the increase in electric prices or decrease in hydrogen prices required to allow electricity production indicate that substantial deviation in cost estimates would be required to change the conclusions. As the PNNL analysis is static in nature, a dynamic model that incorporated the demand curves for electricity, hydrogen and other fuels could yield more information about the equilibrium prices and production levels in a hydrogen economy.

The large relative trade-off between hydrogen and electricity production means there could[c] be more money to be made from hydrogen production than from electricity production at current base-load electricity prices. As such, the demand for transportation fuels and fuels for electricity production and heating will become significantly more integrated than they are now because nuclear plant owners will switch between hydrogen and electricity production depending on which commodity is most profitable at a given time. The desire to switch between hydrogen and electricity production has implications for the nuclear plant and hydrogen plant designs; both must be designed to minimize efficiency losses when production is switched from one commodity to the other.

The PNNL analysis also indicated that the profitability of hydrogen production would be highly dependent on the cost of natural gas. As natural gas prices are fairly volatile and comprise more than the half the levelized costs of production, alternative approaches of hydrogen production for HTGR plants could provide more constant income than a steam methane reformer. High temperature steam electrolysis could be one such alternative approach.

For the most part, information reported in the literature indicates that decentralized production of hydrogen is favored over centralized production because of the low energy density of both pressurized and liquefied hydrogen. Thus, if reasonable economies of scale can be achieved with smaller reactors, then small, local production facilities would be preferred over large, centralized facilities. Increasing the number of nuclear power suppliers (for either hydrogen or electricity) has further implications on non-proliferation of nuclear materials, and the export control measures that contribute to management of these materials. The implications of rapid growth in the nuclear industry on export control policy are explored in Section 5.

5.0 Export Control Implications

This report provides a description of potential events that might drive a dramatic expansion in nuclear power commerce worldwide. Even without a significant expansion in nuclear power, export controls of sensitive nuclear materials, equipment and technology must be strengthened. Traditional export control regimes proceed from the premise that selected items of “sensitive materials, equipment, and technologies” can effectively be denied to potential proliferators whose intentions or dual-use rationales are suspicious. The global effectiveness of bilateral policy under this framework is limited, and the technologically well-endowed countries of the world have allied in a series of multilateral regimes (typified by the Nuclear Suppliers Group [NSG]) built on the same basic principle. Even these multilateral regimes seem unable to prevent determined proliferators from

(c) The analysis in Weimar 2003 shows that hydrogen reocvery would exceed power revenues if hydrogen could be sold at gasoline energy equivalent prices. The cost of distribution systems (an adaptations to vehicles) required to deliver hydrogen as a transport fuel would tend to limit the economic market size (and thus the revenue) from such a plant.

acquiring the technology needed to produce weapons of mass destruction (WMD). The economic theory surrounding prohibition contends that as long as demand exists, even in markets where the purchase of a particular good or service is controlled, supply has incentives to meet demand via the price mechanism. The market then facilitates the creation of a "black market" whereby items in demand can be transferred from suppliers through avenues outside of legitimate commerce channels (thus circumventing export control laws), which facilitates transactions illicitly.

Traditional export control regimes are based on supplier clubs (i.e., "the nuclear have's"), whereby the producers of sensitive materials, equipment and technologies agree to "restrain trade" from the have not's because of a mutual interest in non-proliferation. The Canberra Commission stated that the present situation, in which the world is separated by nuclear "have's" and "have not's", cannot be sustained because "the possession of a nuclear weapon by any state is a constant stimulus to other states to acquire them."

The Non-Proliferation Treaty (NPT) and the regimes that support it have served to effectively slow, but not stop the spread of nuclear weapons. The nuclear have's could not force the nuclear have not's to join the treaty nor have the regime members consistently adhered to their own commitments. The Carnegie Endowment for International Peace recently released a report titled *Universal Compliance A Strategy for Nuclear Security* (2004) in which they conclude that "Some of the failures to contain proliferation result from flaws in the nonproliferation regime itself; others stem from the unwillingness of leaders around the world to enforce commitments and resolutions earnestly passed". The treaty regime was designed for a world in which state actors were the source of anticipated threats; whereby today terrorist groups and other non-state sanctioned actors bent on mass destruction or nuclear trafficking are just as likely to be the source of nuclear threats.

It follows that export control policies will be different in the future. Strengthened measures for non-proliferation, counter-proliferation, and minimizing the effects of WMDs are all components of the policies of the future. The privatization of the nuclear power industry and expanded construction of the next generation of nuclear power reactors and nuclear fuel cycle facilities will force expanded security-related responsibilities for the private sector and the nonproliferation regimes.

Both traditional and non-traditional approaches will be needed to facilitate a paradigm shift in the existing export control practices. Mohamed Elbaradei, the IAEA Director General, believes that new approaches to global security are required and that the underlying causes or "drivers" and motivations that give rise to nuclear proliferation must be addressed. Reformed multilateral controls will require sustained cooperation from dozens of diverse nations to broaden, toughen and enforce non-proliferation rules. The approach must include efforts to:

- Prevent the spread of sensitive nuclear materials, equipment, and technology through a strengthened proliferation regime and enforced compliance to commitments;
- Control radioactive sources from cradle to grave through materials protection and control systems;
- Detect malicious acts involving nuclear and other radioactive materials;

- Interdict sensitive materials, equipment and/or technologies before they get to their target.

The organizing framework for revamped or new export control regimes should take into account international cooperation in suppressing terrorism and countering proliferation.

6.0 Conclusions—The Future of the Nuclear Industry

This report has sought to lay out the factors that might lead to increased global nuclear commerce. The increased business volume, the potential changes in the structure of the nuclear industry, the potential to couple nuclear power with hydrogen production, and the increased concentration of enhanced nuclear capability in countries of concern all weigh on an already burdened export control system. A new paradigm for thinking about global nuclear economics, international R&D, and expert regulation may be emerging based on several factors:

- Recognition that even "peaceful" nuclear power programs in certain NPT States can intentionally or unintentionally (through loss or theft) contribute to the risk of proliferation;
- Recognition that existing and emerging nuclear designs do not meet the economic requirements for a nuclear renaissance;
- Recognition that the carbon benefits of nuclear power are public in nature and are increasingly valuable.
- The possibility of re-inventing the transportation fuels sector using hydrogen, and the technical attractiveness of nuclear power as a process heat source for hydrogen production. The scale at which hydrogen production would be required implies that government involvement will be necessary.

This paradigm is in marked contrast to the current one, in which incremental improvements in plant designs are sought for LWR reactors and government R&D programs are proceeding with limited investment. To a large extent, the choice between these two paradigms leads to one of two "worlds" for nuclear power:

World 1 – A world in which the global average real price of electricity remains stable or falls. Standard energy forecasts including nuclear generated electricity forecasts use this assumption. This world ultimately presages a "graceful exit" scenario for nuclear power in the United States. The pace of this exit is governed by the technical feasibility of plant life extensions, and could be a matter of another 50 years. Based on existing technology, Asia and Eastern Europe are the only viable markets for new nuclear plants. China and Russia develop as dominant nuclear suppliers based on proximity to markets and low cost. Japan, France, and the United Kingdom serve the high end of the Asian market, where the pace of plant construction is the discriminating factor. The U.S. nuclear industry continues a decline in which the technological infrastructure cannot compete for overseas work and the industry is increasingly unable to support operating license renewals for existing nuclear plants that are reaching the end of their design life.

World 2 – A world in which limitations on fossil fuel development and carbon emission costs is incorporated into electricity prices, and real prices of electricity rise. The economics of nuclear plants improve even for existing technology. Beyond these developments, such a world permits a renaissance in which nuclear power is recognized as a public good and is subject to some type of government stewardship. In addition to the real-price effect, significant investment in both nuclear and hydrogen production technologies fundamentally alter the economic equation for nuclear power. Nuclear power becomes the best energy source for those with a high dependence on gasoline—particularly imported gasoline. This world has two possible variants: one in which the United States leads an international R&D consortium for new nuclear technology and one in which it does not.

The economics of nuclear power operation and new reactor designs, despite sound R&D programs, suggest that a nuclear renaissance will happen only if carbon credits or other policy stimuli are imposed worldwide or a hydrogen economy becomes reality. While the former seems politically unlikely, the economics of the latter look promising. Nuclear power for a hydrogen economy would likely be provided by a new generation of plants - HTGRs. The development of such plants would likely be concentrated in one or two broad international consortia.

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Appendix A - Gen III Reactor Designs

Country and Developer	Reactor	Size MWe	Design Process	Main Features	Capital Cost
US-Japan (GE-Hitachi-Toshiba)	ABWR	1300	Commercial operation in Japan since 1996-7. In US: NRC final design certification May 1997, FOAKE	• Evolutionary design • More efficient, less waste • Simplified construction (48 months) and operation	**Build** US$2000/ kWFuture US$1700/kW **Produce** US 7c/kWh
USA (Westinghouse), South Korea	System 80+, APR (PWR)	1300 1400	NRC final design certification May 1997. Further developed for new S. Korean Shin Kori 3 & 4.	• Evolutionary design • Increased reliability • Simplified construction and operation	**Cost** US$1400/kW **Falling to** US$1200/kW in later units
USA (Westinghouse)	AP-600 AP-1000 (PWR)	600 1000	AP-600: NRC final design certification Dec 1999, FOAKE	• Passive safety features • Simplified construction and operation • 3 years to build • 60-year plant life	**Cost** $1000/kW generating cost below US$3.5 cents per kilowatt hour
Japan (utilities, Westinghouse, Mitsubishi)	APWR	1500	Basic design in progress, twin unit planned at Tsuruga	Not available • Simplified construction and operation	
France-Germany (Framatome ANP)	EPR (PWR)	1550-1750	Confirmed as future French standard, design completed 1997	• Evolutionary design • Improved safety features • High fuel efficiency • Low cost electricity	Expected to provide power about 10% cheaper than the French N4
Germany (Framatome ANP)	SWR (BWR)	1000	Under development	• Innovative design • High fuel efficiency	Not available
Sweden (Westinghouse)	BWR 90+	1500	Under development	• Evolutionary design • Short construction time • Enhanced safety features	Not available
Russia (Atomenergo project & Gidropress)	V-407 V-392 (PWR)	640 1000 respectively	Construction of first V-407 unit pending, V-392 units planned	• Passive safety features • 60-year plant life • Simplified construction and operation	Not available
Russia (AEE)	VVER-91 (PWR)	1000	Two being built at Tianwan in China	• Evolutionary design • Enhanced safety features	Not available
Canada (AECL)	CAND U-9	925-1300	Licensing approval 1997	• Evolutionary design • Single stand-alone unit • Flexible fuel requirements • Passive safety features	Not available
Canada (AECL)	ACR	700 1000	Development to 2005.	• Evolutionary design • Light water cooling • Low-enriched fuel • Passive safety features	**Build** US$1000/kWe **Operating** $3 cents/kWh
South Africa (Eskom, BNFL)	PBMR	110 (module)	Prototype due to start building in 2002	• Modular plant, low cost • Direct cycle gas turbine • High fuel efficiency • Passive safety features	**Build** (clusters of 10 – 14 units) US$1000/kW **Generating** US$1.6 cents/ kWh
USA-Russia et al (General Atomics - Minatom)	GT-MHR	285 (module)	Under development in Russia by multinational joint venture	• Modular plant, low cost • Direct cycle gas turbine • High fuel efficiency • Passive safety features	Plant costs expected to be less than US$ 1000/kW

GEN III+ and GEN IV Reactor Designs Under Development

Source: World Nuclear Association. Advanced Reactors May 2003

Reactor Features	**Nuclear Fuel Cycle**	**Cooling System**	**Sustainability**	**Primary / Secondary Use**	**Deployable By**
Reactor Type					
Gas-Cooled Fast Reactor System	Closed Fuel Cycle; On Site	Helium Cooled @ 850°C	Proliferation resistant, good physical protection	Electricity/ Hydrogen	2025
Lead-Cooled Fast Reactor System	Closed Fuel Cycle; Regional	Natural Convection (Lead-Bismuth Salt) @ 550°C - 800°C	Proliferation resistant, good physical protection, modular design	Electricity/ Hydrogen	2025
Molten Salt Reactor System	Closed Fuel Cycle	Heat exchanger (fluoride salts) @ > 700 °C - 800°C	Proliferation resistant, good physical protection; no fuel fabrication	Electricity/ Hydrogen	2025
Sodium-Cooled Fast Reactor System	Closed Fuel Cycle	Sodium Cooled @ 550°C	Actinide management, resource extension	Electricity	2015
Supercritical-Water-Cooled Reactor System	Open cycle w/thermal neutron spectrum reactor; or closed cycle w/ fast-neutron spectrum	Water-Cooled @ 550°C	High thermal efficiency	Electricity	2025
Very-High-Temperature Reactor System	Open Fuel Cycle (Once-through uranium cycle)	Helium Cooled @>1000°C	High hydrogen production efficiency	Hydrogen/ electricity	2020

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