Climate Change and Nuclear Power: Issues of Interaction

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Prepared by

Yun Zhou

Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, 79 John F. Kennedy Cambridge, MA 02138, USA
Yun_Zhou@hks.harvard.edu

Prepared for:

The Nautilus Institute for Security and Sustainability

University of San Francisco Center for the Pacific Rim

2130 Fulton Street LM 200

San Francisco, CA 94117

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Executive Summary

Stabilizing greenhouse gas emissions at a prudent level by 2050 will require a massive transformation of the world's energy system, with the supply of low-carbon energy increasing from its current 20% share of world energy use to 60% (Worldwatch, 2008)**.**. Considering the current status of all of the alternative energy technologies available, effective climate change mitigation will not be accomplished at the required size and time scale by deploying one particular technology alone   As a low-carbon option, nuclear power could contribute to addressing the climate problem over the next half-century.

This report explores arguments related to expansion of nuclear energy use to address climate change. In most configurations of the nuclear fuel cycle, nuclear power is a truly low carbon emission technology for power generation. In addition, many different non-power applications for nuclear power have been suggested, such as providing process heat to produce hydrogen for use in the transport sector, for desalinating water, and for district heating in a combined heat and power configuration though current use of nuclear energy for non-power applications is limited.   Nuclear power is currently one of the few low carbon energy technologies available that can be implemented on a large scale. Light water reactor (LWR) technologies, the most widely used nuclear power technologies today, have improved over time with regard to plant safety. These advantages, nuclear proponents argue, demonstrate that nuclear technology could play an important role in mitigating climate change. As the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment suggested (2007), methods for climate change adaptation should be immediately taken to minimize the adverse impacts of climate change. Nuclear power shows great potential to help in adaptation as it is both a reliable energy source with output that does not depend (with some exceptions) on weather conditions, and is a highly concentrated source of energy, which is desirable in part in that it reduces transport requirements, which, for example, means that transporting fuel to the reactor during episodes of extreme climate conditions requires less transport infrastructure, or can be delayed for some months while on-site fuel supplies are used. As with all other alternative energy sources, nuclear power will be exposed to some vulnerability because of climate change. Nuclear power plants located in coastal areas face flooding risks associated with a combination of sea level rise and storm surges, but this risk can be managed through engineering designs that take potential extreme conditions into account. A higher frequency of drought years and a resulting insufficient supply of water might limit the nuclear power development in some inland areas (where nuclear plants must depend on river or lake water for cooling), but as most nuclear plants tend to be located in coastal areas, the impact of climate change on nuclear power may be limited.

The regional variations of nuclear power development around the globe are also examined in this report. Due to slow economic and population growth, coupled with energy efficiency improvements and strong public opposition, developed countries are not expected to have significant growth in energy (and electricity) demand in the coming decades. As a result, most developed nations do not expect a large expansion of nuclear power. Major developed countries with nuclear power, including the United States, Japan, Korea, and France, are likely to construct new nuclear power plants largely to maintain the nuclear energy shares in their electricity generation mixes. More advanced developing countries, such as China and Brazil, and less advanced developing countries with large and growing populations, such as India and Pakistan, will likely be major contributors to future nuclear power capacity expansion due to increasing energy demand and environmental pressure related to use of coal in particular, as well as other fossil fuels. A number of studies from major energy research institutes estimate that nuclear capacity expansion could result in global nuclear capacity ranging from about 500 GWe to 1500 GWe which will avoid annual CO_2 emissions in the range between about 3.3 and 9.9 Gt CO_2 equivalent in 2050. The World Nuclear Association is more optimistic, setting a lower boundary for total nuclear-generated power at 800 GWe and a high boundary at 2400 GWe by 2050. China and India are also preparing their own nuclear power development plans, which aim to increase the share of electricity produced by nuclear power to 20-30% of their electricity generation by 2050, up from only a few percent today in each country.

In considering the resources required to implement the projected nuclear expansion, all of the studies reviewed for this report concluded that neither global uranium supply nor global nuclear construction capability will constrain nuclear development. Costs of nuclear power are still relatively high, but may be competitive if fossil fuel prices remain high and carbon taxes are introduced (MIT, 2009). There are many approaches that can help to reduce the total generating costs of nuclear power, such as reducing construction delays by standardizing and streamlining licensing and certification procedures, and simplifying and standardizing nuclear reactor designs. China's AP1000 project may play a key role in demonstrating the improved economics of standardized and simplified reactor designs. If China's project turns out to be a great success, it will help to improve investors' perception to nuclear power, which has been seen in recent years a high-risk and long-return-period sector. In addition, some studies suggest that national and international policies can help nuclear power to compete with other (especially fossil-fueled) power sources by setting up a carbon pricing scheme and providing subsidies to nuclear power.

Non-climate issues associated with nuclear power persistent and will likely to be important for some time, even as nuclear technology improves. These issues include public acceptance, nuclear safety, nuclear proliferation, and nuclear waste management. Recent public surveys have indicated that public perception of nuclear power has improved in many countries, as public visibility of energy security and climate change concerns has increased. However, the surveys still show persistent public opposition exists as before. Although the citizens of some developing countries largely embrace nuclear technologies, including China and India, populations in other countries that are candidates for nuclear power, such as Indonesia, still view nuclear power with a skeptical. Nuclear safety has improved since the 1980s, and engineers and scientists have been working hard to provide new generation III technologies that are more resistant to core-melt accidents than earlier LWR designs. These improved designs are under construction in both Asia and Europe. In addition, "next generation" nuclear plant designs are currently under development, including six different reactor designs ranging from LWR-based designs to fast neutron reactor designs[1]. Assistance from vendor countries to purchasers is highly recommended to help established a high standard nuclear safety culture in developing countries. In addition, the international community should continue to promote nuclear safety communication and information exchanges in nuclear countries to improve the operational performance of existing and new nuclear plants.

[1] The Gen IV reactor designs include: very high temperature reactors, supercritical light water reactors, molten salt reactors, gas cooled fast reactors, sodium-cooled fast reactors, and lead cooled fast reactors. See, for example, World Nuclear Association (2009) "Generation IV Nuclear Reactors", available as http://www.world-nuclear.org/info/inf77.html.

Increases in proliferation threats and security risks are large concerns associated with the increase in nuclear capacity and generation. With global nuclear expansion plans as noted above, the more nuclear power plants are built, the more nuclear material will be produced, accumulated and transported, and the more nuclear facilities will need to be protected. A larger nuclear fleet therefore would mean that the world would face additional security challenges in protecting the nuclear facilities and materials throughout the nuclear fuel cycle. It is likely, however, that the increased proliferation threats and risks resulting from the expansion of nuclear power globally will not necessarily scale with the expansion of the uranium enrichment capability and reprocessing capability, assuming that most enriched and reprocessed fuel handling will continue to take place largely in countries that currently possess nuclear weapons, at least for the next couple of decades. Security risks associated with nuclear material management, however, might in the future deserve more attention, including risks such as terrorist attacks to nuclear facilities. The IAEA nuclear safeguards and security department needs to be strengthened to continue working toward limiting illegal nuclear material transfers and nuclear sabotage. From a long-term perspective, multilateral approaches to the nuclear fuel cycle can be an effective solution to prevent nuclear proliferation. While nuclear waste management is currently one of largest controversies about nuclear power, it will not be a major issue for nuclear newcomers in the next couple of decades, since they will not face an urgent need to reprocess their spent fuel and dispose of their high-level nuclear waste generated until their inventories of cooled spent fuel built up. However, R&D programs focusing on waste management and long-term disposal plans are highly recommended for those countries as a preemptive strategy. Lastly, multilateral approaches to the nuclear waste management can be envisioned and approached in a manner similar to the management of other elements of the nuclear fuel cycle.

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1. Introduction

The current and projected future impacts of climate change are increasingly receiving global attention. Human-caused emissions of greenhouse gases, particularly carbon dioxide (CO_2) have been identified as the major drivers of climate change. As a consequence, there is a growing (though not universal) global consensus that limiting future CO_2 emissions is necessary in order to mitigate global warming. The European Union has already started to control emissions through a "cap-and-trade scheme, which provides economic incentives for reducing the emissions of pollutants, particularly greenhouse gases. The UK (United Kingdom) government aims to reduce greenhouse gas emissions by 60% by 2050, relative to current emissions. Although the United States has not thus far ratified the Kyoto protocol to the United Nations Framework Convention on Climate Change (UNFCCC), U.S. policymakers have expressed a strong commitment to implementation of energy efficiency and new energy technologies., Limiting future greenhouse gases emissions alone, however, will not diminish the adverse impacts—including current and near-term global warming—resulting from past emissions[2]. As a result, means of adapting to climate-change-related impacts, in the near- and especially more distant future, will be required as well. As a consequence, the nations of the globe will need to pursue both adaptation and mitigation strategies if the current and future risks of climate change are to be reduced.

"Low carbon" alternatives to fossil energy sources—that is, sources of energy that emit little carbon dioxide to the atmosphere per unit energy provided, relative to fossil fuels—are desired for both sustainable development and for climate change mitigation and adaptation. As such, nuclear power, the use of which produces only limited CO_2 emissions, is enjoying a resurgence of interest worldwide, and particularly in developing countries. Many emerging economies are forecasting that an appreciable fraction of their electricity requirements in the future will be provided by nuclear power. Nuclear power is a low carbon technology that capable of being implemented on a large scale, and, at least for the current generation of reactor designs, is commercially available. Policy pronouncements from a number of countries, including major developing nations, express a desire to acquire of nuclear energy technologies (Nahyan et al., 2008). Currently, nuclear power supplies around 17% global electricity generation (MIT, 2009). As such, nuclear power has contributed to the mitigation of CO_2 emissions since its widespread implementation over the past 40 years. A recent IAEA report estimates that 2.4 Gt of CO_2 emissions were avoided through the use of nuclear power in 2006 (IAEA, 2008). Still to be determined, however, is the degree to which nuclear power can and will play a role in the battle against climate change over the next several decades.

Although nuclear power is a mature technology with low carbon emissions, its application is constrained by important challenges comparing to other energy sources: 1) high cost, 2) safety concerns, 3) waste management arrangements, and 4) proliferation risks (MIT, 2003). In addition, long lead times for construction of reactors and other nuclear fuel cycle facilities (sometimes a decade or more) and uncertainties over licensing procedures make nuclear power more risky, and thus less interesting, for private investors.

[2] Possible impacts of climate change include (but are not limited to): frequent warm spells/heat waves, heavy precipitation, more severe and frequent drought, and intense tropical cyclone activity (IPCC, 2007)

This report explores the following areas in order to provide a complete understanding of interactions between climate change and nuclear power, and the arguments both for and against nuclear power as a climate change mitigation and adaptation strategy:

- Arguments relating to nuclear energy expansion under climate change. This includes a review of the pros and cons of nuclear power as a mitigation and an adaptation strategy. In addition, regional variations in these arguments regarding nuclear development are discussed in the paper.
- Quantitative impacts of nuclear power toward the reduction of CO_2 emissions and the stabilization of atmospheric CO_2 concentrations. A review of a number of estimates of the current contribution of nuclear power towards reducing CO_2 emissions by 2050 is provided, based on different expansion scenarios forwarded by researchers in the field. Regional scenario analyses of nuclear power expansion are included, particularly for China and India.
- Requirements for the successful expansion of nuclear power use on a scale so as to make a significant contribution to climate change mitigation and adaptation. A review of the economic, technical, and political requirements needed to support such as nuclear expansion is provided. In addition, sustainability of sufficient uranium supplies to fuel a much larger global reactor fleet is evaluated.
- A discussion of non-climate concerns related to nuclear power, such as reduced investment in other low-carbon options due to nuclear expansion given limited financial resources, safety, proliferation, and waste disposal, including their current status and both potential solutions and events that might exacerbate these concerns.
- A conclusion summarizing the major findings of this report.

2. Major arguments relating to nuclear energy expansion under climate change

2.1. Advantages of nuclear power as a climate mitigation strategy

Nuclear power has contributed to commercial electricity generation since the 1960s. The reactor accidents at Three Mile Island in 1979 and Chernobyl in 1986, however, shattered the public's trust in nuclear power in many nations, and changed the nuclear industry permanently. Figure 1 shows a major slowdown growth in nuclear capacity in many countries in the period following the two accidents, with the virtual halt in capacity additions in the United States after about 1990 as a particular case in point. In the U.S. new regulations were put in place in the years before and again immediately after the Three Mile Island accident. New regulations resulted in plant startup delays of many years. The delays caused huge uncertainties on nuclear economics. With concerns about current and future climate change increasing in recent years, nuclear power might be endowed with a better chance for a comeback, thanks to its low carbon emissions per unit electricity output relative to fossil-fueled generation. In addition, current light water reactor technologies (which dominate the nuclear industry worldwide) are relatively mature, and nuclear power is capable of being implemented on a large scale.

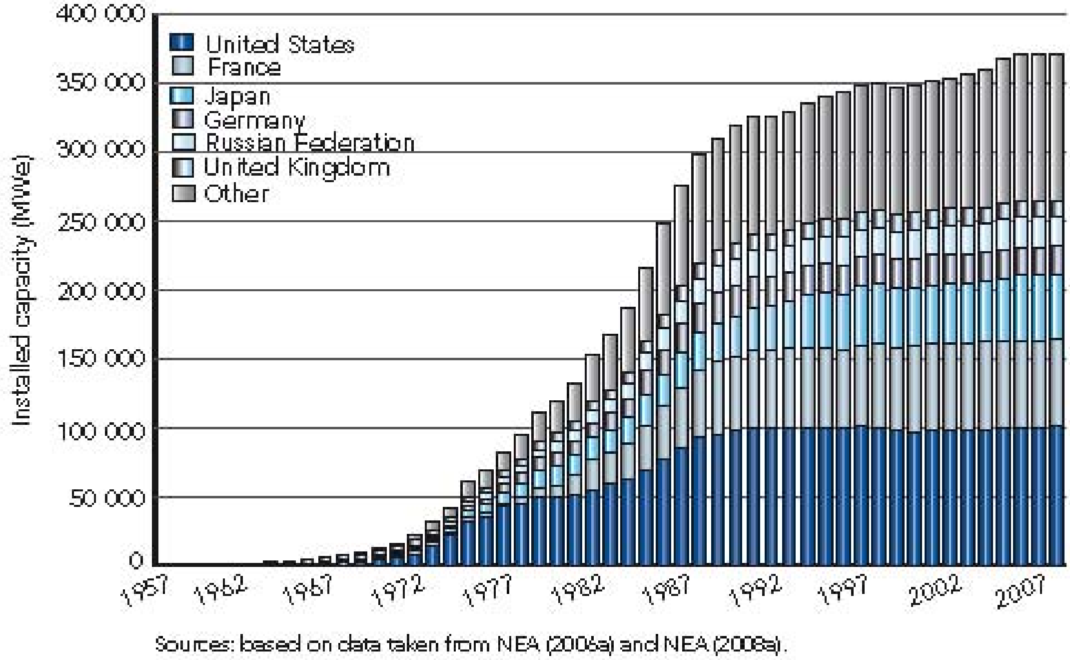

Figure 1: Global nuclear capacity from 1957 to 2008 (NEA, 2008)

Low carbon emissions. Nuclear power is viewed as a low-carbon technology. Advocates of nuclear power describe nuclear power as a "carbon-free" technology. Opponents of nuclear power, however, argue that nuclear power does emit a considerable amount of CO_2 over its full fuel cycle, that is through the full life cycle of nuclear reactors and the fuels they use. Dozens of studies in recent years have examined and estimated the life-cycle CO_2 emissions from nuclear power (for example, Dones et al., 2004; Fthenakis and Kim, 2007; Weisser 2007). Those studies show a wide variation in results, due to different assumptions as to the specific nuclear fuel types, reactor types, fuel cycle technologies, and site locations used. All the studies, however, show that the "front-end" processes in the nuclear fuel cycle, including mining, milling, conversion, and enrichment, make the most important contributions to overall CO_2 emissions from nuclear power. In the studies surveyed, the emissions ascribed to front-end processes ranges from 0.68 to 118 gCO_2/kWh (Andseta et al 1998; Tokimatsu et al 2006). Assumptions as to the quality of uranium ore and the uranium enrichment methodology are the two major factors that result in the wide variation. The quality of uranium ore presents a non-linear scale factor in terms of energy input to mining and milling, meaning that processing low-grade uranium ores requires extra energy input per unit refined uranium output, and thus emits more CO_2 to produce the same amount of yellowcake (U_3O_8) as compared to requirements to produce yellowcake from high-grade uranium ores (Diesendorf and Christoff, 2006; van Leeuen et al. 2007). In addition, gaseous diffusion enrichment technology is considerably more energy-consuming than the newer centrifuge enrichment technology. Gaseous diffusion technology requires roughly 3.4 percent of the electricity generated by a typical PWR (pressurized water reactor) per year to enrich one-year's worth of uranium fuel supply for one reactor (UCS, 2007). Current trends shows that although gaseous diffusion still accounts for about 45% of world enrichment capacity (Sovacool, 2008), most of the existing gaseous diffusion plants are being retired or used less, thus most gaseous diffusion plants will be substituted for by centrifuge enrichment technology in the near future due to the technical advantages of the latter. Centrifuge enrichment plants consume only 60 kWh/ SWU (Separative Work Unit, a measure of the work required to separate the isotopes of Uranium) as compared to the 2400 kWh/SWU required for plants using gaseous diffusion technology. Louisiana Energy Services is building a gas centrifuge facility in New Mexico, and the U.S. Enrichment Corp. is planning to build a similar facility in Ohio (UCS, 2007).. In Sovacool's survey, an expected value of emissions over the lifetime of a nuclear reactor is 66 gCO_2e/kWh. The value is simply obtained by averaging all data from different studies, ranging from 1.36 to 288 gCO_2e/kWh. Most of the surveyed studies only focus on one reactor type in one particular location. Jacobson's survey (2009) provides a range of emission data from 9 to 70 CO_2e/kWh. An additional study from the IPCC (2007) estimates the lifecycle emissions of nuclear reactors as 40 gCO_2e/kWh. According to Gagnon et al. (2002), coal, natural gas, oil and diesel power lifecycle emissions range from 443 to 1050 gCO_2e/kWh, with most of the emissions related to the fossil fuel combustion step in the fuel cycle. These fossil-fuel generation technologies therefore are responsible for the emissions of on the order of 10 to 100 times the CO_2 per unit electricity produced relative to nuclear power. While Jacobson (2009) estimates the life-cycle emissions from solar photovoltaic (PV) power systems range from 19 to 59 gCO_2e/kWh, Weisser (2007) summarizes PV systems as having life-cycle emissions ranging between 43 and 73 gCO_2e/kWh. Most studies show nuclear power to have fuel-cycle/life-cycle emissions that are competitive with those of solar PV technologies. Wind energy and hydropower are typically found to be the lowest emitters, on a per unit output life-cycle basis, among all electricity sources.

There are several trends showing promising improvements that will allow nuclear power to reduce emissions and better compete with other low-carbon technologies. As mentioned earlier, centrifuge enrichment technology is replacing gaseous diffusion technology, which could significantly reduce energy inputs in the nuclear power life cycle. Emissions from the reactor construction phase could be reduced by using advanced and simplified designs that result in shorter construction times and require less construction materials. In addition, advanced reactor designs and taking advantage of the lessons learned from long-term operational experience with nuclear power could provide for longer and extended reactor lifetimes, which would significantly reduce emissions per unit output by spreading the life-cycle emissions of a reactor over more years of output. Overall, though there are differences of opinion as to the absolute greenhouse gas emissions produced by the nuclear fuel cycle, nuclear power can be considered a low-carbon electricity generation technology.

Diverse applications. A number of authors have noted that nuclear technology has many potential non-power applications. These applications include desalination, providing process and district heat, and producing hydrogen for use in the transport sector. These applications can play key roles in mitigating greenhouse gas emissions by displacing fossil fuel inputs in sectors beyond electricity generation, and, in some cases, to adapting to a changing climate, in addition to the climate benefits of nuclear power itself. The IPCC Fourth Assessment Report (2007) estimated that drought-affected areas will likely increase and water availability and supplies are projected to decline. For example, warming will reduce water availability in regions supplied by meltwater from glaciers and snow cover, as glaciers and other snow cover retreat toward higher latitudes and elevations. Reductions in fresh water supply will be one of major impacts of climate change. Africa and some regions in Asia are projected to be the most affected by declining supplies of fresh water. In some areas, desalination could be a solution to ease the water supply shortages. By mid-2007, Middle Eastern desalination accounted for close to 75% of total world capacity (Fischetti, 2007). The world's largest desalination plant is the Jebel Ali Desalination Plant Phase 2 located in the United Arab Emirates. Currently, fossil fuels are typically used in large-scale plants to desalinate sea water. Since desalination is an energy-intensive process, fossil fuel use for desalination results in significant CO_2 emissions. Other alternatives have been discussed to replace fossil fuel use in desalination. Renewable energy sources, such as solar energy, have been explored as potential sources of power and heat for desalination. However, due to high costs and large land requirements, solar desalination has not yet been broadly applied in practice. When fossil fuel prices are high, some researchers contend that nuclear desalination is generally very cost-competitive (WNA, 2008). In addition, as nuclear power plants typically must be located next to large bodies of surface water, there is the possibility that countries bordering oceans could combine nuclear power production with the use of the waste heat from reactors to desalinate seawater.

Hydrogen is viewed as a future fuel for the transportation sector, as its combustion yields primarily water vapor, with no emissions of carbon dioxide. In the future, high-temperature reactors (reactor output temperatures from 750-1000°C), such as General Atomics' High Temperature Gas Cooled Reactor (HTGR), nuclear heat can be used in high-temperature electrolysis (HTE) hydrogen production. High-temperature electrolysis is more efficient economically than low-temperature electrolysis (LTE) for hydrogen production because some of the energy driving hydrogen production is supplied as heat, which is less expensive to produce than electricity, and because the electrolysis reaction is more efficient at higher temperatures. The efficiency improvement provided by high-temperature electrolysis can be appreciated by assuming that the electricity used for electrolysis comes from a heat engine, and then considering the overall amount of energy necessary to produce one kg hydrogen (with an energy content of 141.86 megajoules), both directly as heat in the HTE process itself and also in producing the electricity used for electrolysis. At 100°C, 350 megajoules of thermal energy are required (41% efficient). At 850°C, 225 megajoules are required (64% efficient) (WELTEMP, 2008). Research into HTE and high-temperature nuclear reactors may eventually lead to development of technologies for hydrogen supply that are cost-competitive with natural gas steam reforming. However, the technical and economic feasibility of this application remains to be demonstrated.

Nuclear energy can be used for district heating jn areas with high population densities. As with district heating systems that use other fuels, district heating based on nuclear fuels is generally more energy-efficient compared with individual heating systems. To the extent that the waste heat from nuclear reactors generating power can be used for district heating, the efficiency advantages become even greater. The technical feasibility of using nuclear energy systems for district heating has been demonstrated in several countries. The principles for a conventional combination of cogeneration and district heating applies the same for nuclear as it does for a thermal power station. In Switzerland, the Beznau Nuclear Power Plant provides heat to about 20,000 people (Kenichiro et al., 2006). Russia has several cogeneration nuclear plants which together provided 11.4 PJ of district heat in 2005. Russian nuclear district heating is planned to nearly triple within a decade as new plants are built (WNA, 2009).

Energy supply security. One of the most common approaches to improve a country's energy supply security is to diversify its energy supply sources. For countries such as China and India, with vast and rapidly growing energy needs, there is no single approach to accomplish the goals of reducing greenhouse gases and ensuring energy supply at the same time. While energy demand growth in the developed countries will be almost saturated (that is, energy demand growth in most countries will slow, cease, or even be negative) in the next several decades, developing countries that started their economic development and their energy growth more recently are likely to show significant increases in energy use in the near future. As a consequence, a key challenge that humans face is not just reducing global emissions of greenhouse gases, but doing so while also providing energy for the rapid economic development of developing countries. Figure 2 shows the total electricity generation and contributions from major generation sources from 1990 to 2007 for China. In 2007, China had a total installed electricity generation capacity of 710 GW and generated 3,277 TWh of electricity (National Bureau of Statistics of China, 2007). China's rapid growth in electricity demand has spurred significant investment in new power stations. Since 2004, the total installed capacity in China has increased at an average rate of 90 GWe per year, which is equivalent to the entire current installed capacity of the UK.

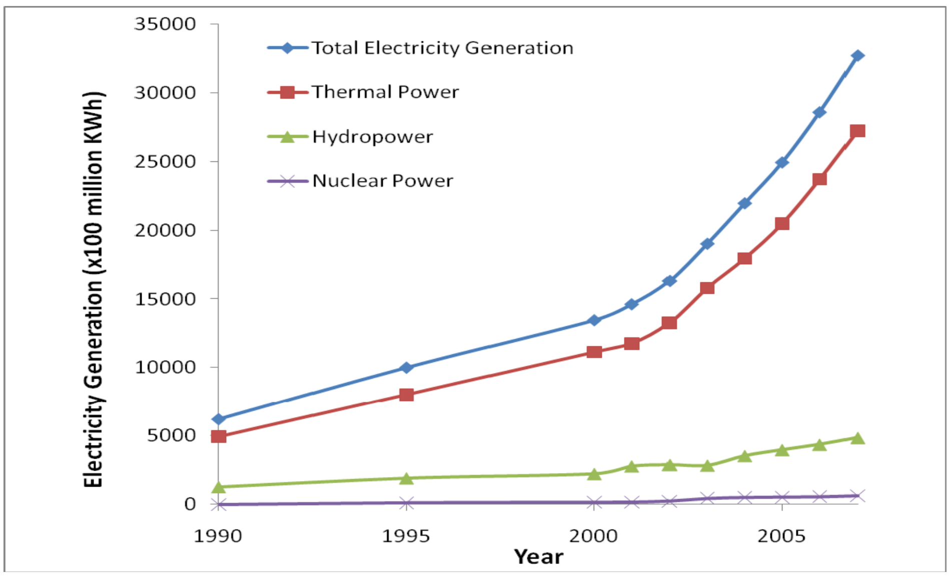

Figure 2: Total electricity generation and components in China from 1990 to 2007

In order to keep up with its growing electricity demand, China builds roughly one large-scale coal-based power plant every week. Currently, renewable energy still plays a small role in the energy mix. China invests a huge amount of money in its renewable energy industry, and aims to provide 30 percent of its total energy needs through renewable sources by 2050 (China Daily, 2007). China heavily advocates implementation of energy-efficient technologies, and lists energy efficiency as a top priority in its current energy policies. However, with such aggressive growth in overall energy demand, it is very challenging to implement renewable energy and energy-efficient technologies at levels such that by themselves they are able to meaningfully address (on a suitable timescale or size scale) the imminent threat of climate change while providing sufficient energy services for rapid economic development. Nuclear technology could strengthen a country's energy security by helping to diversify energy supply options. Nuclear power is not the only solution to energy supply constraints, but, its proponents argue, its attributes mean that it should be a part of the solution.

Maturity of technology and large scale implementation. Over the past 50 years, nuclear power technology has been developed to provide a reliable source of electricity. Scientists and engineers have worked to extend the technology from the generation I reactor designs to the generation III reactor designs. Generation I reactors were developed in 1950-60s, and the term usually refers to the early prototype power reactors. Generation II reactors is a design classification that refers to the class of commercial reactors built up to the end of the 1990s, such as the PWR, the boiling water reactor (BWR), and the Canada deuterium uranium (CANDU) reactor. Generation III reactors are a further development over Generation II reactor designs in that they incorporate evolutionary improvements in technology. In proceeding from Generation I to Generation II, and, recently, Generation III reactor types, deployment of nuclear technology went through a phase of rapid growth, followed by the two major accidents described above (at Three Mile Island and Chernobyl), and then a phase in which most countries reduced the pace at which new reactors were ordered and built. Although new nuclear power reactors have not been deployed widely recently, the scientific background, design and operational management of LWRs are well understood and developed. Nuclear reactor technology, particularly for the most widely used pressurized water reactor type, is in a phase of development ("Gen III") where already successful designs are being improved with regard to performance, safety, maintenance, and economy. This technological maturity is in contrast with some "green energy" technologies, such as carbon capture and storage/sequestration, which are still in the R&D stage. The current Gen III reactor designs include improvements in fuel technology, provide superior thermal efficiency, integrate passive safety systems, and incorporate standardized designs for reduced maintenance and capital costs. Improvements in nuclear technology will potentially lead to a longer operational lives (up to 60 years of operation, versus the current standard of 40 years, though life extension has been/is being applied to many units worldwide). Passive safety features are the most evolutionary improvement in Generation III reactors as compared to older reactor designs. These features mean that no operator action or electronic feedback is needed in order to shut down the reactor safely in the event of a particular type of emergency (usually overheating resulting from a loss of coolant or loss of coolant flow). The unit size of the Generation III designs are similar to Generation II reactor designs, but can be (and are being, for example, in some countries in Asia) boosted to a larger unit capacity, such as 1400 MWe. Furthermore, estimated core damage frequencies for these reactors are generally in the range of 1 core damage event for every 15-20 million years of operation (6e-7 core damage events per reactor year for the European Pressurized Reactor from Areva) and 1 core damage event for every 300-350 million years of operation (3e-8 core damage events per reactor year for the Economic Simplified Boiling Water Reactor from General Electric ESBWR) (Hinds and Maslak, 2006). These core damage frequencies are usually calculated by probabilistic risk assessment (PRA) through Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) methods. Generation II reactors are known to have core damage frequencies as high as 1 core damage event for every 100,000 years of operation (1e-5 core damage events per reactor-year for the BWR).

In addition to its safety attributes, nuclear power is one of a few low-carbon technologies that are mature enough to offer the capability of large-scale implementation on a time-scale suitable for addressing climate change. For example, one pressurized water reactor plant could have 6 units of 1000 MWe capacity at the same location. And the current Gen III designs could easily upgrade each unit capacity up to 1400 MWe.

Globally, new renewable energy installations grew rapidly over the past decade. Global wind power production will reach 0.3 trillion Kilowatt-hours by 2010. Growth rates for wind-powered electricity generation also are expected to be high in the non-OECD countries, with the largest increment in China, which is expected to account for 88 percent of the total increase in non-OECD wind generation from now to 2030 (EIA, 2009).

Despite this progress, renewable energy alternatives currently play only a small role in providing distributed generation in most developing countries. Cost-effective development of renewable energy, such as wind energy, small hydro, and tidal energy, on a significant scale relative to national needs requires specific natural and geographical requirements. As such, not all countries have the natural resources to develop significant renewable energy programs. For many new renewable energy sources, the cost and lead time for developing electricity transmission to accommodate major renewable electricity development can be larger and longer than the cost and lead time for the generating plants themselves. For developing countries, such as China, it is not an easy task to provide the transmission resources needed to bring large-scale renewable electricity to consumers. Although China is the fourth largest wind turbine market in terms of installed capacity in the world, only 60 percent of the current capacity is connected to grids to generate electricity (Forbes, 2009). The remainder is off-grid due to a lack of grid infrastructure. Currently, most wind power investments are directed to large scale wind farms in China. Small distributed wind farms for local uses are not a major focus since the best wind resources in China are located in very remote areas without major population centers or industries. Local needs alone in these areas cannot make wind power generation economic. In addition to the challenge of resource location, the high cost of some of renewable energy options, such as solar, has constrained the pace of large-scale implementation of these technologies, though, like wind power, solar generation capacity has been increasing rapidly in China in the past few years, as in other nations. Although the resource potential of solar power is enormous, the large-scale commercial solar power industry is in its infancy due to its large capital cost per unit of generation and still-developing technology. The current grid-connected solar photovoltaic capacity in China is still marginal relative to national needs, though growing fast. China's first grid-connected solar power station entered operation in December 2008, with a total installed capacity of 1 MWe. The project is scheduled for full completion by the end of 2009 (Xinhua News, 2008). Large scale plants tied to the Chinese grid, such as the 1,000 MW plant installed in Germany in 2006, are still under construction and at least a decade away. As the cost of solar photovoltaic technology continues to decline, solar power will become a more viable option for meeting energy needs.

Small social and landscape impacts. Every energy generation resource causes social and environmental impacts at some level. The social and environmental impacts of each generation resource should be assessed and included in energy planning and development processes. Jacobson (2009) listed wind technology and hydropower as the two top space consumers (the technologies requiring the most land area per unit of generation) among most of the low-carbon technologies. The Jacobson survey listed nuclear technology as the least space-intensive low-carbon option, behind geothermal energy, tidal energy and carbon capture and storage technology. Large hydropower projects tend to cause social and ecological impacts. Construction of huge dams change the landscape and requires people who live in those areas to resettle elsewhere. For example, between 1.2 million and 1.9 million people have already been forced to leave their homes as a consequence of the construction and operation of the Three Gorges Dam project in China (Schreurs, 2007). Strong public opposition has slowed down several other large-scale hydroelectric projects, including the Nu River project, and has made future development uncertain. Another challenge for hydropower is that it can induce biodiversity loss in the local environment (Rosenberg 1997). Wind energy also requires huge land uses, and could cause habitat loss, though in some areas, such as the US Midwest, wind power systems are being integrated with other land uses, mainly agriculture.

*Moderate public acceptance of nuclear power in developing countries***.** After the Three Mile Island accident and the Chernobyl accident, public concerns over nuclear power in many Western countries were a major contributor to the nuclear industry's decline (Wynne, 1980, 1992; Rosa and Clark, 1999; Poortinga and Pidgeon, 2003). In Western countries, public acceptability remains a key factor affecting the practical feasibility of deployment of new nuclear reactors (Rosa, 2005). The situation, however, might be different in many developing countries. Although the Three Mile Island and Chernobyl accidents caused huge social impacts in Western countries, those accidents might not have the same impact in developing countries in terms of the social amplification processes that result from attitudes changing in response to prominently reported events (Pidgeon et al., 2003). In addition, major developing countries are showing interests in nuclear power decades after the accidents. The public of major developing countries, such as China and India, has not experienced or been exposed to significant controversy regarding nuclear power development as yet. Local benefits associated with nuclear facilities and personal experiences (Bickerstaff, 2004) do help reduce nuclear opposition. For instance, the Chinese public seems willing to accept and embrace nuclear technologies and the role they will play in the country's continued development[3]. Further nuclear development will provide thousands of jobs, which has set off a scramble among local governments eager to have nuclear power plants built in their regions. In contrast to Japan, for example, where local officials have in some cases fought to keep nuclear facilities out of their regions (though in other cases, local jurisdictions have received compensation deals to host nuclear facilities), local Chinese officials believe that nuclear power can positively affect the local economy, increase the local tax base, and resolve electricity shortfalls. As such, local Chinese officials have tended to aggressively initiate cooperation with nuclear investment corporations.

2.2. Advantages of nuclear power as a climate adaptation strategy

Climate mitigation strategies will have global benefits by reducing the growth in atmospheric CO_2 concentrations, but these impacts will not be noticeable immediately due to the lag times associated with implementation of strategies and in the climate system itself. Climate change adaptation impacts, however can be immediate and noticeable. Therefore, climate policy is not only about mitigation, but also about adaptation. Observational evidence already shows that the impacts of climate change are inevitable due to past emissions (IPCC, 2007). According to the IPCC Fourth Assessment Report (2007), Working Group II, adaptation to unavoidable impacts due to past emissions should be undertaken in a timely manner. As noted above, there are a number of arguments as to why nuclear power is considered a promising strategy for climate change mitigation, as it provides energy with low carbon emissions. In addition to its mitigation potential, nuclear power could naturally aid in adaptation to climate change.

[3] Communications with Chinese nuclear energy experts in Beijing, Jan 2008.

Weather-proof energy source. According to the IPCC Fourth Assessment Report (2007), observational evidence shows that at least some of the future impacts of climate change are inevitable due to past emissions. Scientists predict that our society will experience more extreme weather and climate events, such as drought, frequent heavy precipitation, and intense tropical cyclones and hurricanes in the coming years. Unfortunately, most major renewable energy resources, or the structures used to harvest them (such as wind power turbines or photovoltaic panels), are susceptible to variations in climate, and hence vulnerable to the impacts of climate change (Breslow and Sailor, 2002). Extreme weather and climate events thus add uncertainty to consideration of renewable energy sources. Wind power, for example, is strongly influenced by other climate elements besides the wind and the wind resource, such as humidity, precipitation, temperature, and the average concentrations of particles in the air. For example, critical combinations of freezing temperature, humidity and windspeed result in restrictive icing of wind power generators (Parry et al., 1996). In general, because they are often configured in smaller-capacity units that are spread around a country geographically and connected to power systems at different points in the distribution grid, distributed renewable energy systems, including solar photovoltaic, wind power, and other systems, would be less vulnerable to extreme weather and climate events than some centralized conventional power systems or to centralized renewable energy systems, such as the large scale wind farms under constructions in China. While output from wind energy and solar energy heavily depends on weather conditions, nuclear power is relatively unaffected by extreme weather events, providing a consistent source of energy regardless of weather, though changes in water availability can hamper nuclear output in some locations (see below).

Base-load energy source. Base-load technologies are generators that can produce a continuous amount of electricity, and can be controlled at least to some extent to adjust the amount of electricity they're producing. Nuclear power as a base-load energy source provides relatively reliable electricity supply that is not sensitive to most climate events, though nuclear power stations usually have limited capacity to rapidly increase or reduce output to follow changes in electricity demand. Non-baseload, intermittent generation technologies, such as wind and solar power usually cannot provide continuous electricity output and the output cannot be completely controlled using current technologies. Power generation based on renewable energy sources necessitates greater use of intermittent generation management and storage, especially in countries with rapidly growing energy demand. For example, Chinese wind farms currently need coal-fired power as a backup when the weather conditions vary (WSJ, 2009). The weather-directed variability of wind and solar energy need to be managed before those technologies can play a bigger role in fighting climate change. Under a climate regime with more frequent extreme weather events, renewable energy options might be even more fragile than they now, whereas nuclear power stations, with their massive construction, are much less likely to suffer significant damage from such events.

Less fuel transportation activity. One of the advantages of nuclear power is that its fuel is predominantly comprised of uranium, which makes it a highly concentrated source of energy that requires less transport capacity. For example, a current 1000 MWe pressurized water reactor usually refills only one third of its fuel assemblies per year, which is around 28.5 tons for a reactor with a burn-up rate of 33 GWth (thermal gigawatts)-days/ton Uranium. By way of comparison, the total weight of nuclear fuel for all nuclear reactors is several orders of magnitude less than the amount of coal or oil needed to generate equivalent amount of energy.

For example, a 500 MWe coal-fired power plant needs around 4000 tons of coal per day with a heat rate of 2,460 kWh/ton. The Nanticoke power station, at nearly 4 GWe, the largest thermal power plant in North America, usually needs a stockpile of several million tons of coal in storage in the winter. More recently designed PWRs, such as the Westinghouse AP1000 model, could have a much higher burn-up rate than existing plants, with an 18-month fuel reloading cycle, which could lower the amount of fuel used and the frequency of reloading fuel assemblies. Additionally, a burn-up rate as high as 100 GWth-d/t is assumed for the new Gen III reactors after 2020. If this projection is correct, the mass of fuel required for one 1000 MW PWR will drop to 9.38 tons annually with a 100 GWth-d/t burn-up. Such an improvement could ease the risk of disruption of long distance fuel transportation (for many countries using nuclear power, likely including most new adopters of nuclear power in the developing world, nuclear fuel will be imported) by extreme weather events driven by climate change, such as intense storms. As an example that illustrates the potential impact of climate change-driven events on fuel supplies, in January 2008, the worst winter snowstorm in five decades hit central, eastern and southern China. China's coal-dominated energy structure exacerbated the disastrous consequences of this extreme weather on China's economy and population. Snow caused bad road conditions that prevented coal from being transported from the inland regions to the major population centers on the coast. The cold weather dramatically increased electricity demand throughout the country. Coal-fired plants in several provinces, such as Zhejjiang Province, suffered a sharp decline in coal reserves. At the shortage's most severe point, coal stockpiles were only enough to generate electricity for three days. Some regions had to cut power supply in their entire industrial areas to ensure local residents would survive. Nuclear power's more concentrated fuel supplies reduce transport needs and reduce risks of fuel shortages caused by extreme events.

2.3. Vulnerabilities of nuclear power as a climate adaptation strategy

Impacts of sea level rise and storm surges. Rising sea levels and storm surges in low-lying areas will cause coastal flooding, as confirmed in the Third Assessment Report by the IPCC. Nuclear power plants built on coastal areas might in some cases face flooding risk, such as.in some locations in the UK (the UK's Dungeness and Sizewell plants are examples). Due to the long operational lifetime of nuclear power plants, particularly the new designs that might have a more than a 50 year lifetime, siting and design of new coastal nuclear power plants will require extra analysis to include consideration of the impacts of sea-level rise and flooding issues, including flooding due to storm surges. Additionally, more robust and reliable physical infrastructure—such as sea-walls and pumps—will be needed to protect existing power plants and to fight against flooding.

Insufficient water supplies. According to the Fourth Assessment report (IPCC, 2007), drought-affected areas will increase globally, and droughts will be severer and more frequent for most areas. Nuclear power plants need a plentiful supply of water. Most of nuclear power plants have to rely on large bodies of surface water for routine service (reactor cooling), and emergency cooling, as well as smaller quantities of ground water for construction and domestic uses associated with the plant. Only a very few nuclear power plants rely solely on ground water as a major water source. Recent research studies show the service water consumption (from evaporation) in a nuclear power plant ranges from 0.4 to 0.72 gal/kWh or .1.5 to 2.7 liters/kWh, depending on the type of cooling technology used (Jacobson, 2009), which does not include emergency cooling water and other uses. Insufficient water supply, both seasonally and in a drier future, could be an issue for large-scale nuclear power development in some areas, particularly non-coastal areas where river water is relied upon to cool the reactor.

2.4. Regional variations of advantages and vulnerabilities of nuclear power

Mitigative and adaptive capacity and activity related to climate change are uneven across different societies. These capacities are influenced by the economic and natural resources, institutions and governance, physical infrastructure, human resources, and technologies available in each nation, as well as the level of regional vulnerabilities due to climate change. As a result, potential contributions from nuclear power as part of mitigation and adaptation are likely to vary greatly from region to region.

Developed countries. The primary developed countries are generally defined to include Japan and Korea in Asia, Canada and the United States in northern America, Australia and New Zealand in Oceania, and most of the Western countries in Europe. Most of these countries are projected not to experience large economic and population growth in the next several decades, which means there is unlikely to be large increases in total electricity demand in these nations. The United States Department of Energy's Energy Information Administration (EIA), in its International Energy Outlook, projects an average 0.6 percent per year energy use increase for the developed countries (EIA, 2009) over the time period up to 2030. The United States might be the only country in the group above that will experience a large increase in population—populations in Japan, for example, and several Western European countries are even now or will shortly be declining. The total marketed energy use in the United States is projected to increase from 100 quadrillion Btu in 2006 to 113.6 quadrillion Btu by 2030 (EIA, 2009). In these developed countries, nuclear power might not contribute much toward additional climate change mitigation due to political controversies and risks associated with nuclear power, and to the slow pace of increase of energy demand, which reduces the need for development of new energy supplies. The International Energy Agency (IEA) estimated that there is a 15 percent difference in CO_2 emissions from the OECD countries in the next two decades between the Reference Scenario (RS) and Alternative Policy Scenario (APS) considering the saturated energy demand growth in OECD countries. The IEA Reference Scenario is a business-as-usual scenario where today's trends in the energy market are expected to continue unchanged. In contrast to the RS, the APS depicts a more efficient and more environment friendly energy future. In the APS, global energy demand is about 10% lower in 2030 than in the RS. Carbon dioxide emissions would be reduced by some 6 Gt, or 16%, below the Reference Scenario figure in 2030 (IEA, 2006). Japan, Korea, France and the United States might be the only countries that will construct new nuclear plants in the future, mostly to maintain the relatively high nuclear fractions in their energy mix by replacing aging reactors. Currently, the nuclear shares of generation in those countries are 30 percent, 40 percent, 75 percent and 20 percent respectively.

Post- Soviet Countries. Countries such as Russia, Slovakia, the Czech Republic, Lithuania and Slovenia have relatively high nuclear shares in their energy mixes. Their nuclear shares are being maintained as their economies grow (MIT, 2003).

More advanced developing countries with large populations. Countries such as Brazil, China, Egypt, Mexico, South Africa and Turkey could be considered as more advanced developing countries. Those countries are more advanced and developed than others in the developing world, but have not yet reached the full status of a developed country in terms of per-capita income and other indicators. Those countries will continue to experience rapid growth both in economic activity and energy demand, and they will be responsible for a large part of total global energy demand and CO_2 emissions increases (EIA, 2009) over the next few decades. Nuclear power could contribute significantly as part of climate change mitigation and adaptation strategies in these countries. For the more advanced developing countries, which have to pursue economic development and face environmental constraints at the same time, the application of renewable energy and energy-efficiency technologies alone cannot stabilize, let alone reduce, national greenhouse gas emissions. These countries need one or more mature and low-carbon technology or technologies with large scale implementation capability to diversify their energy supplies away from fossil fuels and to solidify their energy supply security. Since most of these countries already have technical and economic/financial capabilities (and available capital for investment) that could be made available to support a substantial growth in the nuclear power industry, given a commitment to nuclear power on the part of the government, adopting nuclear power on a broad scale will not be particularly challenging.

*Less advanced developing countries with large and growing populations***.** Although the economies in countries such as India, Pakistan, Indonesia, the Philippines, and Vietnam may have lower rates of economic growth, and/or lower income per capita, than some of the more advanced developing countries mentioned above, their large and growing populations and expanding economies will still require new resources to satisfy their large growth in energy demand. For less advanced developing countries, nuclear power could be considered as an energy option, but not a necessity due to the complications and huge financial resources involved. India recently has announced its ambitions for nuclear energy expansion from its current 3.7 GWe of capacity, and Pakistan already has two nuclear power plants with a total capacity of 600 MWe. The more limited technical and/or financial capabilities of these countries, relative to the more advanced developing countries, will, however, make it more challenging to implement nuclear power as a sustainable energy option in a short time period. Hence, assistance and cooperation from nuclear vendor countries will be very important and valuable to help those countries to build their nuclear energy sectors.

Least-developed countries. Most of the least developed countries are located in Africa or Asia as well. The energy demand in these nations is projected to slowly increase due to the combination of a large and growing population and a relatively slow pace of economic development. As mentioned above, current stress on water supplies in many areas of Africa will likely be enhanced by climate change. Additionally, the technical and financial capabilities in most least developed countries are relatively low, and thus nuclear power may not be a suitable option at this stage of the countries' development, though some least developed countries harbor nuclear energy ambitions. Least-developed countries might be more likely to choose other low-carbon energy options, such as biomass or solar power, that require less in the way of technological infrastructure and are suited to smaller energy systems.

3. Quantitative analyses of the use of nuclear power to help stabilize CO_2 emissions

3.1. Current contribution of global nuclear power toward reducing CO2

Over the past 50 years, the use of nuclear power has avoided significant amounts of CO_2 emissions worldwide. The Nuclear Energy Institute (NEI) estimates that from 1973 to 1995, nuclear energy prevented the cumulative emission of well over six billion metric tons of carbon (NEI, 1997). The MIT Future of Nuclear Power Report (2003) estimated that the future implementation of 1000 MWe of nuclear power it postulated would avoid annually about 1800 million tons of carbon equivalent (equivalent to 6600 million tons of CO_2) if the generation avoided was coal-fired, and assuming no capture and sequestration of CO_2 from the combustion sources avoided. The results of the MIT study are consistent with the IEA estimates of CO_2 emissions avoided by nuclear technologies in the past three decades in Figure 3 (IAEA, 2008). The IEA shows global nuclear power with a total capacity of 266 GWe helped avoid 2.4 Gt of CO_2 emissions in 2006 (IEA, 2008).

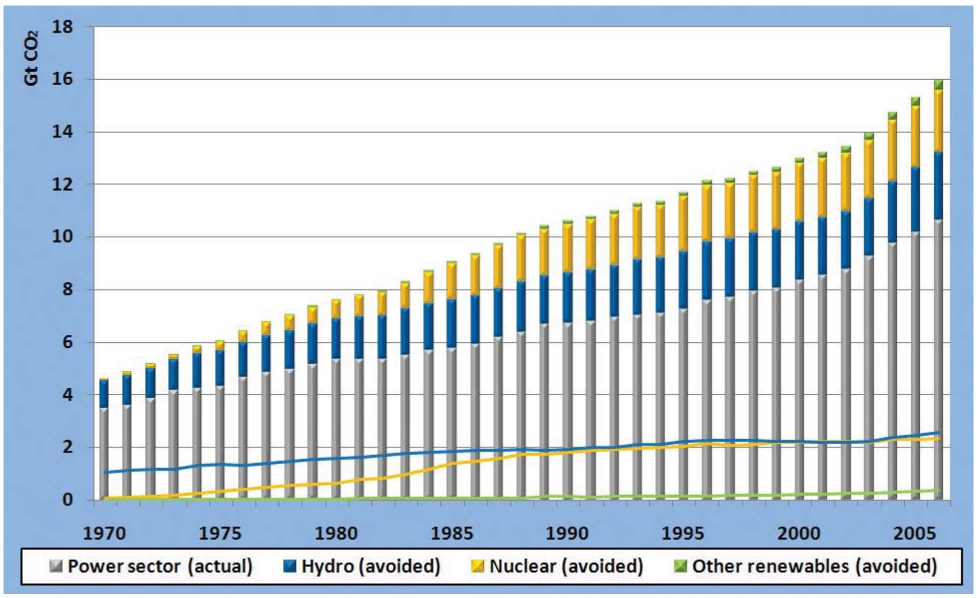

Figure 3: Total Global CO_2 emissions from the electricity sector and estimated emissions avoided by three non-fossil generation technologies

Note: The lines near the bottom of the graph show the estimated emissions avoided by use of hydro, nuclear, and renewables-based power, while the overall total height of the columns show estimates of what emissions would have been if all electricity were produced from fossil fuels.

3.2. Expansion scenarios to mitigate climate change

All business-as-usual or reference scenarios in major scenario studies have indicated that the nuclear share of the world's energy portfolio will decrease on a global basis if governmental policies around the world are not changed. In most of the alternative scenarios, which assume policies and strategies are adopted that support the expanded deployment of low-carbon energy alternatives, nuclear energy might play a significant role in helping to meet increases in energy demand and mitigate climate change. The following summarizes the leading alternative scenarios developed by major organizations.

In the MIT report (2003), the “growth” scenario assumes a 1000-1500 GWe expansion in the use of nuclear power worldwide by 2050, which raises the estimated nuclear of total electricity generation from the current 17% to 25%, based on an annual global electricity demand growth rate from 1.5% to 2.5%. The MIT report assumes that the developed nations remain the focus for a major part of nuclear power deployment in the growth scenario. In particular, the United States must experience a substantial expansion of its nuclear power to realize the level of nuclear capacity assumed in the global growth scenario. Amongst the developing countries, China and India will be the major contributors to nuclear growth in the scenario. The report projects 65% of the capacity expansion will happen in developed countries, while 30% of the expansion will be accomplished in developing countries by 2050. The remaining 5% will happen in the former Soviet Union countries.

In its Nuclear Energy Outlook 2008, the Nuclear Energy Agency (NEA) developed low and high nuclear energy development scenarios based on the energy and electricity demand predictions from the IPCC (2007), the US Department of Energy’s Energy Information Administration (EIA, 2007), the IEA (2006a; 2006b) and the IAEA (2005). The low scenario assumes that other low-carbon alternatives are successfully developed and deployed. The nuclear expansion in the low scenario is mainly to satisfy the need to replace of retired nuclear power plants. The NEA projects a global total nuclear capacity of 580 GWe by 2050 in the low scenario. The high scenario assumes that other low-carbon alternatives are not successfully developed and deployed, and that carbon trading schemes are accepted and enforced. The high scenario projects a global nuclear capacity of 1400 GWe by 2050, of which China and India together will have a total 200 GWe capacity. With the NEA projections, the share of nuclear power in electricity supply would range from 9% in the low scenario to 22% in the high scenario by 2050, as compared to 16% at present. The nuclear expansion in the high scenario would save nearly 9 Gt CO_2 per year in 2050 if the generation avoided is coal-fired, and assuming no capture and sequestration of CO_2 from the combustion sources avoided. The NEA’s scenarios are similar to nuclear scenarios prepared by the IEA (World Energy Outlook and Energy Technology Perspectives), the IAEA and the EIA. The NEA high scenario projection is slightly above the IPCC’s highest projection for nuclear capacity, and is about twice the EIA’s alternative scenario projection.

The World Nuclear Association’s Nuclear Century Outlook (2009) provides a projection of future global nuclear expansions spanning the whole of the 21st Century. The World Nuclear Association (WNA) Outlook argues that its projections are the boundaries of a domain of likely nuclear growth. It gives a low boundary of about 800 GWe and a high boundary of about 2400 GWe in 2050, in which China and India together will have 17 percent and 31 percent shares, respectively. The WNA Outlook implies that while nuclear newcomers might contribute, over 80% of nuclear growth will occur in nations already generating nuclear power. The WNA’s projections are much more optimistic than scenario outcomes described by other organizations. Figure 4 summarizes nuclear projections in 2030 and 2050 from different scenarios and organizations.

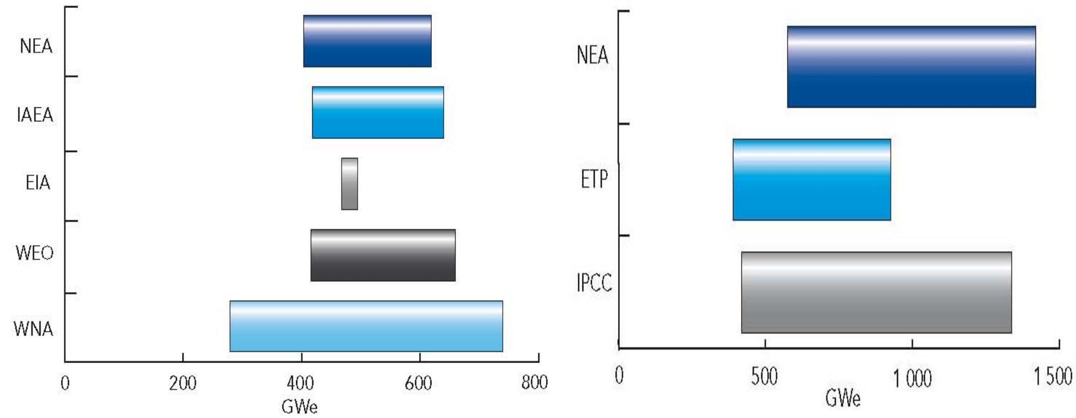

Figure 4: Projected nuclear capacities in 2030 (left) and projected nuclear capacities in 2050 (right) from different scenarios (NEA, 2008)

Although the scenarios summarized above vary in terms of their projections of nuclear capacity, all of them agree that other low carbon alternatives cannot fill the emission reduction gap if nuclear power does not grow, assuming an emissions target consistent with a 450 ppm Stabilization case for atmospheric CO_2. The 450 ppm Stabilization case requires that the maximum atmospheric CO_2 concentration be less than 450 ppm by 2050, and no longer growing. Additionally, the scenarios described above agree that most of expansion of nuclear capacity will occur in countries that already have nuclear capability. China and India, two leading emissions contributors and energy consumers, are expected to adopt nuclear power on a large scale. The WNA‘s projections for China and India are much more optimistic than other projections, assuming 500 GWe of capacity in India and 750 GWe capacity in China by 2050 in the high boundary scenario, while high projections from other groups assume 100 GWe and 150 GWe by 2050, respectively.

3.3. Nuclear programs in China and India

While major research and energy institutes provided nuclear expansion scenarios for China and India, these two countries have also developed their own long-term nuclear plans. China’s National Development and Reform Commission (NDRC) recently suggested installed nuclear power capacity might even exceed 60 GWe and approach 70 GWe by 2020, due to faster than expected construction of new nuclear capacity. This growth rate is much more aggressive than most of the above projections. In this report, three nuclear expansion scenarios are presented as possibilities. The first scenario is the reference case and is based on China’s current long-term nuclear power plan, which anticipates that nuclear power will have a 20 percent share (the current world average nuclear share) of the total national installed capacity by 2050. The second scenario is a high-growth scenario, which anticipates continuous nuclear expansion resulting in over a 30 percent share of installed generating capacity by 2050. The third scenario is the low-growth scenario, which anticipates a 10 percent nuclear share by 2050. But this growth will depend on China ramping up what has essentially been a modest industry that has never before been incorporated into national economic planning. And there is still the question of whether China can manage the technological, financial, and social challenges associated with nuclear expansion while simultaneously addressing proliferation, waste disposal, and safety concerns. India currently has 17 nuclear power plants and is building an additional six. The deal with the U.S. on transfer of advanced nuclear technologies and possible uranium imports could provide India with the opportunities to considerably boost its nuclear power plans. India has been developing fast breeder reactors and other nuclear fuel cycle technologies to exploit its reserves of thorium. Recently, India's Prime Minister, Manmohan Singh, delivered a speech emphasizing the importance of nuclear energy in India's future energy picture. He announces a total installed capacity goal of 470 GWe of nuclear power by 2050 using thorium technology (Ramesh, 2009). Singh's speech claimed that with this level of growth in nuclear capacity, nuclear energy could produce 50% of India's electricity by 2050.

4. Requirements for expansion of nuclear power capacity

4.1. Technology development and construction capability

Most researchers agree that the 1 GWe or larger PWRs that dominate current installations and reactor fleets worldwide will continue to be the main types of reactors deployed for the next two or three decades. Generation II and Generation III reactors will be deployed while Generation IV and fast breeder designs continue to be developed. Pressurized water reactor designs are relatively mature for large-scale implementation. While two EPR (Gen III designs by the Areva nuclear technology corporation) sites are under construction in France and Finland, China is constructing the first AP1000 (Gen III Westinghouse, Corp. design) reactor in the world. As mentioned earlier in this report, most of the nuclear expansion worldwide will occur in countries that are currently generating nuclear power. China and India are expected to be the leading countries in this nuclear expansion. Although China and India do have fundamental nuclear industrial capabilities, they will still need to rely heavily for many years on technology purchases and transfers from overseas if they are to implement a large-scale nuclear expansion in a short time frame. The U.S.-China AP1000 project and the US-India nuclear deal offer opportunities to help develop sustainable nuclear development in these two countries. For nuclear newcomer nations, most of them will likely not have nuclear industrial capabilities, and they will have to rely on foreign technologies to start their own nuclear programs. Although nuclear technologies are not included in the Clean Development Mechanism (CDM) of the Kyoto Protocol, developed countries should be encouraged to assist and cooperate with developing countries to help ensure an effective regulatory system and a sound nuclear safety culture in the developing countries that are and will be engaged in nuclear programs.

To implement the projected expansion, all of the major studies above concluded construction capability will not constrain nuclear development. In the peak historical years of nuclear power growth, 33 nuclear power reactors were connected to the grid in both 1985 and 1986. In the 1980s, an average of one reactor every 17 days was added to the world's electricity supply systems, most of this in only three countries (France, Japan and the United States) (NEA, 2008). Extrapolation of historical experience from the 1970s and 1980s, taken together with the growth in the world economy since that time, suggests that there should be more than enough capacity to build NPPs at a rate to meet any scenario in those studies. Recently, several authors have expressed concerns that there might not be enough forging capability to support the potential nuclear expansion, considering the current limited forging steel industry with capacity suitable to produce reactor pressure vessels (Ferguson 2008; Bloomberg, 2008). The reason, however, why forge capacity suitable for pressure vessels is currently limited is the large reduction in new nuclear plant orders in many countries after the 1980s. The real issue is whether there is demand for these large parts, not whether these large parts can be manufactured technically. Before the question is answered (that is, until demand for reactor vessels increases), steel forging companies will be reluctant to invest in additions to their production capacities to make the large nuclear equipment, perceiving a financial risk if demand is not as predicted. For example, after China showed its commitment to nuclear, soon thereafter the Chinese government invested around 0.8 billion US dollar in its domestic forging industry. The largest-capacity manufacturing site for large items such as reactor vessels will open in 2010, according to news reports (Xinhua News, 2009). Certainly, the current construction capacity for reactor vessels might be limited, and it is likely to take several years to redevelop the capability to build significant numbers of NPPs simultaneously around the world. Given that capability will rise as demand rises, however, the current level of reactor vessel construction capability should not be considered as an obstacle to limit the development of nuclear power.

4.2. Economic and financing requirements

One of the important challenges in building a nuclear power plant is affording the huge construction costs. Nuclear power plants are relatively expensive to build everywhere, though they typically offer lower costs to operate compared with fossil-fueled generating alternatives. Although the overnight cost of building a nuclear power plant is much higher than that of coal or gas-fired power plants, the total generating costs of nuclear power could be comparable to alternatives. The MIT future nuclear report (2003) shows that when a carbon charge is introduced, the cost of generating nuclear power would offer total cost benefits over competing fossil-fueled technologies in the United States. The report calculated the costs of building and operating three electric generation alternatives: nuclear, coal and natural gas. With an overnight capital cost of $2000/kWe and O&M costs of 15 mills/kWe-hr[4], nuclear power can provide electricity for 6.7c/kWh, assuming a 40 year capital recovery period and an 85 percent lifetime average capacity factor. Based on these assumptions, the introduction of a carbon tax of $100/tC can make nuclear energy competitive with coal and natural gas. In the United Kingdom, nuclear power is listed as third behind natural gas-fired and small hydropower plants in terms of generating costs, based on a discount rate of 10% (IEA, 2005). The relative cost-effectiveness of nuclear power depends on a variety of factors. Key factors are the availability alternative generation sources, the level of energy demand, and the investment environment, in addition to the capital cost. Nuclear power can be economically competitive when low-cost and abundant fuel sources of other types are not available. Countries that do not have rich fossil fuel sources, such as Japan and France, have found nuclear power cost-competitive, though the nuclear power sector in those countries has been supported by a variety of government programs—in addition to payments from ratepayers—for many years (IAEA, 1990). In addition, there are potential means to reduce the overnight (capital) costs if reactors, such as streamlining licensing and certification procedures and design standardization and simplification. In France, construction costs and delays are significantly diminished because of streamlined government licensing and certification procedures. To date, most nuclear power plant projects have been customized and constructed individually. Design standardization could provide cost savings and economies of scale, as well

[4] One "mill" is a thousandth of a dollar, or a tenth of a cent. Thus one mill is $0.001, and 15 mills/kWh is 1.5 cents/kWh.

as reduced development expenses. The Westinghouse AP1000 design follows the simplification principle by decreasing the number of components, including pipes, wires, and valves, which helps to reduce the time and cost of construction. This simplification is one of major reasons why Westinghouse won its bid in 2005 to construct two nuclear power plants in Sanmen and Haiyang, China. Of course, no vendor can guarantee that new and more standardized designs can be built with less cost unless it such savings are demonstrated in reality. If China's AP1000 project succeeds, it would be a good demonstration of the economic advantages of standardization and serial construction. Historically, however, nuclear construction projects were always associated with large cost overruns and project cancellations and delays, often in large part due to regulatory oversight and safety concerns, which translate directly into higher finance charges. Another Generation III EPR project under construction at Olkiluoto in Finland is thus far exhibiting quite discouraging progress. As of May 2009, the plant was at least three and a half years behind schedule, and more than 50 percent over-budget (PSR, 2009).

Construction schedules and licensing can experience long delays (and have in the past, on many nuclear projects), which discourages investors who prefer a quick return on investment. Public perception also plays an important role in the decision-making process of investors. Investors tend not to invest in projects that may involve significant political controversies and public debate. Therefore, the direct way to ensure successful financing is to reduce scheduling and regulatory uncertainties. For example, the use of construction vendors with proven skills and track records could help to assure fewer delays in construction due to errors, and governmental policy support to the nuclear industry could help increase investor confidence regarding nuclear power.

In general, government financing has been a traditional way to fund large-scale projects such as building a nuclear power plant (or a major hydroelectric plant, for example). Government financial resources, however, are not necessarily sufficient to meet all demands for construction capital. In this case, industry financing would need to provide a significant part of project support. In the past, nuclear power plant projects in many countries were entirely funded by the state-owned nuclear industry and owned by the government. For countries such as China and Brazil, their booming economies have helped ensure sufficient capital investment into nuclear power plants. China does not encourage direct foreign investment unless foreign investors participate in a joint venture through technology purchases (WNA, 2009). A centralized system, such as China, is prone to allocate and guarantee investments on prioritized projects, such as its nuclear power development. For example, although the global finance crisis affected China, it did not decrease its investment on nuclear development, and instead the government ensured that more financial aid was available for the nuclear industry. The nuclear industry in other countrie, however, might not enjoy the luxury of such strong government financial support. Financing nuclear program is really a huge challenge in a liberalized electricity market environment. In the United States, due to various problems associated with the nuclear power industry, the financial community has been unwilling to invest in new nuclear plants. In 2005, the U.S. Congress authorized the Department of Energy to provide federal guarantees for new nuclear plants. However, some people argue such a federal loan guarantees will not reduce the risks associated with new nuclear programs, rather, such guarantees will just transfer the risks from the utilities to taxpayers (UCS, 2009). For other developing countries, which cannot provide much government funding, it might be necessary to explore various other funding options, including direct funds (likely loans) from international organizations and development banks, overseas private investment, and commercial loans. It should be emphasized, however, that nuclear is a quite expensive energy alternative accompanying with huge financial risks. Any developing country that wants to explore the nuclear option needs to be aware of and cautious regarding these risks.

4.3. Policy support

Nuclear R&D expenditure. While governmental research and development (R&D) expenditure on renewable energy, particularly solar and wind had escalated to $773 including Japan and France million in OECD countries by 2000, R&D expenditures on nuclear power in the OECD countries excluding Japan and France, had significantly decreased to $308 million (IEA, 2000). In the United States, since 1988, federal spending on nuclear energy R&D has been less than spending on coal research and, since 1994, has been less than spending on renewable energy research. Figure 5 shows, for the period from 1985 to 2010, the cumulative expenditure for nuclear R&D was less than half that for coal and renewable energy (2000 dollars; Gallagher et al., 2009). Here, the spending on fission includes civilian nuclear waste management. Numbers from Nemet and Kammen's study (2006) also showed a similar pattern.

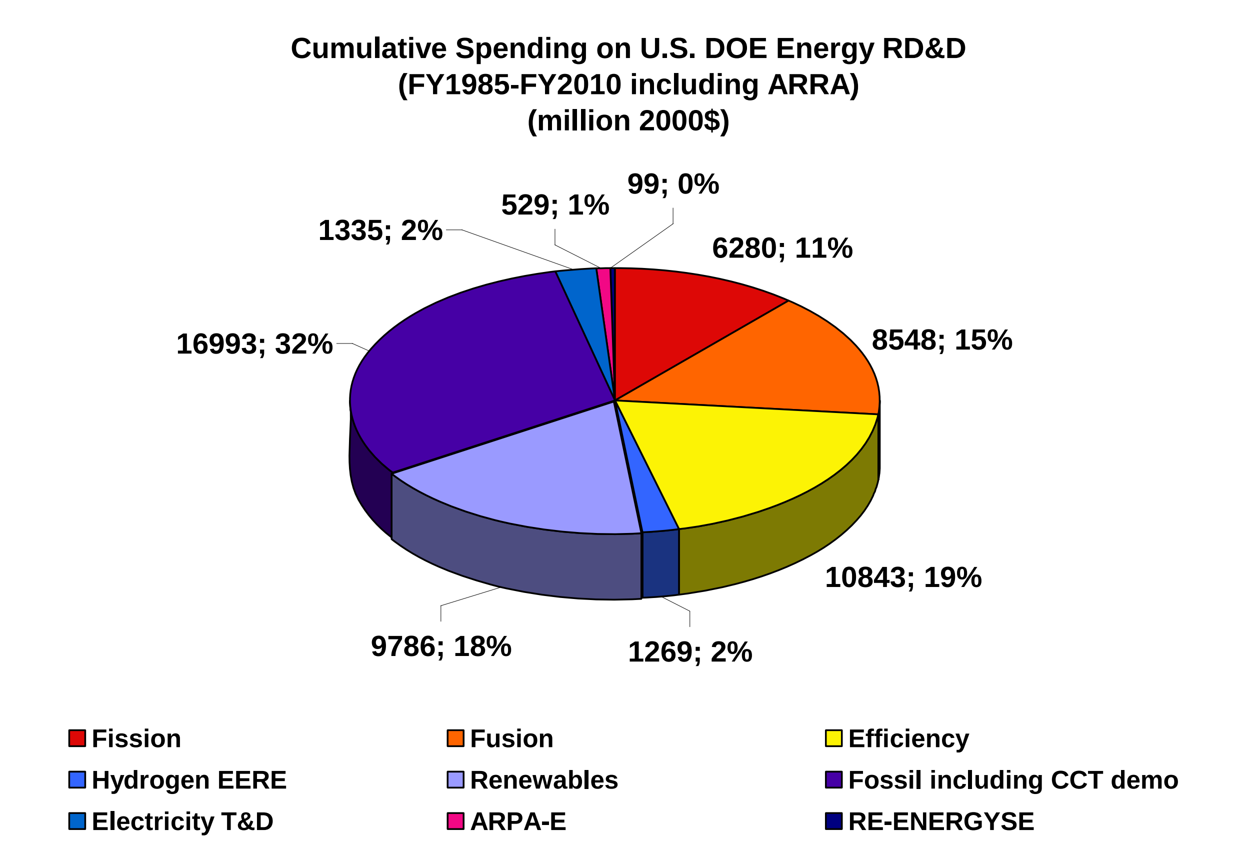

Figure 5: Cumulative DOE research, development & demonstration expenditures from 1985 to 2010 (request)

In recent years, some controversy has surrounded the apparently higher investments in renewable energy R&D, since renewable energy has historically supplied much less electricity as compared to nuclear power. In emerging countries, such as China, that have proposed a large nuclear expansion plan, the nuclear R&D capability and expenditures are relatively low. In general, nuclear countries such as China tend to spend more money on increasing the total installed nuclear capacity, rather than developing advanced nuclear technologies or fundamental nuclear science. At this stage, it will take time for those countries to strengthen their R&D programs. However, a successful nuclear expansion requires more R&D programs on a variety of aspects of the nuclear fuel cycle, such as reactor safety and waste management. In addition, R&D programs on advanced nuclear technologies, such as Generation IV and small reactors designed not to require on-site refueling[5], could provide the nuclear industry with a successful and sustainable development path for the future. In the next several decades, developed countries with nuclear capabilities will likely still lead the global R&D effort on nuclear technology development. Nuclear assistance and cooperation are highly recommended to help developing countries lift their nuclear R&D capabilities and improve their nuclear technology development.

*Subsidies for nuclear power***.** Governmental subsidies have always played an important role in the energy sector. Currently, subsidies to fossil fuels and renewable energy are widespread globally, helping to make them competitive with other fuels in the market. For example, Europe uses a feed-in tariff as an effective means to require energy retailers to buy electricity produced from renewable sources at a fixed price over a fixed period. However, although subsidies for renewable energy are typically well-accepted by the public, subsidies for nuclear power are often used as an argument against nuclear power. The history of nuclear power shows that governmental subsidies are crucial in the early stages of nuclear industry development. China released a preferential tax policy to waive the value-added tax for the Daya Bay nuclear power plant. Later on, it extended this policy to the entire nuclear energy industry. In addition, China has issued a more preferential tax policy to favor the development of nuclear energy industry in 2008, including income tax rebates and value-added tax rebates for the nuclear power industry. Recently, the United States Congress passed The Energy Policy Act of 2005 to support U.S. nuclear development. This Act authorized assistance for new nuclear power plant construction including loan guarantees, insurance against delays not caused by the utility, and production tax credits for the first 6 GWe for new plants. To ensure a successful nuclear expansion, governments will likely need to provide suitable and effective subsidy policies to facilitate nuclear power development.

Over many years**,** the option to "Include Nuclear Activities" in the Clean Development Mechanism (CDM) and Joint Implementation (JI) arrangements of the international Framework Convention on Climate Change has been controversial. Although supported by countries such as France, China and India, a majority of European Union (EU) members, as well as key developing countries such as Indonesia, ruled out the inclusion of nuclear in the CDM proposal. Some arguments suggested that if nuclear power becomes eligible for the CDM, the CDM will provide a new subsidy for those nuclear industries, while the carbon reduction credits from new nuclear plants will help those nuclear vendor countries meet their emission reduction targets. In addition, some researchers and policymakers worry that including nuclear in the CDM will reduce current investment flows to renewable energy and energy efficiency technologies, and be biased towards high-growth countries like China and India large enough to accommodate nuclear

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[5] Gen IV reactors are a set of theoretical nuclear reactor designs currently being researched, ranging from light water reactor designs to fast neutron reactor designs. Small reactor technologies without on-site refueling are in concept reactors whose power levels are below 300 MWe and can be treated as a sealed nuclear "battery" without refueling during its lifetime.

power. Some groups argue that the CDM should be structured to ensure an equitable distribution of resources among all developing countries (Greenpeace, 2001).

4.4. Fuel sustainability

As mentioned before, one of the major advantages of nuclear power is the high energy output provided per unit of uranium fuel input. In addition, the abundance of uranium is considered one of the advantages of nuclear power over coal, oil, and gas. The volume Uranium 2007: Resources, Production and Demand, also known as the "Red Book", compiled by the IAEA, shows that an estimated 5.5 million tons of global uranium resources exits, which is 130 times the global production of uranium estimated for 2007 (IAEA, 2008). Unconventional uranium sources, such as those in phosphate rocks and in seawater, are available to explore when cheap uranium sources become scarce and uranium prices increase. In addition to natural uranium resources, a number of researchers describe reprocessing of spent nuclear fuel and advanced nuclear technologies, such as fast breeder reactor designs, as having the capability to significantly contribute to the extension of existing uranium supplies. A number of publications project that the global supply of uranium resources is sufficient to fuel major nuclear expansion scenarios through 2050 (NEA, 2008; MIT, 2009: WNA, 2009). Uranium resources are described as being geographically more evenly distributed than any other energy resource, though a relatively few countries—including Australia, Canada, and countries in Central Asia, hold the largest shares of the most economic high-grade uranium ores. Given this distribution of Uranium resources, the risk of supply disruption is minimal as compared to oil and natural gas reserves, which are concentrated in the Middle East (EIA, 2009). In addition, countries can maintain stockpiles of nuclear fuel with relative ease, given that Uranium fuel storage requires far less space than for fossil fuels. Lastly, nuclear fuel costs are only about 5 percent of total generating costs, while costs for coal-fired and natural gas-fired plants make up 40% and 60% of costs, respectively (NEA, 2008). All of these arguments suggest that the availability of nuclear fuel will not constrain future nuclear expansions.

4.5. Public acceptance

Public acceptance has been a significant factor affecting the nuclear industry in Western countries since the two major nuclear accidents: one at Three Mile Island in the United States, in 1979; and one in Chernobyl, Ukraine, in 1986. The Three Mile Island accident of 1979 was a partial core meltdown. The accident began with mechanical failures, but, failures of plant operators to recognize the situation as a loss of coolant accident due to inadequate training and ambiguous control room indicators really determined the extent of the accident. Ultimately, the accident was evaluated as a Level 5 accident according to the IAEA's the International Nuclear Event Scale (INES) with limited off-site release. While the Three Mile Island accident caused a partial core meltdown and limited off-site release of radioactivity, the Chernobyl accident was a Level 7 accident with nuclear plant explosions resulting in severe radioactivity release and the evacuation and resettlement of over 336,000 people in the surrounding area, with radiation-induced illnesses in tens of thousands of people in the region affected by the accident. The accident raised concerns about the nuclear power safety in general, slowing the expansion of nuclear power for a number of years. There are a number of concerns associated with nuclear power, including safety, proliferation, and waste disposal, which are largely unique to nuclear energy as a power source. Surveys of public opinion show reactor safety is the most important factor associated with nuclear power in the United States, European countries, Japan, Australia and New Zealand. In contrast, safety issues are less of a concern in south and south-west Asian countries (IAEA, 2008). The second most important factor is the storage and disposal of nuclear waste. In Japan, debate over arrangements for spent fuel management has created severe public opposition to nuclear power. In the United States, Yucca Mountain, in Nevada, was the proposed site for the nation's first long-term geologic repository of nuclear waste, from 1987 to 2009. In 1987, Congress amended the Nuclear Waste Policy Act and directed the DOE to study only Yucca Mountain, which was already located within a former nuclear weapons test site. As of 2008, US$9 billion had been spent on the project. The Yucca Mountain proposal, however, has been highly contested by environmentalists and residents near the area, and the Yucca Mountain proposal was debated at the national level for many years. Finally, The Yucca Mountain project was cancelled in 2009 after President Obama was elected.

Considerable variation does exist from country to country regarding public perceptions of the acceptability of nuclear energy. While recent polls still show strong public opposition to building new reactors in many Western countries, the general public in new emerging economies and nuclear newcomers often have a more neutral or positive attitude toward nuclear energy (IAEA, 2005). However, recent protests over nuclear power in Indonesia showed public skepticism does and could exist in developing countries. According to the news, local residents worry about health problems result from nuclear waste (Greenpeace, 2007). A variety of factors, such as cultural differences, economic status, the political environment, and the availability of information affect the way that the public in a given nation perceives nuclear power, and the perception of nuclear power in most countries has a tendency to evolve over time as experience with nuclear power accrues, and as more information about the nuclear sector becomes available to the public. Though recent polls still show strong opposition to building new reactors as dominant in many countries, polls also show some increasing support for nuclear power as concerns over energy security and climate change have become more widely perceived by the public (IAEA, 2005).

5. Non-climate-related Risks Associated with the Nuclear Expansion

5.1. Nuclear Safety

Nuclear safety has been a large public concern since the reactor accidents at Three Mile Island in 1979 and Chernobyl in 1986. Keeping nuclear power plants safe is one of the top priorities in expanding nuclear energy. Since the Three Mile Island accident, the safety of nuclear reactors has greatly improved. The World Association of Nuclear Operators (WANO) created safety performance indicators and conducts peer reviews to improve safety performance. Figure 6 shows that industrial accidents at nuclear power plants have been decreasing for the last two decades (WANO, 2006). New light water reactors are expected to be considerably safer than older reactors, with an estimated core-damage probability lower than 10^{-6} per reactor-year for internally initiated accidents. The passive-protection plant designs included in Generation III reactors require significantly less reliance on monitoring equipment and human operators, which reduces the failure probabilities. Some researchers do argue, however that the PRA as a statistical approach has limits when applied to very low probability events, such as major nuclear-plant accidents. These quantitative risk calculations cannot completely measure the absolute risk of low-probability catastrophic accidents (Keystone, 2007).

There have not been any major nuclear accidents since the Three Mile Island and Chernobyl accidents. However, this accident-free interval doesn't necessarily indicate an excellent nuclear safety culture. Safety problems still exist. Since 1979, there were 35 instances causing individual reactors in the United States to shut down in order to restore safety standard (UCS, 2007). The potential expansion of nuclear energy use on the kind of scale suggested by the scenarios reviewed earlier in this report does, however, pose significant safety challenges for developing countries, which usually have a less-developed safety culture and lower safety standards than developed nations. In addition, solid safety regulatory systems and enforcement mechanisms for safety regulations are needed as well. For example, in China, more conventional construction companies, such as those that build coal-fired power plants, are expanding their business into the nuclear areas. It remains a question as to whether the conventional construction industry can comply with the safety needs of the nuclear industry. To assist, a number of researchers suggest that the international community and vendor countries should take the responsibility to help establish strong safety cultures and to create effective regulatory systems for the developing countries. In addition, the international community should continue to promote open and transparent communications and information exchanges on nuclear safety to improve the nuclear operational performance in nuclear countries.

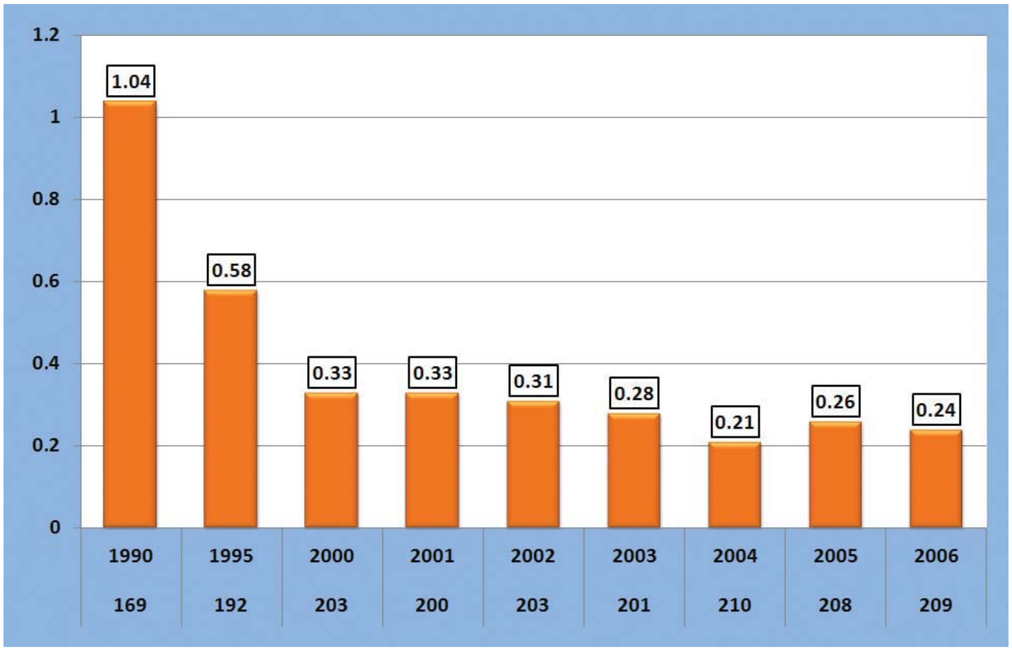

Figure 6: Industrial accidents at nuclear power plants per 200 000 person-hours worked

5.2. Proliferation and security risks

The growth of global energy demand worldwide, coupled with a growing response to climate change and energy security, may, as indicated above, generate a global expansion of nuclear power use, especially in developing countries. Many developing countries express a marked desire to acquire nuclear energy technologies. At the same time, the expansion of nuclear power could increase threats of proliferation of nuclear weapons and related security risks.

The increased proliferation threats and risks resulting from the expansion of nuclear power globally will not necessarily scale with the expansion of worldwide uranium enrichment capability and reprocessing capability, because most such capabilities will in the near-term still only exist in countries that currently possess nuclear weapons (Braun et al., 2008). While threats and risks stemming from misuse of uranium enrichment capacity and the diversion of plutonium from reprocessing will not significantly escalate from its current level, the storage and transport of nuclear material in consumer countries could create opportunities for illegal diversion and terrorist acquisition and attacks in the next couple of decades. For example, the number of annual long distance transports of nuclear materials to consumer countries could increase dramatically under a global nuclear power expansion, due to the limited nuclear fuel enrichment and fabrication facilities available worldwide. The effectiveness of current safeguard technologies, such as storage canister designs, monitoring and tracing technologies, and nuclear material verification technologies, need to be examined under the set of new circumstances that correspond to an expansion in the number of nuclear energy users, and in the volume of nuclear material used. In general, researchers suggest, the IAEA safeguards need to be strengthened to continue working towards limiting sensitive technologies and weapon-grade material transfers and assuring peaceful uses of nuclear technology even as use of nuclear energy expands (Bunn, 2008).

Multilateral approaches to the nuclear fuel cycle, such as the Nuclear Fuel Bank[6], could be effective solutions to provide assurance in limiting the potential risk of nuclear proliferation under a nuclear expansion scenario. Obviously, the more nuclear power plants that the world constructs and operate, the more nuclear material will be produced, accumulated and stored, and the more nuclear facilities such as reactors, commercial enrichment facilities and fuel manufacturers will need to be protected to avoid potential sabotage. Today's security standards are considered inadequate to defend against possible sabotages. For example, spent fuel pools in the United States have been found to be highly vulnerable to terrorist attack (Alvarez et al., 2003). The design basis threat (DBT) indicator provided by the U.S. Nuclear Regulatory Commission (NRC) does not consider attacks by aircraft. As noted above, most nuclear power expansion is likely to occur in developing countries. Without previous experience in providing security at nuclear facilities, those countries could face challenges in developing more reliable nuclear security protection strategies.

5.3. Nuclear waste management

Another persistent public concern associated with nuclear energy is the management of radioactive waste. For high-level waste and spent fuel, geological disposal is expected by most nuclear authorities to be the long-term solution for waste management. Several countries, such as Switzerland and United States, proposed to build geological disposals, but no country as yet has begun to do so; instead, interim storage of spent nuclear fuel and other high-level wastes is used in many countries.. "Dry cask storage", in which spent nuclear fuels, after cooling in spent fuel

[6] The "nuclear fuel bank" is a proposed approach to provide countries with access to enriched nuclear fuel without the need for them to have access to enrichment technology. The basic concept is that countries that have enrichment technology, would donate an amount of enriched fuel to a "bank". Countries who do not have access to enrichment technology could then take fuel from the bank. In March 2008, the IAEA outlined 12 proposals for a multilateral approach ranging from providing backup assurances of supply to establishing an IAEA-controlled low enriched uranium reserve and setting up international enrichment centers (IAEA, 2008). Major proposals are from Germany, the U.S., Russia, and the Nuclear Threat Initiative.

pools at reactors for five or more years, are sealed into thick steel containers, which are pumped dry and filled with an inert gas, and then encased in a massive concrete cask. Several countries, such as the United States and France, have been conducting research on deep underground storage methods. A number of factors, however, including social, political, and ethical issues, surround the siting of potential nuclear waste repositories. For example, after a long period of public debate and political controversy, the Obama administration has cancelled the Yucca Mountain project and has stated there is no plan for permanent disposal of high-level wastes. In general, the current spent fuel storage capacity at a nuclear power plant is sufficient to store spent fuel from 15 years of reactor operations, but new designs could expand the at-reactor storage capacity. As a result, for nuclear newcomers, the management of nuclear waste and spent fuel may not be a major concern for the first 20 or so years of reactor operation, but will become a concern thereafter. For countries whose reactors went online after 1990, long-term nuclear waste management proposals will need to be developed. China, for example, has proposed a permanent geologic repository to store accumulated spent high-level radioactive waste. An underground research laboratory will operate for 20 years and actual disposal is anticipated to start in 2050. The preliminary concept for China's repository will be a shaft-tunnel model, located in saturated zones in granite (strata of granite saturated by groundwater). Currently, the Beishan area, located in Northwest China's Gansu Province, has been selected as a potential area for the repository.

Multilateral approaches to nuclear waste management could be an effective solution to help small countries that do not have geographical conditions that allow siting of a permanent waste repository, such as Japan and Korea. For example, An East Asia alliance on nuclear waste management has been envisaged by a number of researchers.

5.4. Less investment in other low-carbon technologies

When a developing country decides to invest in nuclear technology, there is a possibility that it will allocate less investment to other low-carbon technologies due to limited financial resources. For a developing country that is interested in nuclear energy programs, it might consider developing a framework to analyze and evaluate all of the possible low-carbon options that it can pursue. The framework could include:

- understanding the country's political and economic backgrounds on its potential nuclear programs
- analyzing different scenarios with other low-carbon options
- evaluating the country's regulatory system to examine its "fit" to a nuclear safety culture
- evaluating the country's capability to handle nuclear materials and nuclear security
- evaluating the proliferation risks associated with nuclear imports/exports.

In addition, a nuclear newcomer country should establish an effective reporting mechanism and system of reporting and consulting on potential risks with the IAEA. Nuclear technologies might be not a perfect fit for many countries. A developing country needs to think through all risks and problems it might experience before "jumping into the nuclear pit".

6. Conclusions

Nuclear power, as a proven low carbon emission energy source and a mature technology with high potential for large-scale implementation, is enjoying a resurgence of interest worldwide. A number of studies suggest that nuclear power may not only play an important role in mitigating climate change, but may also play a significant role in adapting to climate change. Numerous studies have provided projections of future energy demands and nuclear generating capacity expansions by 2050 ranging from 500 GWe to 1500 GWe over current global capacity. These studies used computer-based energy modeling based on various country-specific factors, such as the level of current nuclear power deployment, ongoing economic development, and natural resource endowments. These studies conclude that most of the nuclear expansion will happen in countries that already have nuclear power, with newcomers to nuclear power accounting for only a small portion of added global capacity. In these projections, even though the United States and other currently developed nations will continue to contribute considerably to global nuclear capacity. China and India will be the two top players in the nuclear expansion due to their large populations and high economic growth. While nuclear power has many challenges and requirements, it is unlikely to be constrained in the future by either the supply of uranium or the capability of reactor construction. The costs of nuclear power and investment risks could be one of major challenges that slow down the expansion. A number of authors suggest that nuclear costs and investment risks are unlikely to be obstacles to nuclear power expansion if government policies support nuclear power expansion and if a carbon tax is applied to raise the effective costs of fossil-fueled power, though other authors have expressed a different opinion. To date, however the studies reviewed for this report have not detailed the methods by which a nuclear expansion might be implemented. Rather, the studies have tended to view the global nuclear expansion as a whole, instead of studying how potential nuclear power countries can implement the nuclear expansion and how developed countries and vendor countries might be expected to help developing countries to overcome the barriers to nuclear expansion. Safety, proliferation and management of nuclear wastes are still unresolved problems that will continue to affect public perception and raise public debate. International cooperation and communications regarding these problems are viewed as a key to handling these issues. Multilateral approaches to nuclear fuel cycle and waste management have been recommended by a number of authors for countries that need nuclear power, but cannot economically or geographically develop enrichment, reprocessing and nuclear waste storage services in their own countries. A number of authors have suggested that vendor countries should be responsible for helping to establish and maintain excellent nuclear safety cultures in the developing countries that choose to utilize nuclear power.

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