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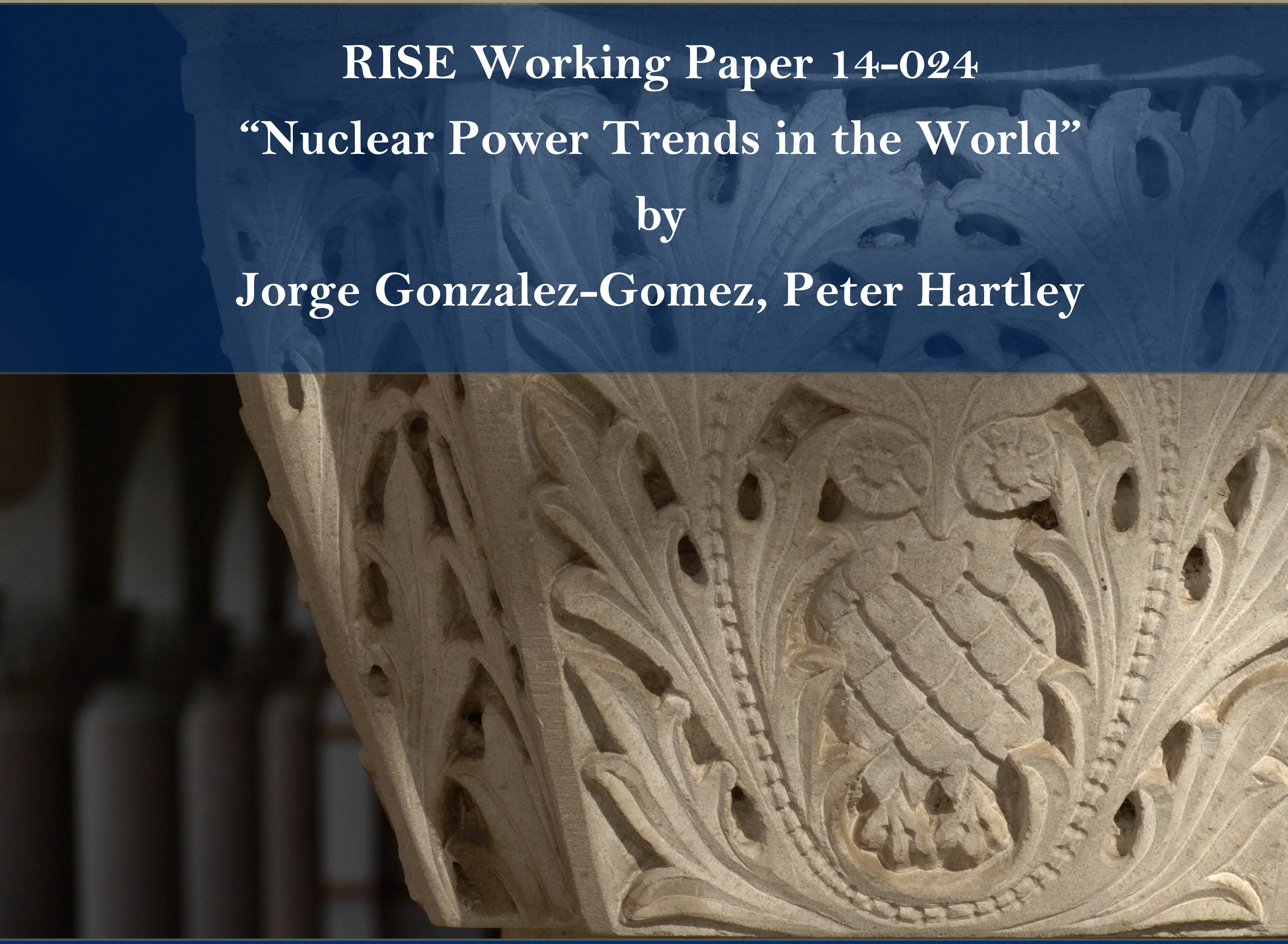

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“Nuclear Power Trends in the World”

by

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Nuclear Power Trends in the World

By Jorge Gonzalez-Gomez
And
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Introduction

Nuclear power has a much greater potential than the chemical reactions underlying fossil fuel combustion to provide large quantities of energy. Many nuclear engineers thought that they had ascertained how to harness that power in a safe and economically competitive manner by the end of the 1960s, and that the era of fossil fuels was drawing to a close. Although nuclear power plants were expensive to build, the marginal cost of generating electricity once they were built was extraordinarily low compared to any plant based on fossil fuel. The accident at Three Mile Island in 1979 dramatically changed public opinion in the United States, even though it led to no deaths or injuries of plant workers or members of the nearby community. By increasing opposition to nuclear power, the accident resulted in lawsuits that delayed the construction of new plants and dramatically raised the up-front capital costs, making nuclear power uncompetitive with new fossil fuel plants. This situation was reinforced by the invention of combined cycle gas turbines (CCGT) in the middle of the 1980s, which substantially lowered the cost of generating electricity from natural gas and made that fuel much more competitive as a power source.

The much more serious accident at Chernobyl in Ukraine in 1986 appeared to seal the fate for nuclear power in western nations. The Chernobyl incident was rated at level 7 on the International Nuclear Event Scale, resulting in a severe nuclear meltdown as one of the reactors exploded. Further explosions and the resulting fire produced a radioactive cloud that spread nuclear material as far afield as Norway and Ireland. Momentum for the installation of nuclear energy for electricity generation waned in the industrialized economies of Western Europe as well as in North America. Many countries, such as the United States, Germany, the United Kingdom and Sweden shelved ambitious plans for expanding the use of nuclear power. France was one country that did not, however, and today generates more that 75% of its electricity from nuclear power and is the world's largest exporter of electricity due to the low marginal cost of nuclear generation.

Japan also remained keen to continue to pursue nuclear power despite the Three Mile Island and Chernobyl incidents. The major reason the government gave, as in France, was that nuclear power was seen as path to energy security. The issue of energy security, or resilience in the face of energy shortages or energy price shocks, became much higher on most government's agendas after the oil market turmoil of the 1970s. Japan's first nuclear power plant began operation in 1966, and currently nuclear power supplies around one-third of Japan's electricity. Accidents in the late 1990s and early this century, however, have provoked a reconsideration of previously ambitious nuclear plans in Japan.

The trend away from nuclear power was supported by the stability of oil prices in the beginning of the 1980's and the rise of cheap, ample natural gas supplies coupled with the development of CCGT. Besides safety considerations and competition from cheaply priced fossil fuel, there were other aspects of nuclear power that limited its worldwide appeal. Specifically, waste products that create proliferation and pollution risks and need to be managed for a very long period of time, and a history of construction cost overruns for new nuclear power plants, also helped dispel the notion of "electricity too cheap to meter."

However, the recent increase in environmental opposition to fossil fuel, concerns about the availability and price stability of hydrocarbon fuels, and expectations of rapidly rising electricity demand in the world have renewed interest in nuclear energy. Moreover, the technologies for generating electricity from nuclear power have matured and the many advances in safety, especially in gaseous core reactors, have also helped to make nuclear energy a feasible option for clean electricity generation in the world.

The benefits of carbon-free electricity generation from nuclear power have caught the attention of policy makers and environmentalists alike. As a result, many countries, including the U.S., UK, Egypt, South Korea, India and China, have shown renewed interest in nuclear power.

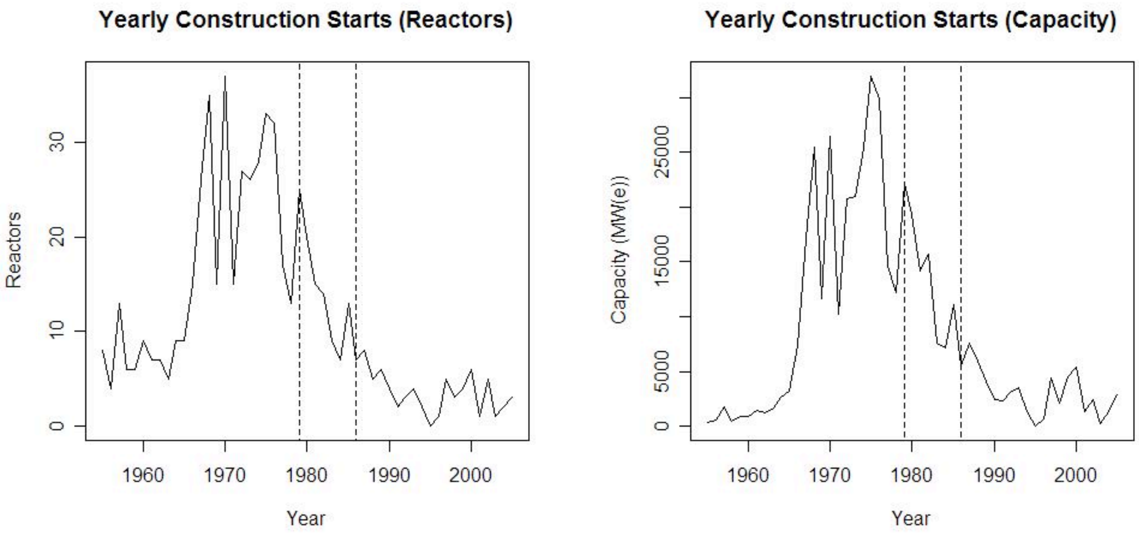
In this paper, we analyze the current trends in nuclear energy investment for electricity generation in the world. The roadmap for our study starts with an overview of the trends regarding nuclear power in the world. We then analyze the energy security benefits of nuclear power in Japan and its potential to serve as a diversified energy source in the developing world. Finally, as a case study of the potential value of nuclear energy in the developing world, we compare the distribution of levelized costs between nuclear power plants and CCGT plants for Mexico. The analysis focuses especially on uncertainty in CCGT costs as a result of uncertainty in natural gas prices compared with the relative stability of the operating costs of nuclear plants. We show, however, that differences in interest rates, construction costs and other key determinants of the levelized cost of nuclear power pants can easily negate these energy security benefits from nuclear power.

Nuclear Power in the World

At the end of 2005, there were 443 nuclear reactors in operation in the world with a total capacity of approximately 370 GW(e). An additional 27 reactors under construction would add approximately 22 GW(e). Moreover, nuclear power produced almost 20% of the world's electricity. Finally, around 12,086 reactor years of operating experience had been accumulated.

As we mentioned in the introduction, the Three Mile Island and Chernobyl accidents in 1979 and 1986 affected views on nuclear power. Figure 1 presents the historical record of construction starts in the world, both in the number of reactors and the total capacity.

Figure 1: New nuclear reactor starts (world total)

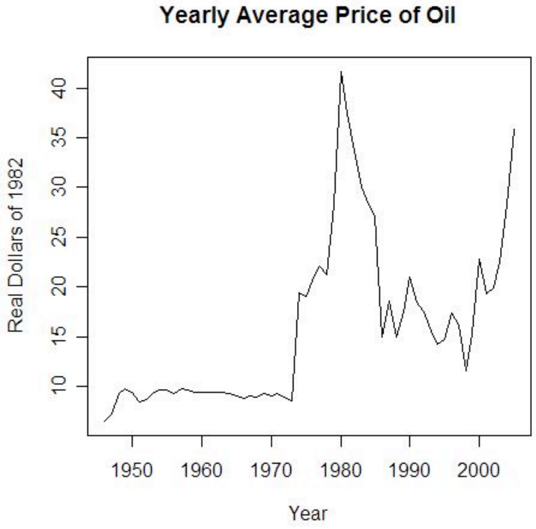


Source: *International Atomic Energy Agency,* "Nuclear Reactors in the World", Referenced Data Series No.2, April 2006

It is clear that after the Three Mile Island incident, there was a decrease in investments in nuclear power. Then, after 1986 as nuclear safety concerns increased again, oil prices fell and natural gas became more competitive as a fuel for electricity generation, new plant construction began to slow considerably around the world.

The drop of oil prices in 1986 eroded the cost advantage of nuclear power, leading to a further drop in its importance as an alternative energy source. Figure 2 shows the average real price of oil (in 1982 dollars).

Figure 2: Real oil prices

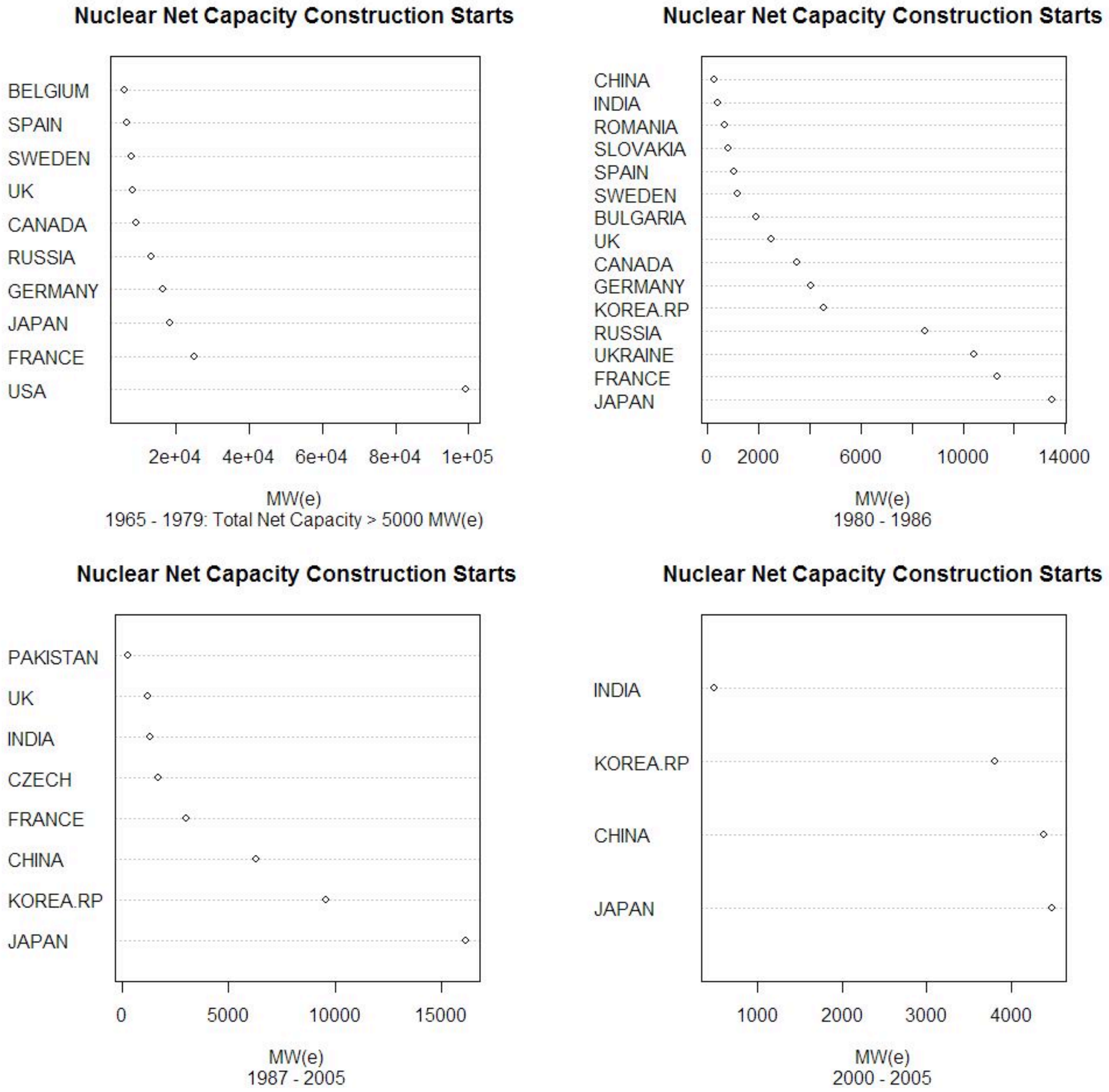


Source: Federal Reserve Bank at Saint Louis

Still, other aspects of nuclear power remained relatively attractive despite the safety concerns and the availability of cheap substitutes. Specifically, concerns about energy security kept nuclear power alive in some countries, especially France, Japan, South Korea and China, between 1987 and 2005.

Figure 3 shows the net nuclear capacity construction starts from 1965-1979 (1979, Three Mile Island's accident year) from 1980-1986, (1986, Chernobyl's accident year) and from 1987-2005. The figures highlight the continued commitment to nuclear power in Asia. Over the last two years, from 2005-2007, interest in nuclear power has increased further.

Figure 3: New nuclear reactor starts (by country and period)



Source: *International Atomic Energy Agency,* “Nuclear Reactors in the World”, Referenced Data Series No.2, April 2006.

As the graphs in Figure 3 show, before the accident in Three Mile Island, the United States was by far the biggest investor in nuclear power. After the Three Mile Island accident, the world did not stop investing in nuclear power, although the lack of support from the United States was felt across the nuclear industry. European countries such as France, Germany, the UK, USSR and Spain continued their investments in nuclear power through 1986, while France, the UK and some Asian countries continued investing after Chernobyl. In the first part of this century, investments in nuclear power were restricted to Japan, China, the Republic of Korea and India. It is important to note that in the case of India, nuclear power served a dual purpose of providing energy security and increasing India's strategic experience towards building its nuclear weapons program.

In the last two years, the outlook for nuclear power has dramatically changed. Demands for greenhouse gas emissions controls, rising energy security concerns and high oil prices have reintroduced nuclear power as a clean energy source for the future.

Recent Changes in Nuclear Power

An historical supporter of nuclear power, Finland is the first European country to order a Generation IV reactor. The nuclear industry has focused on this new Finish nuclear project, the Olkiluoto[1] project, which includes a 1,600 MW(e) generation IV reactor to be built by Areva. The construction of the Olkiluoto Project started in September of 2005. Since the four year project currently is experiencing a 25% cost overrun and a two year construction delay, it would appear that the Olkiluoto Project is not showing that the nuclear industry has solved its previous problems as some in the industry had hoped.

Even so, the poor performance of the Olkiluoto Project has not diminished interest in nuclear power in Europe, especially given security concerns regarding Russian natural gas imports and heightened concerns about global warming. France has authorized the construction of the Flamanville 3[2], a European Pressurized Reactor (EPR) with a 1,650 MW(e) capacity, also to be constructed by Areva. The UK has 19 reactors generating one fifth of its electricity, but until recently plans had called for all but one of those retired by 2023. A 2006 review of energy policy put nuclear power back on the national agenda. Finally, in January 2008 the UK Labour government with the support of the main Tory opposition party (but not the minority Liberal Democrats) announced support for new nuclear plants. The government said that there would be no cap on the number or capacity of new plants that could be built. Although the government does not plan to subsidize nuclear power, and has said that "the decommissioning and waste costs arising from new nuclear build are to be borne by the operators," it is supporting the industry with new procedures and streamlining planning permissions for all large-scale energy infrastructure. Moreover, nuclear power will likely benefit indirectly from the UK government commitment to carbon pricing and the operation of the Emissions Trading Scheme.

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[1] Information obtained from http://www.ol3.areva-np.com/.

[2] *Electricity de France*, Press Release 04/12/2007.

The United States is also pursuing an aggressive campaign supporting nuclear power. The U.S. Congress has approved a substantial tax credit and other incentives for nuclear generation, as part of the Energy Policy Act of 2005, which are likely to improve the economic viability of qualifying new reactors[3]. Moreover, nuclear power in the United States has shown better economics in recent years from its shorter refueling outages, and increasing average capacity factors, from 65% in the mid-1980s to 89.9 % in 2006. Finally, the Nuclear Regulatory Commission (NRC) has approved more than 60 requests for power uprates (increases in the maximum power level at which a commercial power plant may operate).

United States incentives to support nuclear power include:

- a 1.8 cents/kwh tax credit for up to 6,000 megawatts of new nuclear capacity for the first eight years of operation with a restriction of up to $125 million annually per 1,000 megawatts;
- the Nuclear Power 2010 Program to demonstrate the new regulatory procedures offering to pay up to half the licensing costs incurred by industry applicants;
- and, an insurance system that would cover some of the cost of regulatory delays. The first two plants to get the insurance will be covered 100% up to $500 million, while the next four plans will receive 50% insurance up to $250 million.

At the moment of this writing there were 4 Combined Licenses[4] (COL) under reviewed by the NRC: Bellefonte Nuclear Sites 3 and 4, Calvert Cliffs Unit 3, North Anna Unit 3 and South Texas Project Units 3 and 4.

Economics of Nuclear Power

In this section we analyze the economics of nuclear power. We start by analyzing the front end of nuclear power encompassing the process of uranium mining, manufacturing and enrichment. Then we analyze the back end of nuclear power: reprocessing and waste management. Finally, we analyze its cost structure and its natural place in generating electricity to supply base load power.

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[3] Larry Parker and Mark Holt, “Nuclear Power: Outlook for New U.S. Reactors”, CRS Report for Congress, Updated March 9, 2007.

[4] The COL is part of the change in the regulatory framework to support nuclear power. The COL is a construction and operation license.

Uranium Mining, Manufacturing and Enrichment[5]

One factor that could in theory limit a resurgence of nuclear power is a shortage of uranium, or a shortage of facilities to convert to uranium into fuel suitable for use in nuclear reactors. These do not, however, appear to be realistic concerns.

Uranium is as common as tin or zinc. Even seawater has a concentration of .003 parts per million. In contrast to oil, natural uranium ore is broadly distributed in the world, with large deposits in developed countries such as Canada (producing 25% of world's uranium), followed by Australia (19%) and Kazakhstan (13%).[6] The reasonably assured plus inferred resources at $130 real 2005 dollars per kilogram of uranium is 4,743,000 tonnes U, with Australia holding around 24%, Kazakhstan 17%, Canada 9%, and the USA and South Africa 7% each. Moreover, Australia and Canada have the highest percentages of reasonably assured resources recoverable at a uranium price between $40 to $80 real 2005 dollars per kilogram of uranium. The world currently uses around 66,500 tonnes U per year. Hence, the world's resources of uranium recoverable at $130 real 2005 dollars per kilogram of uranium are enough to last for some 70 years at the current consumption rate.

It is important to note that, as with other minerals and energy commodities, current known recoverable resources heavily depend on the current price of the commodity, current mining costs and past mining efforts. Moreover, the economic conditions surrounding uranium mining were relatively unfavorable in the 1990's and from 2000-2005 there was no new exploration for uranium. Therefore, the amount of uranium in the earth's crust that is economically recoverable using current technology is likely to be higher than the stated known recoverable resources. For example, on the basis of analogies with other metal minerals, a doubling of price from preset levels could be expected to create about a tenfold increase in measured resources. Even a doubling of the known resources to 10 million tones would result in more than 200 year's supply at today's rate of consumption.

This analysis also ignores the likelihood of technological change in both mining procedures and reactor technologies. For example, a widespread use of the fast breeder reactors could increase the utilization of uranium 50 fold or more, and since 1993 the

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[5] Appendix 1 lists the sources of information for this section.

[6] OECD Multilingual Summaries, "Uranium 2005 – Resources, Production and Demand: Executive Summary", OECD, 2006.

power output from nuclear reactors has increased by a factor of 5.5 while uranium input increased by only slightly more than a factor of 3. Therefore, the nuclear industry believes that there is plenty of uranium for years to come.

Once the uranium has being mined, the next step in the front end of the nuclear cycle is its conversion to uranium dioxide, which can be used in those types of reactors that do not require enrichment such as CANDU reactors. Most of the uranium dioxide is converted to uranium hexafluoride, which maintains a gaseous form at low temperature as is necessary for the enrichment process. The enrichment process increases the concentration of U-235 to 3.5% or 5% by removing over 85% of the U-238 isotope.[7] There are two processes to enrich uranium: gaseous diffusion and gas centrifuge; although a third process, laser enrichment, is being develop by General Electric. Unfortunately, the process to enrich uranium can be used to produce uranium fuel for power generation or, if the U-235 is produced at a much higher concentration, for nuclear weapons. This makes the uranium enrichment process the most controversial element in the uranium fuel cycle. The product of the enrichment stage is enriched uranium hexafluoride, which is then converted into uranium oxide. The fuel fabrication facilities then press and bake the uranium oxide to produce pellets that are encased to form fuel rods. Once encased in fuel rods, the uranium can finally be used as fuel in common nuclear generation plants. There is currently no shortage of enrichment facilities and this also would not be a barrier to the more widespread use of nuclear power.

Reprocessing and Waste Management

The need to dispose of highly radioactive waste products is another key factor that has fuelled opposition to nuclear power. Over time, typically from 12-24 months, fission fragments and heavy elements increase their concentration as U-235 is depleted, making it impractical to continue using the fuel rod. Used rods are unloaded from the nuclear reactor and placed in adjacent water pools were water shields the radioactivity produced and absorbs the heat. The used rods are kept in these pools for a period varying from months to several years. Once the radiation has subsided, they are transported either to a reprocessing facility or final disposal.

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[7] The high density of the depleted uranium has resulted in a few uses in the keels of yachts, aircraft control surface counterweights, antitank ammunition, and so forth. Depleted uranium also has the potential to be used as a source of energy in “fast-breeder reactors”.

Around 25 tonnes of used fuel are taken each year from the reactor core of a 1000MWe nuclear reactor. Spent fuel contains approximately 96% of its original uranium, where the content of U-235 has being reduced to less than 1%. Around 1% of the used fuel is plutonium and the remaining 3% consists of other waste products. Spent fuel rods also generate a considerable amount of heat and they usually require special shielding and cooling during handling and transport.

If the spent fuel is reprocessed, the recovered plutonium is blended with enriched uranium to produce MOX (mixed oxide fuel), while the recovered uranium can be sent to an enrichment facility or used by reactors that use natural uranium. With reprocessing, around 97% of the used fuel is recycled, leaving only 3% as high-level waste. If the spent fuel is not reprocessed, the total amount of spent fuel can be treated as high-level waste. The high-level waste is usually vitrified and then sealed inside steel canisters for eventual disposal.

Unfortunately, no country has yet succeeded disposing of high-level waste. The scientific community is very confident, however, that deep geologic disposal is safe. Although pilot programs have demonstrated that deep geologic disposal is feasible, the concept has not been proved on a commercial scale.

Another option for waste disposal that has been suggested is the deep borehole approach.[8] Under this approach, waste canisters are placed in boreholes drilled into stable crystalline rock several kilometers deep. The borehole's upper section would be filled with sealant materials such as clay, asphalt, or concrete. The main advantages of the deep borehole approach include: (a) a much longer migration path to the biosphere; (b) low water content, low porosity and low permeability of crystalline rock at multi-kilometer depths; (c) the typically high salinity of any water, if present; and (d) the ubiquity of potentially suitable sites. Unfortunately, the cost of this approach remains largely unknown and in several countries, regulatory problems may prohibit it or raise its cost to unacceptable levels.

Therefore, the final disposal of high-level waste remains a problem for the nuclear industry. Fortunately, with reprocessing the related volume is low and there is still the possibility that technological advances in reprocessing, enrichment and the generation of

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[8] "The Future of Nuclear Power: An Interdisciplinary MIT Study", MIT, 2003.

electricity may allow society to postpone the decision on where to place high-level wastes.

Other Environmental Considerations of Nuclear Power

Nuclear power is one of least carbon intensive technologies with emissions from the full energy chain (FEC) of only 2.5-5.7 grams of greenhouse gas emissions (expressed as grams of carbon-equivalent) per kWh compared to 105 to 366 gC_{eq}/kWh for fossil fuel chains. Nuclear power also involves fewer disturbances of valuable natural habitats than do most large-scale hydroelectric projects.

Despite the benefits of nuclear power to diminish green house emissions by substituting dirtier technologies, the Kyoto protocol incorporates conditions that exclude nuclear energy as an option for implementation under two of the three mechanisms[9].

The Cost Structure of Nuclear Plants

An important characteristic of nuclear power plants is that the up-front capital costs are large compared with fossil fuel plants, but the operating costs are considerably lower. For a typical nuclear power project, at 5% discount rate the overnight investment cost (from $1,000 USD/kWe to $2,000 USD/kWe) represents around 50% of the present value of all costs of building and operating the plant. This compares to 30% for coal plants and 15% for natural gas plants[10].

Given the cost structure of nuclear power plants, it is natural to think that, like coal plants, they are optimally used to supply base load power. The saving in operating costs during peak periods of demand (when more expensive options such as natural gas would otherwise have to be used) compensates for the higher up-front capital costs. This tendency is reinforced by the fact that the plants take a long time to shut down and start up again. The maximum aggregate capacity of nuclear plants is therefore limited by the minimum demand for power in off-peak periods (unless pumped storage or export options are available for the excess power). Nuclear plants thus are designed and operated to maximize their utilization over their life period. In consequence, changes in the price of uranium have a much smaller effect on the equivalent annual cost of a nuclear power

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[9] Nuclear Energy Agency, “Nuclear Energy and the Kyoto Protocol”, OCDE.

[10] International Atomic Energy Agency, *“Nuclear Technology Review: 2006”,* Vienna, August 2006.

plant than does a change in the natural gas price for combined cycle natural gas plants, or a change in the coal price for coal plants. In addition, uranium prices are much less highly correlated with oil prices than are natural gas prices. As a result, the costs of generating nuclear power are quite stable and very different from the costs of using either natural gas or oil. Even coal prices have a higher correlation with oil prices than does the price of uranium.

The fact that nuclear power plant generation costs are not highly sensitive to the price of uranium, and even less sensitive to the price of oil, makes them very valuable for improving energy security. On the other hand, the overall cost of nuclear power is more sensitive to interest rates than are less capital-intensive technologies.

The Energy Security Value of Nuclear Power: The Japanese Case

One of the important benefits of nuclear power, and in our opinion, one that helped nuclear power survive after the Chernobyl accident, is energy security. The existence of a negative relationship between oil prices and macroeconomic performance in industrialized oil-importing nations has been well-documented, and the 1970s oil shocks brought this relationship to the forefront of Japanese energy policy. Following the malaise of the 1970's, Japan undertook concrete steps to reduce the negative impact of any unexpected increases in oil prices on macroeconomic performance of Japan's economy. The Japanese government initiated policies to promote nuclear power and natural gas as fuels to generate electricity, thus facilitating a decline in Japan's dependence on oil.[11]

Expansion of nuclear power has been a cornerstone of Japanese energy policy over the past two decades. Japan's new national energy strategy specifies a goal to boost nuclear energy's share from about 30 percent to 40 percent or higher through 2030 and beyond.[12]

The Baker Institute studied the economic savings, in terms of higher macroeconomic output in times of energy price volatility, associated with the development of nuclear capacity in Japan. More specifically, by developing an econometric model relating output

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[11] See Baker Institute Study, The Role of Nuclear Power in Enhancing Japanese Energy Security, October 2005 available at www.rice.edu/energy

[12] IEEJ Presentation to Merrill Lynch Japan Conference, September 13, 2007

to energy price fluctuations, the study attempted to quantify the energy security value of nuclear power generation in Japan. By examining past episodes of energy price volatility, we were able to simulate the magnitude and probability of sudden cost increases or supply shortages of imported oil and gas and the damage that can come to the Japanese economy from such price increases or supply disruptions, including loss of GDP.

The modeling exercise took into account: available fuels; possible price scenarios; electricity demand trends varied according to differing assumptions about future GDP growth, population growth, and weather; and requirements for pumped storage as a means to meet fluctuations in demand. Fuels were chosen on the basis of technologies believed to be commercially viable over the next thirty years in Japan.[13]

The study finds that there is a clear energy security value for nuclear power in Japan. Nuclear power can provide more stable fuel costs as oil prices vary because uranium prices are only very weakly correlated with oil prices. By contrast, both natural gas and coal prices are much more closely linked to oil prices. By stabilizing price fluctuations, a greater proportion of nuclear fuel in the primary energy mix can then protect overall national economic performance during times of disruption. Our study therefore shows that a broad mix of fuels, including nuclear power, has helped Japanese consumers enjoy lower and more stable electricity costs than would have been possible without it. For example, Japan’s nuclear power capacity saves cumulatively about 2.0 trillion Yen in Gross Domestic Product (GDP) – or 42 million Yen per megawatt (MW) – in the presence of a single oil price shock when prices are otherwise stable over the study period. In the case of a 25% shock to the price of oil in 2006, the simulation found the value of nuclear power to be about 15.7% of the capital cost of construction of a nuclear power plant in Japan. Larger, more frequent oil shocks provide a higher value for nuclear power.

More generally, while lower capital cost facilities such as natural gas combined cycle plants are preferred when generating for peak demand periods, nuclear and coal-fired generation facilities are preferred base load providers because they have comparatively low variable costs and long hours of continual, base load operations. Nuclear power’s base load role allows a steady opportunity to capture a margin between prices and operating costs that can be used to defray the large up-front capital costs.

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[13] Op Cit, Baker 2005

However, that study also shows that it is possible to stimulate too much investment in nuclear power, especially when electricity cannot be stored (these days in the form of hydroelectricity) or exported. Specifically, nuclear power plants are very expensive to ramp up and down, so if too much of the generating capacity is in the form of nuclear power, some of the generated electricity will be wasted. Modeling results demonstrate that if all new electricity generating capacity in Japan were to be limited to nuclear power, average electricity prices would increase substantially above their current levels. In addition, if non-nuclear generating capacity had not been available during the staged shutdown of nuclear reactors in Japan for eight months in 2003 due to a high incidence of reported accidents, the costs would have been exceedingly high, the Baker study shows.

Thus, while playing a key role in protecting Japan's economy from the potential cost of volatile oil prices, too heavy a reliance on nuclear power would actually raise the country's electricity costs to the point of diminishing returns. This is not a problem for France, for example, because strong inter-connections with Germany, Italy, the UK, Belgium and Spain allow France to export excess nuclear power when domestic demand is low. In addition, France has constructed a substantial amount of pumped storage so that its nuclear power plants can be operated continuously without much of an increase in generating costs.

In summary, the Baker study concluded that diversity of fuel sources increases flexibility to keep overall costs low during sudden or prolonged disruptions. Having alternative choices also helps keep costs low in the face of more normal day-to-day fluctuations in fuel prices.[14]

Similarly, the IEA estimates that the loss of GDP caused by a $10 oil price increase would average .8% in Asia and 1.6% in very poor highly indebted countries. The loss of GDP in the sub-Saharan African countries would be more than 3%. Therefore, the security value of nuclear power could be similarly important for developing countries.

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[14] Op Cit, Baker 2005

Nuclear Power in Developing Countries[15]

The value of nuclear power depends on a country's demand for base load electricity and, hence, the stage of economic development and the overall size of the economy. Therefore, it is not surprising that within the developing countries, China and India are the two countries with large scale nuclear programs. Questions remain, however, whether nuclear power can make sense in smaller economies. Several small Eastern European countries such as Bulgaria, the Slovak Republic and the Czech Republic, which have previous experience with nuclear power, are expanding their nuclear programs.

In many developing nations, a large increase in population and economic growth is forecast for the coming decades. For example, the International Energy Agency (IEA) projects that energy use in developing countries will grow about twice as fast as the world average, by 106% between 2002 and 2030. For electricity use, the IEA forecast is 209% in developing countries. Therefore, one of the reasons developing countries are revisiting nuclear energy is to satisfy this increasing demand for electricity by diversifying fuel options.

Large metropolitan areas, or areas with concentrated energy intensive industries are better suited for nuclear power than rural areas with low densities or without integrated grids. Since economic growth is associated with a large migration from rural areas to urban areas, nuclear power provides an alternative that can built near large demand centers. In this context, nuclear power can yield significant environmental benefits by reducing urban air pollution and associated health problems resulting from the combustion of coal and other fossil fuels.

Many developing countries also have limited domestic energy resources and are heavily reliant of imported energy, making nuclear power an attractive option for diversification. Even for countries rich in natural resources, where energy security might not be as important, nuclear power can increase export revenues by reducing domestic demand for natural gas, coal or oil that could then be exported for revenue. Use of nuclear power can also reduce the rate of resource depletion, another reason it is under consideration in countries with limited oil and gas resources.

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[15] This section is largely based on: Annex I of Op. Cit. International Atomic Agency, 2006.

On the other hand, a high cost of capital is a major obstacle for nuclear power in the developing world where capital is scarce and electricity generation might compete with more pressing infrastructure and human capital investment needs. Still, in the developing world the nuclear option presents opportunities that are appealing to national governments. For example, high first-of-a-kind nuclear power costs in some cases, such as Republic of Korea, are accepted as part of a long-term national energy strategy to reduce 'technology learning' and spin-off economic benefits from developing the country's high technology sector.

One clear problem with nuclear power in developing countries is the scale of current nuclear plant designs (although smaller designs are expected for the next decade). For example the 1600MW(e) Olkiluoto project is 16 times the size of standard combined cycle 100MW(e) natural gas unit.

While the main reason to invest in nuclear power for a developing country is likely to be the diversification of electricity generation capacity and energy security, the high cost of capital and the scale of nuclear projects will likely remain large obstacles to the rapid deployment of nuclear power in developing countries. In the next section, we examine the case of Mexico to highlight some of these trade-offs.

Does Nuclear Power Make Sense in the Developing World: The Mexican Case[16]

The Mexican electric system is composed of two government-owned firms, Comision Federal de Electricidad (CFE) and Luz y Fuerza del Centro (LFC). They own the transmission infrastructure and have monopoly rights to sell electricity in delimited geographic areas. Following reforms in 1992, private investors can now sell their electricity to CFE, consume it within the enterprise or export it to surrounding countries. The Comision Reguladora de Energia (CRE) regulates the electricity and natural gas sectors, while the Secretaria de Energia provides oversight and develops public policy for all the heavily regulated energy markets in Mexico (supplied by mostly government-owned entities). Finally, given the relatively serious pollution problems in Mexico City, environmental laws are another important part of the institutional framework affecting electricity supply in Mexico.

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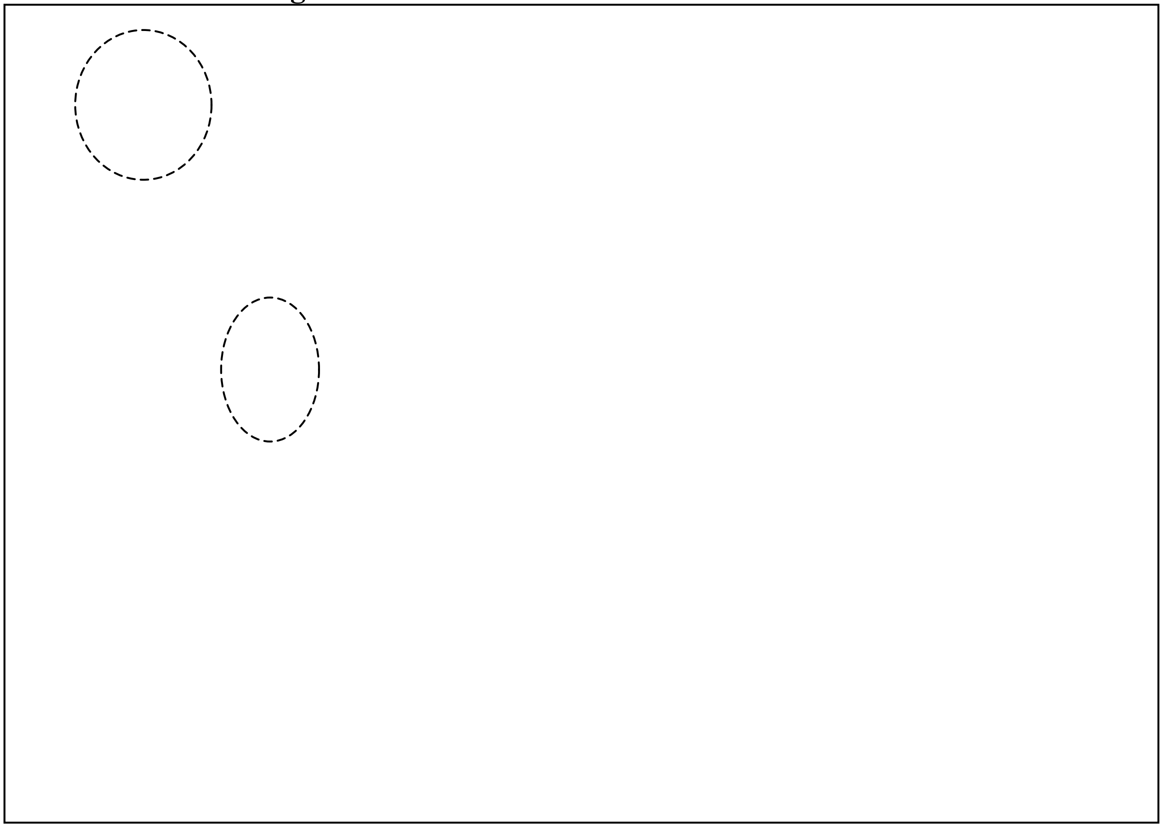
[16] This section is based on: Dirección General de Planeación Energética, *"Prospectiva del Sector Eléctrico: 2007-2016",* Secretaría de Energía, 2006

The National Electric System (SEN) consists of a large interconnected system (SIN) together with the isolated systems in Baja California (although those are connected to the Western Electricity Coordinating Council (WECC) in the Unites States and Canada). Figure 4 shows the interconnections of the SEN. Moreover, the SEN can be further divided into electricity that serves the public, electricity generated by the CFE, LFC and private parties.

Figure 4: Interconnection of the SEN in Mexico



Source: Op. Cit. SENER 2006.

For international commerce, there are 9 interconnections between the US and Mexico and one between Belize and Mexico. Five of the nine connections with the US are high voltage direct current connections that operate only in emergency situations. The main flows of electricity are between SEN and the Western Electricity Coordinating Council (WECC), where there is a medium voltage (230kV) connection capacity of 800MW. Flows of electricity between SEN and the Electric Reliability Council of Texas are very limited, and are mostly designed for emergencies. In 2006, the infrastructure for international commerce was unchanged from 2005 and international trade amounted to a net balance of 776GWh, an increase of 0.6% from 2005. The relation between the SEN and the WECC represents 82.5% of the net balance.

CFE and LFC own the entire transmission and distribution network. In 2006, there was an increment of 13,507km in the network, resulting in a total network length of 773,059km. The main components of the transmission lines are: 6.7% of 400kV and 230kV, 6.8% of 161kV and 69kV and 52.8% of 34.5kV and 2.4kV. The other 42.1% represents low voltage lines.

Expansion of the SEN is planned to take place in phases. Not only is there a schedule of capacity under construction in the near term. The government has also produced a plan of future tenders to begin new construction projects.

The Legal Structure

In 1992, the Mexican Constitution was amended to allow private investment in electricity generation in Mexico. Currently, private investors are allowed to participate in the electricity generating sector in five possible modes: autoabastecimiento (self-supplied), cogeneración (cogeneration), productor independiente (independent producer), importación y exportación (importer and exporter) and pequeña producción (small producer). Each mode was designed to attract different private investors according to their needs and available technologies; specifically,

- Self-supplier: this is designed to allow investment in electricity generation by large industrial consumers.
- Cogeneration mode: this modality allows private investors to use residual heat and steam from their industrial process to generate electricity. The electricity generated can only be used by the producers or any joint firm that owns the project.
- Independent producer: this mode was designed to allow private investment in larger generation plants (a minimum of 30 MW capacity is necessary) with the sole purpose of selling electricity to CFE or exporting it.
- Small producer: this mode accommodates private investors in small capacity (up to 30 MW) plants with the sole purpose of selling electricity to CFE or exporting it. Rural communities can also use this mode (if capacity is lower than 1 MW) for self-supplied electricity.

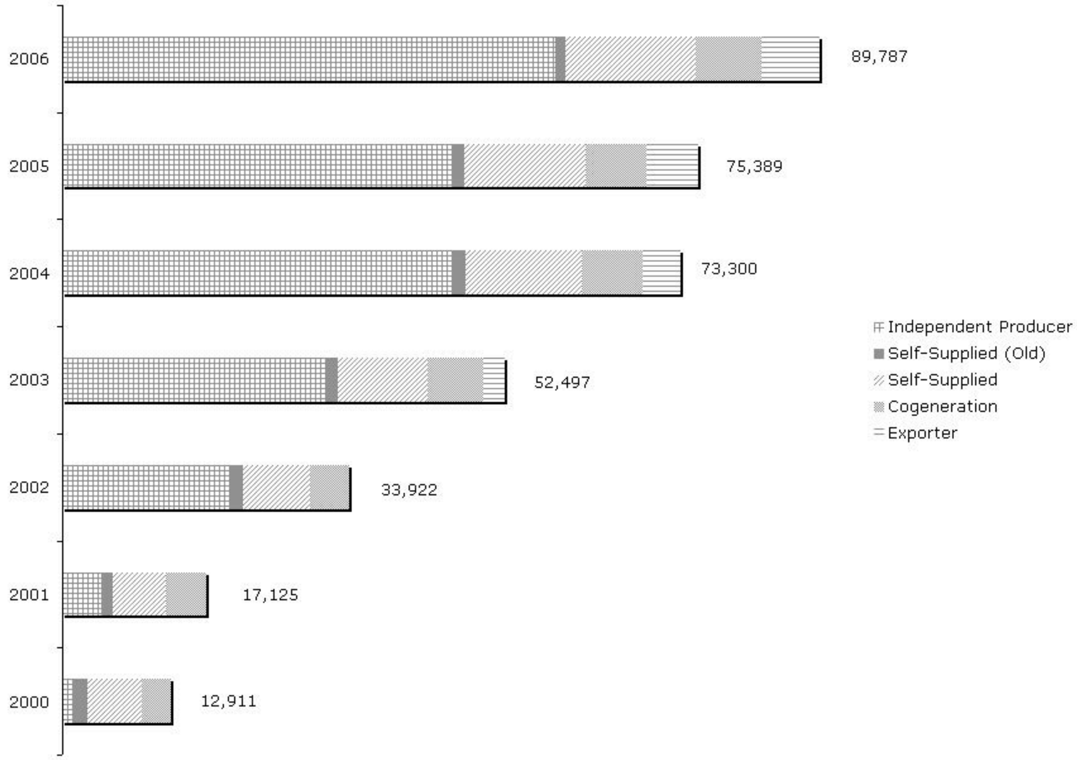
- Exporter and importer: this mode is designed for private investors wishing to export and import electricity.

A producer can operate under more than one mode when these are not mutually exclusive.

The legal framework goes beyond the simple generation license. For example, the producer can establish an interconnection contract with CFE to connect to the National Electric System (SEN). The interconnection contracts provide back-up electricity and the possibility of selling excess electricity to CFE. They may also specify required transmission augmentations. The CRE has published the exact methodologies it uses to determine the cost of each of the possible contract provisions. The interconnection contracts will apply to renewable (where the amount of electricity produced cannot be controlled) in addition to more conventional generating capacity.

Figure 5 shows the evolution of the private investment in generating capacity in Mexico since 2000. Total capacity supplied by independent producers, remote self-suppliers, exporters and cogenerators increased by 26.3%, 13.7%, 7% and 7.7% respectively over the period 2000-2006. Private investment thus has helped reduce the cost of electricity for big industrial consumers below what it would otherwise have been.

Figure 5: Private Investment by Modality 2000-2006



Source: Op. Cit. SENER 2006.

In 2006 alone, the CRE signed 90 new licenses to generate or import electricity. This brought the total agreements signed since the inception of the new law to 580. The active licenses (approximately 90% of the signed ones) cover an electric generating capacity of 19,245 MW. Independent producers represent 53.5% of the signed contracts, followed by self-suppliers at 25.7%, exporters at 9.5% and cogenerators at 7.9%. Independent producers have a total capacity of 12,557MW, which represents around one-third of the effective combined capacity of CFE and LFC of 38,382 MW. Exporters represented 7.7% of the privately owned electricity generated in Mexico in 2006.

CCGT is the technology of choice among independent producers. This technology represents 65.7% of the total electricity produced by private investors in Mexico.

With regard to nuclear power, the Constitution of Mexico established a monopoly for the Mexican government in matters pertaining to nuclear fuels and materials. Therefore, the government in Mexico has a monopoly on the generation of electricity from nuclear power.

The demand for electricity in Mexico

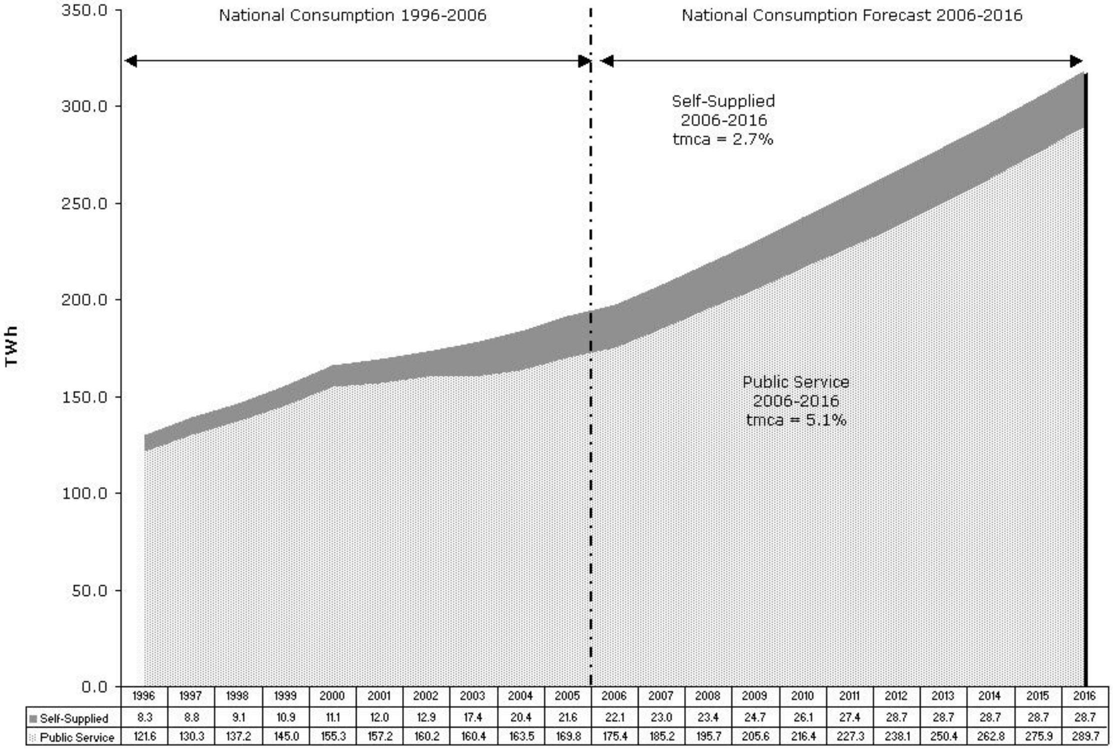
The demand for electricity in Mexico is of two types. The largest component is the demand for electricity publicly supplied by the CFE and LFC, generated either by the CFE or LFC or by independent producers. Secondly, there is self-supplied electricity, which may also result in private parties trading electricity with the grid.

The industrial sector is the largest consumer of electricity in the country with a 58.8% share of the total followed by the residential sector with 25.3% and the commercial sector with 7.5%. Despite the importance of the industrial sector, residential sector demand grew at a higher rate over the last ten years.

National consumption of electricity in 2006 was 197,435GWh representing a 3.2% increase over 2005, while GDP also increased by 3.2%. The officially expected increase in electricity demand for the period 2007-2016 (Figure 6) is based on the relationship of electricity consumption to the Gross Domestic Product (GDP) and population. The growth rate of the latter is estimated to be 0.9% for persons and 2.8% for households.

Current plans also are based on an expected decrease in real natural gas prices at an annual rate of 0.7%. Other important assumptions are the projections for self-generation, cogeneration and the introduction of new technology that helps reduce the demand of electricity where sensible. In summary, the planning scenario assumes a 3.6% annual increase in electricity demand for the nation as a whole. Reflecting the fact that more of the growth is expected in the currently urbanized areas, the forecast of electricity consumption of the SEN is an annual growth rate of 4.8%.

Figure 6: Forecasted National Consumption of Electricity 2007-2016



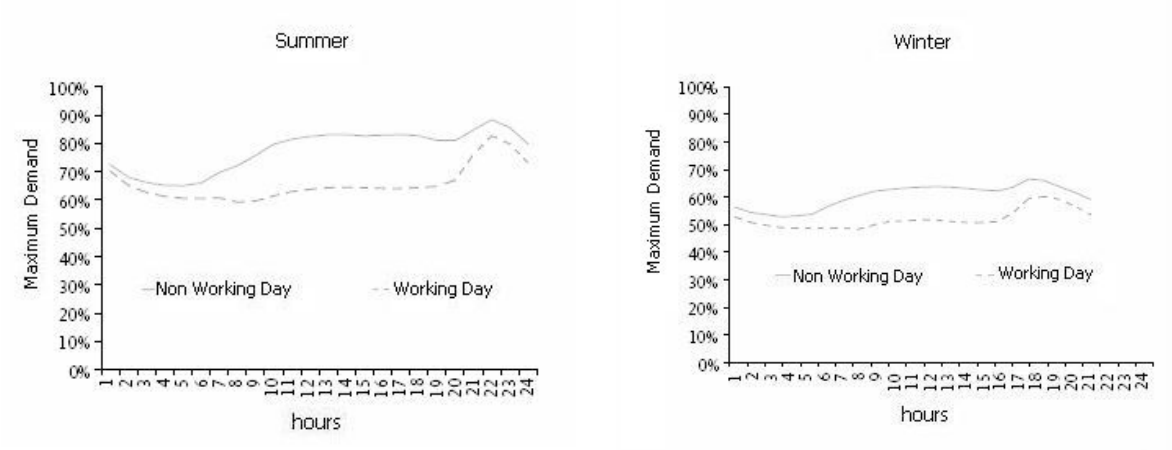
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
■ Self-Supplied	8.3	8.8	9.1	10.9	11.1	12.0	12.9	17.4	20.4	21.6	22.1	23.0	23.4	24.7	26.1	27.4	28.7	28.7	28.7	28.7	28.7
▨ Public Service	121.6	130.3	137.2	145.0	155.3	157.2	160.2	160.4	163.5	169.8	175.4	185.2	195.7	205.6	216.4	227.3	238.1	250.4	262.8	275.9	289.7

Source: Op. Cit. SENER 2006.

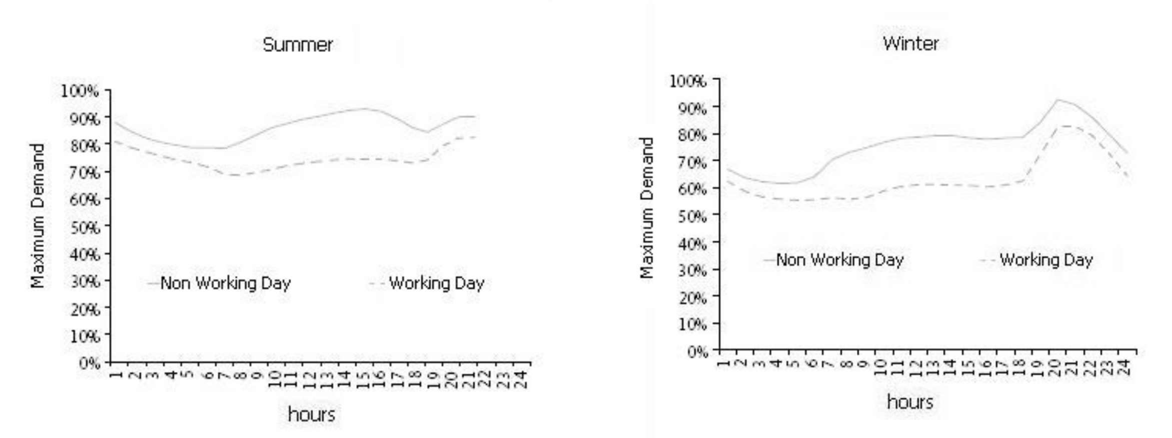
Given its geographical extent and diversity of economic structure and climates, Mexico also has a diversity of load curves. Figure 7 illustrates the load curve patterns for typical working and non-working days. The set of graphs is divided by season, summer and winter, and by region, north and south. The north shows high variations between summer and winter (around 30% of the maximum demand). Moreover, there are two sets of peak hours from 10:00 to 18:00 and from 21:00 to 24:00. The first peak is during the hottest portion of the day, while the second one reflects the large number of air conditioners used at night. In the south, the differences between summer and winter are less pronounced, although the period from 20:00 to 23:00 hours represents the peak hours during the day.

Figure 7: Load Curve by Region, Season and Day

(a) South



(b) North



Source: Op. Cit. SENER 2006.

The Mexican load curve is actually relatively flat compared to the curve encountered in many countries. This pattern may be partly explained by the introduction of peak hour pricing for industrial consumers.

The tariff structure for electric energy is divided according to usage and voltage level. The tariff structure for medium and high voltage, and for high consumption residential service, is more complex than the normal residential tariff structure. The complex tariffs depend on marginal cost and a monthly automatic adjustment that depends on changes in fuel prices and inflation over the previous month. Moreover, the tariff structure also depends on geographical location, time and season.

Apart from the agriculture tariffs, which are adjusted annually, all other tariffs are adjusted monthly. The residential (except for high consumers) and public service tariffs are adjusted by fixed factors. The remaining tariffs are adjusted by an "automatic monthly adjustment" that, as we mentioned earlier, includes variations in the fuel price and inflation.

As in many other countries, the commercial sector has the highest mean prices among all final users. Economists often speculate that this might reflect the fact that the elasticity of demand is lowest in this sector. Meanwhile the agriculture tariff is the lowest.

Electricity losses in Mexico are quite significant, amounting to 17.6% of the electricity generated. Technical losses arise in transmission, generation and self-use of electricity. Non-technical losses are usually from theft by the informal commercial sector and other clients who evade payment. In 2006, the non-technical losses represented 8.7% of total generation and around 50% of the total of losses of electricity.

Mexico Generating Capacity

In 2006, Mexico had a total generating capacity, including exports, of 56,337 MW, which represented a 4.6% increase over 2005. The total effective capacity managed by the CFE but constructed by independent producers rose from 8,251 MW in 2005 to 10,387 MW in 2006. Independent producers can also export electricity or use it themselves. Some licensed suppliers also have not yet started producing.

Hydrocarbons generate 64.6% of the total electricity produced. Moreover, natural gas is used to produce 42.6% of the total electricity generated for public consumption (rising from 12.1% in 1996), compared to 21.6% generated from residual fuel oil and only 4.8% from nuclear power. Natural gas is mainly displacing residual fuel oil, yielding substantial environmental benefits.

Hydroelectric plants supply around 13.6% of the total electricity generated for public consumption. The CFE has invested in hydroelectric plants with large capacities, such as El Cajón (750MW) and La Yesca (750MW). Three hydroelectric investment projects, La Parota (900MW), the expansion of Villita (150MW) and Rio Moctezuma (114MW) will be completed within the next five years.

Since hydroelectricity storage capacity is limited, electricity generation has to approximate demand most of the time. The electric system thus also needs reserve capacity to satisfy the demand for electricity in case there are technical transmission problems or some generating capacity goes off-line. In Mexico, the reserve capacity of the system, and hence the future investment in electricity generation capacity, is determined through a deterministic. An Operational Reserve Margin (ORM)[17] of 6% is targeted. In 2006, the ORM was 14.0% partly due to the lower than expected economic growth. From 2011 onwards, the ORM is expected to decline to 6%.

Prospects for Nuclear Investment in Mexico

In principle, a number of factors make nuclear power an attractive option for Mexico. The relatively flat load curve with a reasonable quantity of hydroelectric capacity that can be used to shave remaining peaks off the load implies that Mexico has quite a large base load that can be cost effectively served with nuclear power. The substantial natural gas capacity could also complement nuclear and hydroelectric power by serving the intermediate part of the load curve.

In addition, the demand for electricity is expected to grow quite rapidly in the near future requiring a substantial expansion in generating capacity. A relatively large percentage of the demand, and the expected demand growth, also is concentrated in the Mexico city area and could be conveniently served by large base load nuclear power generators. Using nuclear power to supply more of the Mexico City load would also have the advantage of limiting air pollution in that region.

Finally, Mexico already has one nuclear power plant, Laguna Verde, which has two boiling water reactors (BWR-5) with total capacity of 1364.88 MWe. The steam cycle was constructed by General Electric and the generator by Mitsubishi Heavy Industries. The construction of Laguna Verde started in October of 1976 and the second unit achieved criticality in September of 1994. The first reactor entered online in July of 1990 and the second unit in April of 1995.

The last investment prospectus from the CFE emphasized coal and renewable energy (wind, geothermic and hydroelectric) over nuclear as a way to diversify electricity

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[17] The Operational Reserve Margin is defined as the difference between the Effective Gross Capacity and the Maximum Demand over the Maximum Demand.

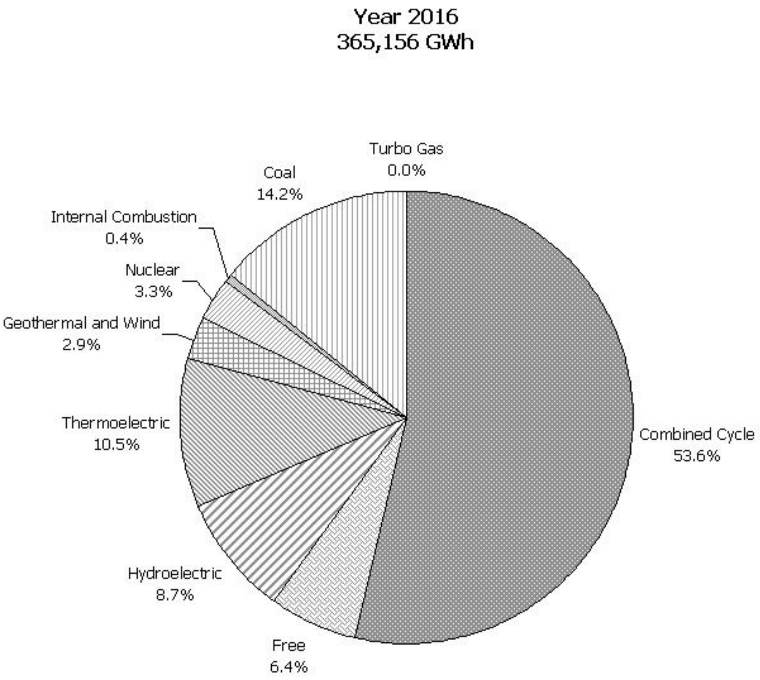
generation capacity. However, while Mexico produces some coal it currently consumes more than it produces. Hence, an increase in coal-fired capacity would require more coal imports. New coal-fired capacity would also be less satisfactory than expanding nuclear from the perspective of limiting local air pollution problems.

For the period of 2007-2016 the CFE plans to add 22,153MW out of which 5,498MW is already under construction or tendered. Moreover, 5,867MW are planned to be retired. The most recently tendered construction projects are composed of 2,677MW of CCGT, 678 MW of coal, 416 of distributed capacity (small turbogas plants), 184 MW of wind power, 1,500MW of hydroelectric power, and 42MW of internal combustion. The last of these to be completed are expected to enter operation in 2012.

An additional capacity of 16,187 MW that has not yet been tendered will be installed in the period of 2009-2016. Although these projects haven't been completely defined, CFE has suggested the location and technology for some of them. Specifically, they have suggested 8,385 MW (51.8%) of CCGT, 2,100 MW (13.95%) of coal capacity, 1,164 MW (7.2 %) of hydroelectric capacity, 406 MW of wind power, 158 MW of geothermal capacity, 69 MW internal combustion leaving 3,826 MW (23.64%) with the technology currently unspecified. Figure 8 shows the expected generation of electricity by type of fuel in 2016. Clearly, the bulk of the anticipated investment in Mexico is in natural gas, coal, hydroelectric and wind. Currently, there is no intention to increase nuclear generating capacity.

In particular, natural gas is expected to represent 53.6% of generating capacity by 2016. Unfortunately, a high proportion of natural gas, such as the one forecasted for Mexico, could compromise energy security. Mexico is forecast to become a large importer of liquefied natural gas, which will expose the electricity cost structure to fluctuations in the world price of natural gas. Increasing the proportion of nuclear would reduce the sensitivity of electricity costs to such price fluctuations. Furthermore, nuclear fuel is amenable to being stored in a strategic stockpile as insurance against unforeseen short-term disruptions to energy supplies as Mexico currently does with coal. While Mexico does not currently have large-scale natural gas storage, the Mexican industrial and petroleum company Cydsa recently asked permission to use salt caverns on the border between Veracruz and Tabasco states for such a purpose.

Figure 8: Expected Generation by Fuel in 2016



Source: Op. Cit. SENER 2006.

Admittedly, natural gas plants can be viewed as similar to a financial option in the sense that natural gas plants can be used less if natural gas prices are relatively high. This is only feasible, however, if there is sufficient non-gas capacity to meet demand during those periods. If demand has instead to be curtailed through high electricity prices, there are likely to undesirable macroeconomic consequences as we analyzed for the case of Japan discussed above.

The state monopoly on the use of nuclear power remains a relatively large obstacle to its use. In contrast to coal, natural gas, wind and even hydroelectric plants, nuclear power plants can’t be operated by private investors under the Mexican constitution. Given the large up-front cost of constructing nuclear plants, and the many needs of the Mexican government for funds to invest in other infrastructure, it is not surprising that there aren’t plans to increase nuclear generating capacity. Regrettably, institutional factors in this case can impede the diversification of generating capacity in Mexico.

Comparing CCGT to Nuclear Power Plants in Mexico

In this section we present a brief summary of the more extensive comparison presented in González-Gómez (2008). We compare the total costs of nuclear and CCGT for the generation of electricity when natural gas prices are uncertain. Unfortunately, the comparison is made under the limiting assumption of a constant capacity factor. As mentioned above, a constant capacity factor implies that natural gas plants can't be used less if natural gas prices are high. This tends to increase the levelized costs of natural gas plants. Hence, a constant capacity factor places an upper bound to the uncertainty of the levelized costs of CCGT. On the other hand, assuming a constant capacity factor limits the macroeconomic consequences of fluctuations in natural gas prices.

Total costs are compared by comparing the resulting the distributions of levelized costs. Specifically, the distribution of levelized costs for CCGT is solely a function of uncertainty in natural gas prices. We assume that both plants will enter on-line in 2014. We assume that a CCGT takes 3 years to construct while a nuclear power plant would take 5 years. We also assume that combined cycle plants have an economic life of 30 years compared to 40 years for nuclear power plants.

González-Gómez (2008) characterizes the uncertainty of natural gas prices by separating past price movements into two components: a short-term component and a long-term component (discussed in more detail below). These characterizations were then projected into the future to obtain realistic scenarios for evaluating the relative costs of CCGT and nuclear power. The forecast of the long-term component is based on the Annual Energy Outlook for 2007.

Finally, we also present a sensitivity analysis for some key parameters that determine the levelized costs of nuclear and combined cycle natural gas technologies.

Levelized Costs

Denote the capacity factor for technology $i=N, CC$ as ϕ_i, the overnight costs[18] per megawatt of capacity as K_i, the proportion of overnight costs incurred in period t for technology i as $\gamma_{i,t}$, the maintenance and operating costs per megawatt of capacity per

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[18] The overnight cost of a construction project is the amount that would have to be paid as a lump sum at the beginning of construction in order to completely pay for construction costs.

year as M_i, fuel costs per megawatt hour[19] at time t as $\rho_{i,t}$ and the discount factor as r. Then, the discounted total cost per megawatt of capacity from technology $i=N,\ CC$ is given by:

$$TC_i = \sum_{t=0}^{4} \gamma_{i,t} \frac{K_i}{(1+r)^t} + \sum_{t=5}^{T_i+5} \frac{8760\phi_i \rho_{i,t} + M_i}{(1+r)^t} \tag{1}$$

The levelized costs of technology i, C_i, then solves:

$$TC_i = 8760\phi_i C_i \sum_{t=5}^{T_i+5} (1+r)^{-t} \tag{2}$$

The fuel cost for combined cycle plants, $\rho_{CC,t}$, is given by heat rate times the natural gas price at Henry Hub minus .58 USD/MMBtu.[20] We convert the present value cost in (1) to a levelized cost in (2) to take account of the fact that CCGT plants do not last as long and therefore have to be replaced more frequently. The levelized cost represents the constant annual payment that would be required to build a repeating sequence of plants of the given type forever into the future.

The levelized costs for a mix of generating capacity is then given by $(1-q_N)C_{CC}+q_N C_N$. The rest of this section focuses on the analysis of the distribution of levelized costs.

Natural Gas Prices

As we already mentioned, Gonzalez-Gomez (2008) characterizes natural gas price into two components: a short-term component and a long-term component. The prices were first transformed to limit the maximum possible value for the simulated natural gas prices.[21] The two components were then isolated using the Hodrick-Prescott filter. For this comparison we decided to use a Hodrick-Prescott filter consistent with 5 years representing the dividing line between long-term and short-term movements.[22] The short-term component was modeled as an EGARCH(1,1)xARMA(1,1) with seasonal effects.

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[19] In the case of natural gas, the fuel costs or generation costs is a random variable implying a distribution of levelized costs.

[20] This is the official assumption of the CFE with respect to natural gas prices.

[21] Specifically, for an assumed maximum feasible (real) price of p^*, the transformed series $\ln(-\ln(p/p^*))$ was analyzed. The forecast values then are guaranteed to lie between 0 and p^*. For this discussion, we focus on the results when $p^* = 25$ USD/MMBtu.

[22] Gonzalez-Gomez (2008) discusses the statistical fit for several alternative definitions of the dividing line between short-term and long-term components and for different maximum prices p^*.

The high, low and reference price scenarios for Henry Hub natural gas prices presented in the Energy Information Administration's (EIA) Annual Energy Outlook (2007) were used to create the support for the possible forecast distributions of the long-term component. Unfortunately, the long term forecast of the Energy Information Administration ends in 2030. Therefore, we extend the forecast for the period 2031 to 2043 by extrapolating the linear trend from 2026–2030 to the period 2031–2043 as illustrated in Figure 9.[23]

Figure 9: Extension to the long-term component of natural gas prices.

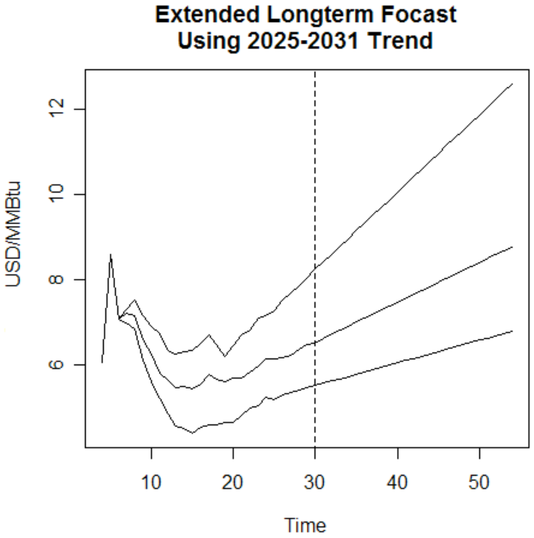

Figure 10 presents selected percentiles of the resulting distribution of future natural gas prices over the period the plants would be expected to operate. The interpretation of this graph is as follows. For a given month and year, say October 2025, the 0.99 percentile line gives a real natural gas price that is greater than 99% of the simulated prices, the 0.70 percentile line gives a real price greater than 70% of the simulated prices and so forth. The systematic pattern in these percentile lines is a result of the pronounced seasonality in natural gas prices. Prices have a much larger probability of being high in certain months and low in other months. Also noticeable in the figure is the asymmetry in price movements. In months when prices can be high (the middle of winter) there is also a much higher chance that prices will spike up (when the weather is more severe that

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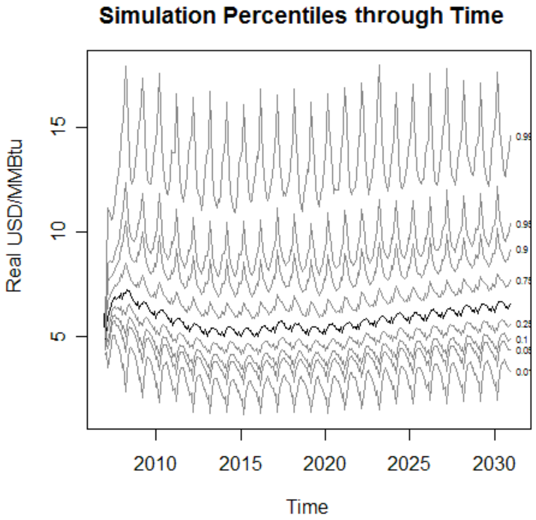
[23] Again, Gonzalez-Gomez (2008) presents more alternatives but we decided to choose the scenario that is most pessimistic for the levelized cost of CCGT relative to nuclear power.

anticipated). On the other hand, the movements down to lower prices (when the unexpected news favors lower prices) are much smaller. This asymmetry essentially reflects the effects of limited capacity. When demand is very high, capacity constraints limit the ability to cope and prices have to rise. When demand is unexpectedly low, however, opportunities to store more gas would mute the price declines.

Figure 10: Selected Percentiles of the chosen long-term simulation of HHNG prices.



Cost Estimates

Gonzalez-Gomez (2008) used the costs estimates from the Nuclear Energy Agency and the International Energy Agency in 2005, EIA (2005), to obtain suitable values for the cost structure of nuclear and combined cycle natural gas plants.

Table 1 summarizes the range of the parameters and the reference scenario that we analyze. We choose the same cost structure ranges as Gonzalez-Gomez (2008). In particular, given the experience of Mexico with combined cycle plants, an overnight construction cost for combined cycle plants in the middle of the 430 to 860 USD/kWe range is used in the reference scenario. We also assume that 10% of the costs are in the first year, with 45% being covered for each of the two subsequent years. For the heat rate, we will use 6.83 MMBtu/MWh for the reference scenario and a range from 5.68 to 8.53 MMBtu/MWh for the sensitivity analysis.[24] We will use 27.5 USD/kWe for the reference

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[24] The selected range corresponds to a 40% to 60% range of efficiencies for combined cycle plants.

scenario for maintenance and operating costs. Finally, for the basis differential between natural gas prices in Mexico and at the Henry Hub we use the official assumption of minus .58 USD/MMBtu. The price corresponds to the delivered price at the new liquefied natural gas terminal in the Pacific Ocean (Manzanillo).

Table 1: Ranges and reference scenario for key parameters.

	CCNG Plants		*Nuclear Plants*	
Parameter	***Range***	***Ref.***	***Range***	***Ref.***
Overnight Construction Costs (USD/kWe)	430-860	645	2,500-4,000	3,000
O&M (USD/kWe)	NA	27.5	NA	98.75
Heat Rate (MMBtu/MWh)	5.68-8.53	6.83	NA	NA
	Common to both technologies			
Discount Rate	5.0-9.0	7.0		

In the case of nuclear power plants, we assume a 5 year construction period with capital costs distributed equally at each year.[25] Nuclear fuel costs in EIA's 2005 study ranged from 3.5 USD/MWh in Canada to 13 USD/MWh in Japan. We will use 8.25 USD/MWh.[26] Maintenance and operation costs ranged from 50 to 115 USD/kWe. We will use 98.75 USD/MWh. Overnight capital costs ranged from 1,050 to 2,150 USD/kW. However, the ranges seemed obsolete given recent estimates of 2,500 to 4,000 USD/kW by Florida Power and Light, Progress Energy, EdF Flamanville, Bruce Power Alberta, and others.[27] We selected 3,000 USD/kW as the reference scenario. Finally, it is important to note that Mexico is expected to have lower nuclear power costs than United States given the large regulatory burden faced by public companies in the United States.

We select a 7.0% rate for the real discount factor in the reference case, with a relatively large range of 5.0% to 9.0%. It is important to mention that we are referring to the after tax real rate of return. Therefore, 9% is relatively high even for a country such as Mexico.

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[25] According to the NEA/IEA costs update, for projects taking more than 5 years around 90% of the costs are within the first 5 years after construction commences. The extra time is usually spent in pre-construction studies.

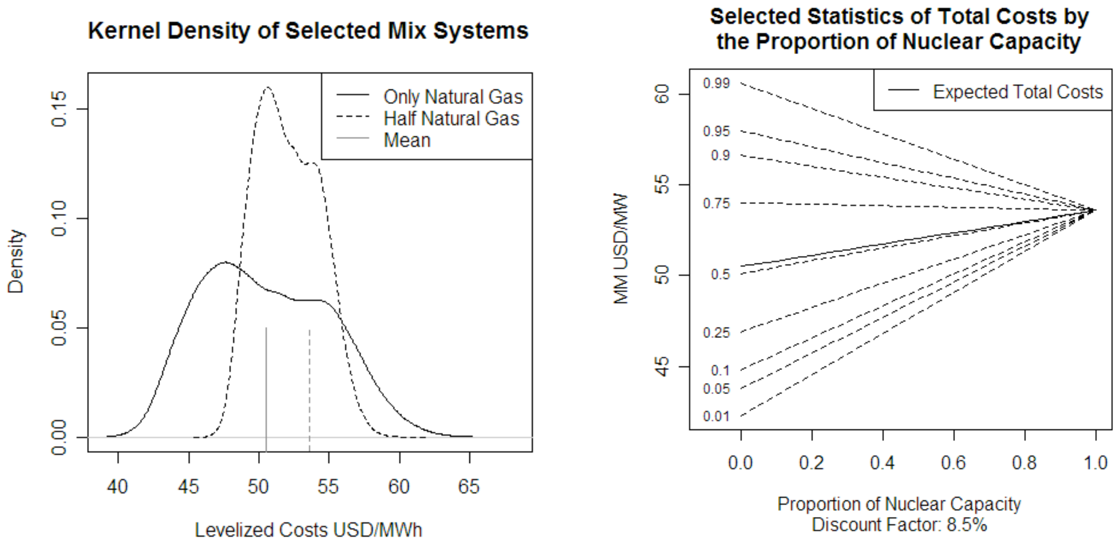
[26] It is important to mention that fuel costs include every stage of the fuel process: from mining and processing to final disposal.

[27] The information is publicly available from the World Economic Association, http://www.world-nuclear.org/info/inf02.htm.

Levelized Total Costs

Using the simulated distribution of natural gas prices and the above parameters, Figure 11 shows the kernel density estimates of the distribution of levelized costs for 50% or 100% combined cycle and selected percentiles of the distribution of levelized costs as the proportion of nuclear power increases. Note that under our assumptions that only natural gas prices are uncertain, the levelized costs are constant if all the capacity is nuclear.

Figure 11 Selected Statistics of the Distribution of Levelized Costs.



The average levelized costs of combined cycle plants is 50.50 USD/MWh with a maximum in 10,000 observations of 68.23 USD/MWh and a minimum of 39.03 USD/MWh. The estimated standard deviation equals to 4.52 USD/MWh. On the other hand, the levelized cost of a nuclear plant in the reference scenario is 53.60 USD/MWh, or around 3.10 USD/MWh higher than the *average* cost of a natural gas plant.

With equal capacities of nuclear and natural gas plants, the average levelized cost increases by 1.55 USD/MWh, but the range is narrowed from 39.03–68.23 to 46.32–60.92 USD/MWh. On the other hand, the 90th percentile is reduced from 56.65 to only 55.13 USD/MWh, so the probability that increasing the nuclear proportion to 50% will save substantial costs is not large. The lower probability of incurring very high costs as the proportion of nuclear power increases represents the energy security value of nuclear power, while the increased average cost in a sense represents the "insurance premium" needed to limit cost increases. More generally, Figure 11 clearly shows the increase in mean and decrease in variability of levelized costs as the proportion of nuclear power increases. For the reference scenario, the optimal investment proportion lies somewhere between zero and 100% depending on the trade-off between higher average costs and the reduced variability.

In the following, we will analyze the sensitivity of our results to the selected parameters of the reference scenario.

Overnight Costs

Figure 12 shows an example of the three types of graphs that we will use to analyze the sensitivity of the distribution of levelized costs, and thus the potential energy security benefits of nuclear power, to changes in the reference parameters. In a nutshell, the bottom of Figure 12 shows the benefits from nuclear power, while the top shows its costs.

In all three graphs in Figure 12, the overnight cost of a nuclear power plant is the dependent variable graphed along the horizontal axis. In subsequent figures, the sensitivity to different parameters will be examined so a different set of values will appear on the horizontal axes of each component graph.

The top graph in Figure 12 shows the *mean* levelized cost for three different proportions of nuclear plants in the system – 0% (all CCGT), 50% of each type, and 100% (all nuclear). At a level of 2,717 USD/kW for nuclear overnight cost, nuclear power plants have the same levelized cost as the mean value for natural gas plants. Unfortunately, nuclear levelized costs are very sensitive to overnight capital costs. For the range of values given in Table 1, levelized costs go from a low of 48.13 USD/MWh to a high of 64.54 USD/MWh. An increase in 60% in overnight costs (from 2,500 to 4,000 USD/MWh) implies a 25.42% increase in levelized costs from nuclear power. This is a large effect compared to corresponding effect of overnight costs on combined cycle plant levelized costs as we will see below.

The bottom left graph of Figure 12 shows the *probability* that combined cycle levelized costs are lower than nuclear levelized costs also as a function of the overnight costs of nuclear power.[28] In particular, the probability that combined cycle levelized costs could

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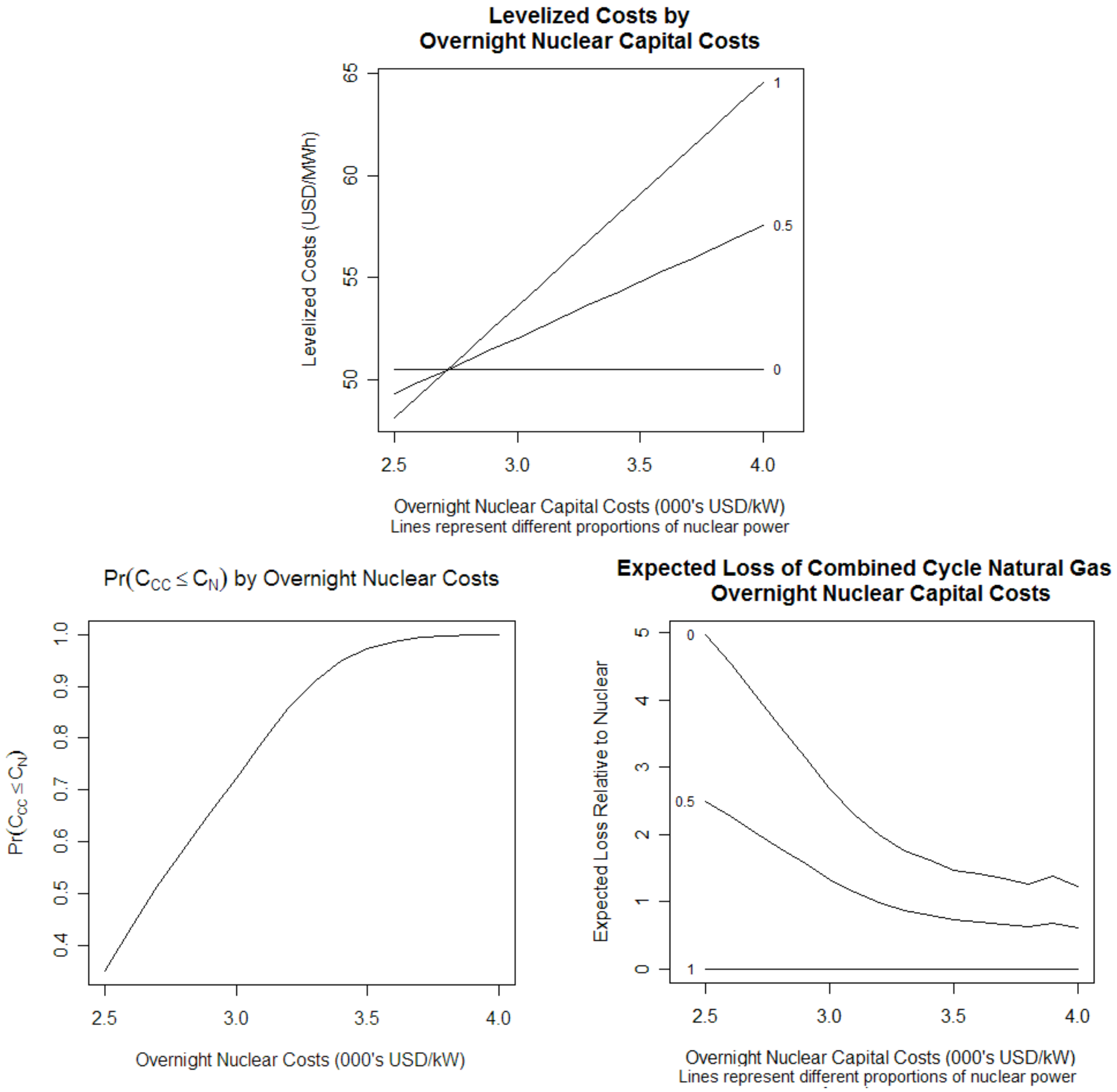
[28] Notice that this probability does not depend on the proportion of nuclear power since:

get as high as 64.54 USD/MWh (the maximum levelized costs of nuclear power when overnight costs are 4,000 USD/kW) in the simulations is less than 1%.

Figure 12 Costs and benefits from nuclear as a function of nuclear overnight cost.



Finally, the bottom right graph of Figure 12 in a sense represents the "option value" of the nuclear capacity, again graphed for three different proportions of combined cycle plants in the system. Specifically, the figure shows the *expected* loss due to high realizations of natural gas prices. Thus, the 0% nuclear capacity curve represents, for each value of nuclear overnight costs on the horizontal axis, the excess cost of CCGT

$$Pr(q_{CC}C_{CC} + (1- q_{CC})C_N < C_N) = Pr(C_{CC} < C_N).$$

relative to nuclear times the probability that CCGT costs will be that high summed over all natural gas prices where CCGT costs are higher.[29] For example, in the reference case where the overnight nuclear costs are 3,000 USD/kW, a gas plant would be expected to incur slightly below 3 USD/MWh in additional levelized costs relative to a nuclear plant in those instances when the CCGT would be more expensive. This is less than the 3.10 USD/MWh difference in expected levelized costs of the two plants under the reference case. We call nuclear power *profitable* (in an expected value sense) if the expected loss of combined cycle plants relative to nuclear power is larger than or equal to the difference in expected levelized costs. In this case, nuclear power is *profitable* at an overnight nuclear cost below 2,972 USD/kW. It is important to note that these "option values" only represent the reduction in expected average costs from limiting the effect from high realizations of the natural gas price. There would be additional energy security benefits from increasing the proportion of nuclear plants in the system because they reduce the *variance* or volatility of levelized costs.

For combined cycle plants, the overnight costs in Table 1 range from a minimum of 430 to maximum of 860 USD/kW. The corresponding *average* levelized costs range from 47.91 to 53.09 USD/MWh, which implies that a doubling of the overnight costs of combined cycle natural gas plants implies only a slight increase of 10.8% in the average levelized cost. This reflects the fact that capital costs are a smaller proportion of total costs for CCGT plants. The benefits of nuclear power increase as the overnight costs of CCGT plants increase. Nevertheless, for the reference case overnight costs of nuclear power, the levelized costs of nuclear exceed the average levelized costs of the combined cycle plants even at the maximum overnight costs for CCGT.

Discount Factor Analysis

The other parameter that significantly affects the levelized costs and the relative benefits of nuclear power is the discount factor. The effect of the discount factor on levelized costs depends on the *time profile* of the cost components. The easiest way to explain this is to consider two extreme cases. In one case, imagine that all the costs are immediate and there are no future operating or maintenance costs. In that case the total costs according to equation (1) will not depend on the discount factor r. However, equation (2) then shows that the levelized costs must rise as r increases. In the other extreme case, suppose

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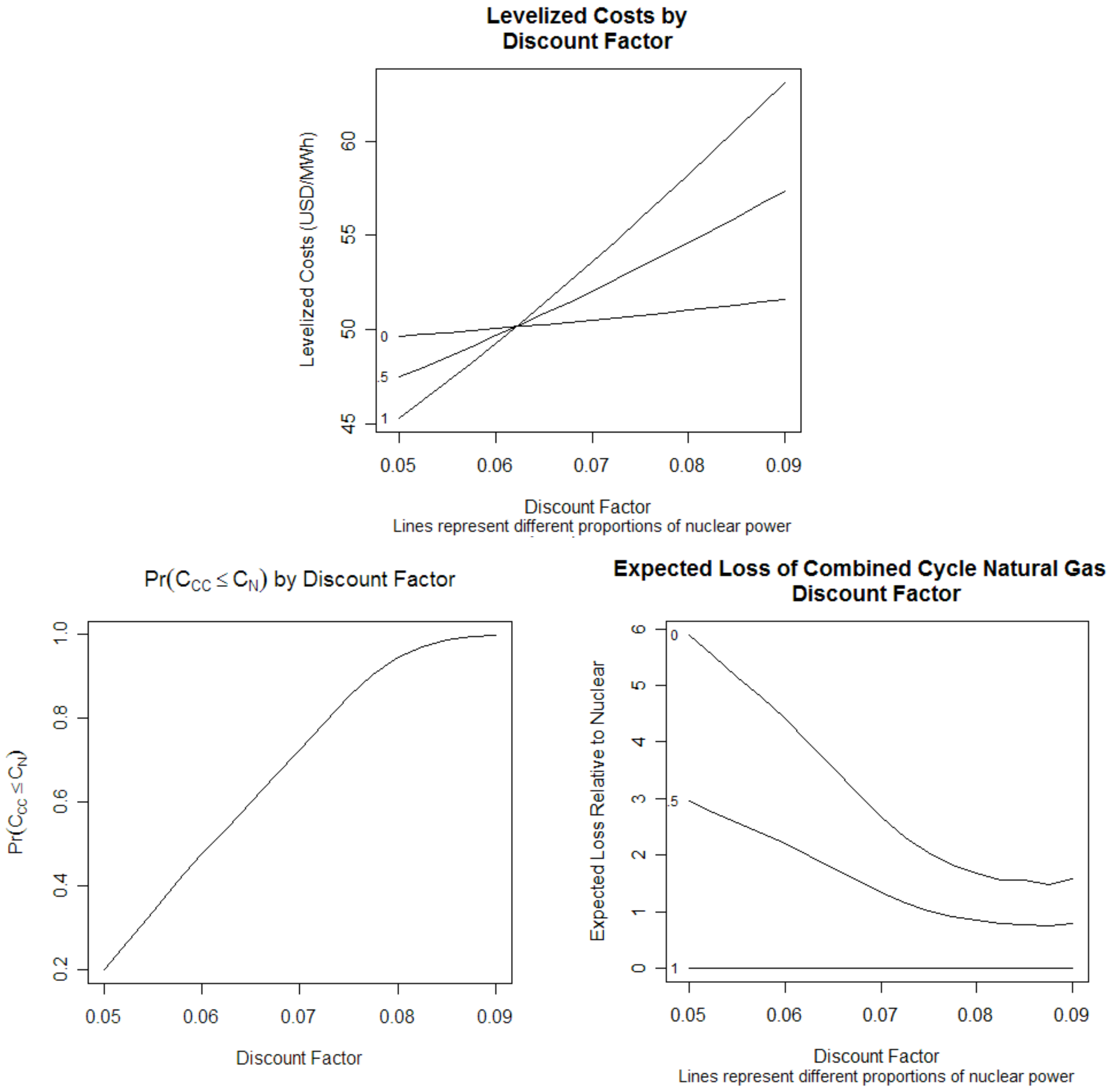
[29] In mathematical notation, the value graphed is the conditional expectation $E\{C_{CC} - C_N \mid C_{CC} \geq C_N\}$.

the costs are entirely operating and maintenance costs and are identical for each year of the plant's life. Then equations (1) and (2) together imply that the levelized cost would equal the fixed annual charges and thus would be independent of r.

Figure 13 Costs and benefits from nuclear as a function of the discount factor.



Levelized Costs by Discount Factor

$Pr(C_{CC} \le C_N)$ by Discount Factor

Expected Loss of Combined Cycle Natural Gas Discount Factor

In the reference case we assumed a relatively high real after-tax discount factor of 7.0%. We selected a range from 5% to 9% to perform the sensitivity analysis. Figure 13 shows the resulting expected costs and benefits from nuclear power as a function of the discount factor.

Since the nuclear plant is more like the first extreme case mentioned above, and CCGT more like the second, we expect an increase in *r* to raise the levelized cost of nuclear more than CCGT. This is exactly what the first graph in Figure 13 shows. As the discount factor increases from 5% to 9% the levelized costs for nuclear power plants increase from 45.28 to 63.11 USD/MWh, while for CCGT they increase from 49.66 to 51.60 USD/MWh. Hence, a 44% increase in the discount factor implies a 4% increase in the levelized costs of combined cycle plants but a 28% increase in the levelized cost of nuclear power plants.

At a rate of 6.20%, the levelized costs of nuclear power and combined cycle plants are the same; while up to a discount factor of 6.92% nuclear power is *profitable* (in the expected value sense) under the reference case scenario.

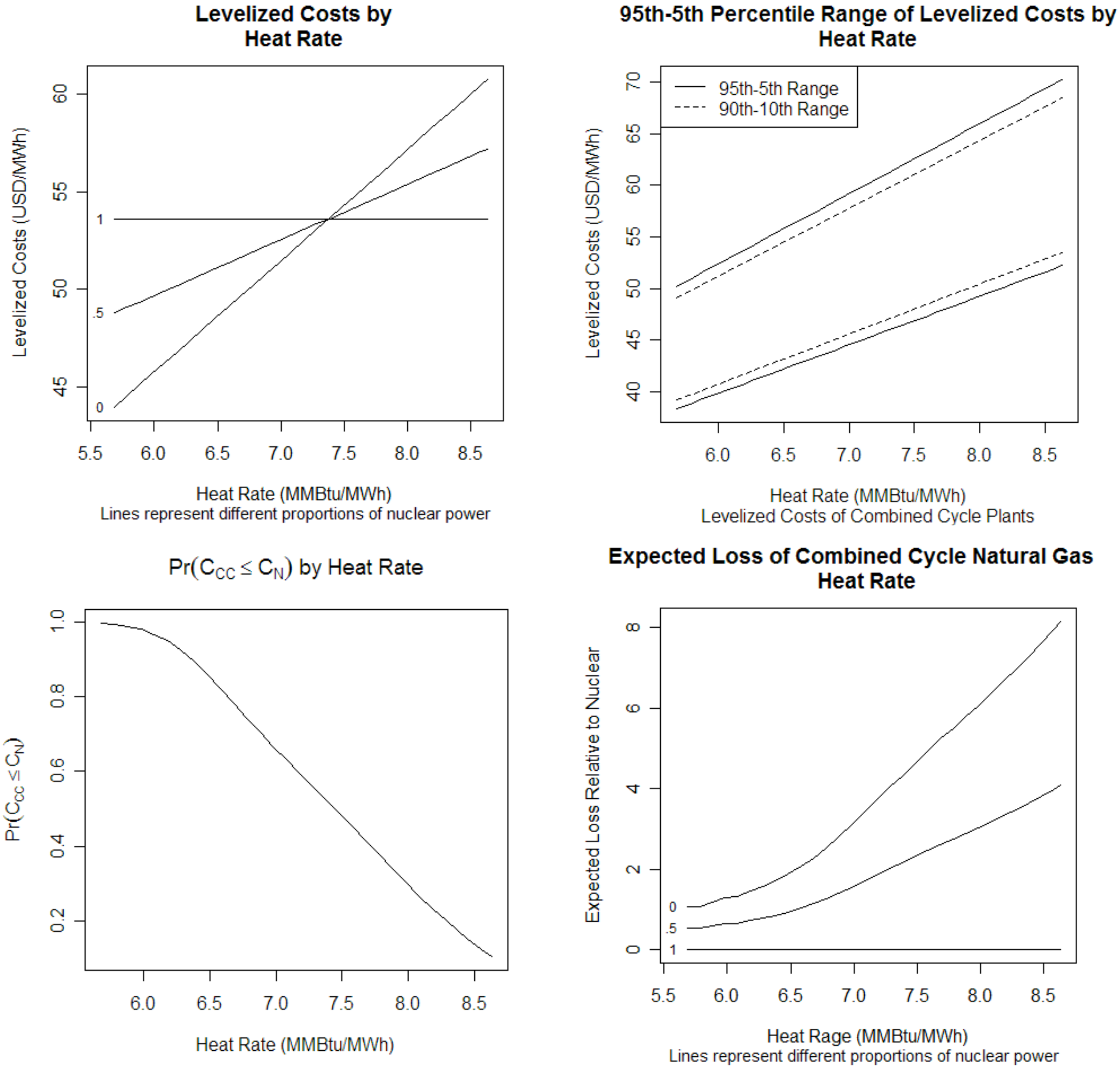
Heat Rate

Since fuel costs represent a large part of levelized costs for natural gas plants, changes in the heat rate have a very significant effect on the levelized costs of CCGT. The heat rate will also affect not only the expected value of the distribution of levelized costs, but also the standard error of the distribution. Specifically, an increase in the heat rate will riase the variability of CCGT levelized costs.

For the reference scenario, we assume a heat rate of 6.83 MMBtu/MWh, and for the sensitivity analysis a range of 5.68–8.63 MMBtu/MWh. Figure 14 shows the expected costs and benefits of nuclear power as function of the heat rate of combined cycle plants. As the heat rate increases and combined cycle plants become less efficient, the levelized costs of natural gas plants increases and the length of the 95th-5th range of CCGT levelized costs expands.

The levelized costs for combined cycle plants in the first graph of Figure 14 ranges from 43.97 to 60.73 USD/MWh. Therefore an increase of 51% in the heat rate implies an increase of 38% in the levelized costs of combined cycle plants. The heat rate is by a large margin the most significant parameter affecting the levelized costs of combined cycle plants.

Figure 14 Costs and benefits from nuclear as a function of the heat rate.



Nuclear power plants are *profitable* (in the expected value sense) for heat rates equal or above 6.88 MMBtu/MWh, while the levelized costs of nuclear and combined cycle plants are the same at a higher heat rate of 7.38 MMBtu/MWh.

The Energy Security Value of Nuclear Power

The sensitivity analysis showed that, for a given expected future distribution of natural gas prices, the overnight costs for nuclear plants, the discount factor and the CCGT heat rate largely determined the benefits of nuclear power relative to combined cycle plants. Clearly, for realistic future values of real natural gas prices, nuclear power plants remain competitive for a large range of overnight costs, small discount factors and high heat rates for combined cycle plants (less than 50% efficiencies). In addition, since a larger proportion of nuclear capacity would produce less variable costs, nuclear plants provide an additional benefit in so far as uncertainty in electricity costs has a negative macroeconomic effect. These additional benefits have not been accounted for in the above analysis. Nevertheless, although the benefits associated with limiting the uncertainty of total costs are present, they would not appear to be large enough to drive a new nuclear renaissance in Mexico.

Without high confidence in nuclear overnight costs and the discount factor, it is impossible for us to make any kind of recommendation with respect to the future of nuclear power in Mexico. Moreover, our comparison exercise clearly shows that uncertainty around the key parameters of nuclear power investment can easily overcome uncertainty of natural gas prices.

Conclusion

In this paper, we analyzed the current trends of nuclear power in the world. Our analysis indicates that the Three Mile Island and Chernobyl accidents, coupled in particular with the decreasing cost of using natural gas to generate electricity, have reduced support for nuclear power almost everywhere in the world. Notable exceptions are countries such as France, China, South Korea, India and Japan that place a high value on energy security or wish to pursue nuclear technology for its military benefits.

Next, we provided a short introduction to the economics of nuclear power. We emphasized that the cost structure of nuclear power helps diversify the generating capacity and thus provides insurance against uncertainty in electricity prices that can damage economic growth.

Finally, we argued that nuclear power faces many obstacles in developing countries including the large up-front investment costs, the large scale of the plants, and the high technological sophistication necessary to operate the plants. Simultaneously, the benefits can be equally large including diversification of the generating capacity, a reduction in urban air pollution and the ability to increase energy security at relatively low cost by stockpiling fuel.

Analyzing the case of Mexico in detail, we noted the institutional obstacles that limit investment in nuclear power. On the other hand, we also highlighted the degree of dependence of the Mexican electric system on natural gas. We then compared the levelized costs of nuclear power to the distribution of levelized costs from combined cycle plants. The latter were random because the future real costs of natural gas were taken to be random. We derived a realistic representation of these possible future costs by analyzing the structure of past natural gas prices and using projections of future possible price trends in as derived by the EIA. Although we found that nuclear power is competitive with CCGT for a large range of overnight investment costs, discount factors and combined cycle plant heat rates, uncertainty around key parameters of nuclear power can easily overcome the uncertainty in natural gas prices.

References

Energy Information Administration, United States Website: http://www.eia.doe.gov .

Gonzalez-Gomez, Jorge. *"Essays on Investment Planning in Electricity Generating Capacity",* Ph. D. Dissertation. Rice University, 2008.

International Atomic Energy Agency, *"Energy, Electricity and Nuclear Power Estimates for the Period up to 2030",* Referenced Data Series No. 1, IAEA, Vienna, 2007.

International Atomic Energy Agency, *"Nuclear Technology Review: 2006",* IAEA, Vienna 2006.

International Atomic Energy Agency, *"Nuclear Power Reactors in the World",* Referenced Data Series No. 2, IAEA, April 2006.

Nuclear Energy Agency and International Energy Agency, *"Projected Costs of Generating Electricity:2005 Update",*OCDE, 2005.

Nuclear Energy Agency, *"Nuclear Energy and the Kyoto Protocol",* OECD 2002.

Nuclear Regulatory Commission, United States of America Website: http://www.nrc.org.

OECD Multilingual Summaries, *"Uranium 2005—Resources, Production and Demand: Executive Summary",* OECD 2006.

Parker, Larry and Holt Mark, *"Nuclear Power Outlook for New U.S. Reactors",* Congressional Research Service Report for Congress, Updated March 9, 2007.

The Economic Future of Nuclear Power: A Study Conducted at the University of Chicago, University of Chicago, 2004.

The Future of Nuclear Power: An Interdisciplinary MIT Study, MIT, 2003.

Uranium Information Center, Australian Uranium Association Website: http://www.uic.com.au.

Wold Nuclear Association, *"The New Economics of Nuclear Power",* WNA Report

World Nuclear Association Website: http://www.world-nuclear.org.